Integration of Environmental Costs in Ontario's Pavement Management Systems

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.

Abstract

This study aims to quantify the health and environmental damages of emissions released by pavement management activities in Ontario. The construction, maintenance, and rehabilitation of pavement results in greenhouse gases and pollutants which have significant impacts on human health and the environment. Traditional lifecycle costing methods used in pavement management systems do not account for the cost of these impacts. Marginal damages which relate atmospheric releases to economic cost can be applied by decision-makers to understand the damages of activities (such as pavement management) but require careful consideration of underlying factors. Marginal damages from various methods across the literature were adjusted for application in this study. The present work quantified environmental costs for the construction and lifecycle maintenance of five pavement design alternatives based on emissions of carbon dioxide and four air pollutants. Concrete roads were found to have the highest environmental costs (equivalent to 77% of agency costs) whereas asphalt roads rehabilitated with Cold-in-Place recycling had the lowest environmental costs due to the reduction in raw materials used. For the asphalt road alternatives, environmental costs were equivalent to 35% of agency costs. Future work will address limitations in data availability and additional design types. These findings provide insight for further integration of externalities in pavement management systems including of noise, user costs, and use phase emissions.

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I would also like to thank the administrative coordinators at the Department of Civil and Environmental Engineering, Victoria Tolton, Eleanor Clarker, and Lisa Schneider, who work tirelessly to support all the students in this department.

On a personal note, I need to thank my family, my parents and siblings, who have always provided me support as well as reality checks when I needed them and who ensure that I never forget who I am. You are home. In addition, to all the friends, both here in Waterloo and farther in the GTA, Ottawa, Beirut, thank you for always being willing to listen to me and providing me with countless hours of distractions from work.

Finally, I would like to acknowledge that the work presented in this thesis was conducted at the University of Waterloo which exists on the Haldimand Tract, six miles of land on either sides of the Grand River, which were promised to the Six Nations of the Grand River in the Haldimand Proclamation of 1784. This land is the traditional territory of the Neutral, Anishinawbe, and Haudenosaunee Peoples.

Dedication

For my dadi, and my nani, both of whom I lost in the last year. I carry the grief of your loss in my heart. You are part of me.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

APEEP/ AP2	Air pollution emissions experiment and policy analysis model / version 2
BenMAP	Benefits Mapping and Analysis Program
CAMx	Comprehensive air quality model with extensions
CMAQ	Community multiscale air quality modelling system
CO	Carbon monoxide
CO_2	Carbon dioxide
CIR	Cold-in-Place recycling
CTM	Chemical transport model
EASIUR	Estimating air pollution social impact using regression
LCC/ LCCA	Lifecycle cost /lifecycle cost analysis
MD	Marginal damage
M&R	Maintenance & Rehabilitation
M&O	Mill and Overlay
MTO	Ontario Ministry of Transportation
NOx	Nitrogen oxides
SCAR	Social cost of atmospheric releases
SO_2	Sulphur dioxide
PaLATE	Pavement Lifecycle Assessment Tool for Environment and Economic Effects
PM_{10}	Particulate matter with diameter less than 10 microns
$PM_{2.5}$	Particulate matter with diameter less than 2.5 microns
PMS	Pavement management system
PSAT	Particulate source apportionment tool
RAP	Reclaimed asphalt pavement
USEPA	United States Environmental Protection Agency
VOC	Volatile organic compounds
VSL	Value of a statistical life
WMA	Warm-mix asphalt

1 Introduction

Air pollution and climate change are environmental issues which have significant effects to human and social systems including damages to agriculture, infrastructure and contribution to premature mortality. While these effects have economic consequences, they are not presently valued in the traditional pricing of goods and services. This study values the damages of pollution from pavement management activities in Ontario and includes them in the prices of road construction as an example for such applications across economic sectors.

1.1 Atmospheric Releases

Atmospheric releases refer to the release of any chemical species into the atmosphere. Certain species are considered air pollutants, or climate forcers based on their impacts to human health or contribution to climate change respectively. Many species may be considered both an air pollutant and a greenhouse gas. The effects of four common air pollutants and one greenhouse gas are described in Table 1.1. The four pollutants are listed as criteria air contaminants by Environment and Climate Change Canada for their impacts to human health and contribution to ground level ozone, haze, and acid rain (Environment and Climate Change Canada, 2017). These include fine particulate matter which has a diameter of 2.5 microns or less ($PM_{2.5}$), nitrogen oxides (NOx), sulphur dioxide (SO_2), and carbon monoxide (CO). In addition to these five pollutants, carbon dioxide (CO_2), a greenhouse gas which contributes to climate change was also considered in this study.

Table 1.1 Atmospheric releases examined and their impacts to health and the environment; adapted from Shindell (2015)

	Effect on global mean surface temperature	Enhanced regional hydrologic cycle impact	Pathways to health impact
$PM_{2.5}$	Warming & Cooling[a]	✓	Surface $PM_{2.5}$
SO_2	Cooling	✓	Surface $PM_{2.5}$
NOx	Cooling	✓	Surface $PM_{2.5}$ & ozone, NO_2[b]
CO	Warming		Surface ozone
CO_2	Warming		

[a] $PM_{2.5}$ is made up of organic and inorganic particles, which have varying effects on mean global temperature

[b] In addition to contributing to O_3, and $PM_{2.5}$, NO_2 is also considered to have direct adverse health effects (Environment and Climate Change Canada, 2017)

The effect on global mean surface temperature describes whether the pollutants contribute to climate change and its subsequent effects such as changes to weather patterns and an increase in tropical diseases (Environment and Climate Change Canada, 2015b). The enhanced regional hydrologic cycle impact refers to effect of atmospheric releases on precipitation at a regional scale which would affect agricultural yields, thereby impacting human health. The health impacts of the pollutants are described in terms of their contribution to surface ozone or fine particulate matter, the two most harmful pollutants to human health. Exposure to these pollutants has been linked to an increased risk of cardiac and respiratory diseases, as well as an increased risk of premature mortality. $PM_{2.5}$ can be directly emitted in to the atmosphere (known as primary $PM_{2.5}$) or it can be formed through chemical reaction of pollutants such as NOx and $SO_{2,}$ which is known as secondary $PM_{2.5}$. Ground level ozone which refers to ozone in the troposphere, is formed through atmospheric reactions between NOx and volatile organic compounds (VOCs) (Environment and Climate Change Canada, 2017).

The unique effects of these atmospheric releases and their contribution to environmental and health damages will be evaluated in this study to understand the full impacts of pavement management activities.

1.2 Marginal Damages

Pollution is an environmental externality as the costs of pollution are not borne by polluters. The private cost of a good or service, which refers to the cost paid to consume that good or service, does not include the social and environmental costs created in the production or consumption of the good or service. These environmental and social costs which fall outside the private costs, are referred to as externalities, and are an example of a market failure. Environmental externalities are often accounted for through regulations which attempt to internalize pollution costs through fines or pollution limits. Policies such as a carbon tax and cap and trade programs are examples of instruments that internalize costs by placing a price on carbon dioxide emissions or by converting it to a market good which can be bought and traded, respectively.

Marginal damages are meant to represent the social cost of pollution based on the damage caused to society and the environment. The term 'marginal' refers to the cost of environmental damages caused by an additional unit of pollution. Figure 1.1 shows a typical total cost curve, and indicates an example marginal damage curve from which it is derived. The curve assumes that there is a threshold pollution level below which there are no environmental damages, and, damages increase with pollution.

The steps in a full impact assessment of calculating marginal damages associated with atmospheric releases are outlined in Figure 1.2. A change in atmospheric releases is modelled to evaluate overall change in ambient atmospheric concentration. Concentration response functions from the epidemiological literature and population demographics for the location of interest are used to determine the health related impacts of the concentration change. The final step involves the valuation of impacts to calculate the damages in economic terms.

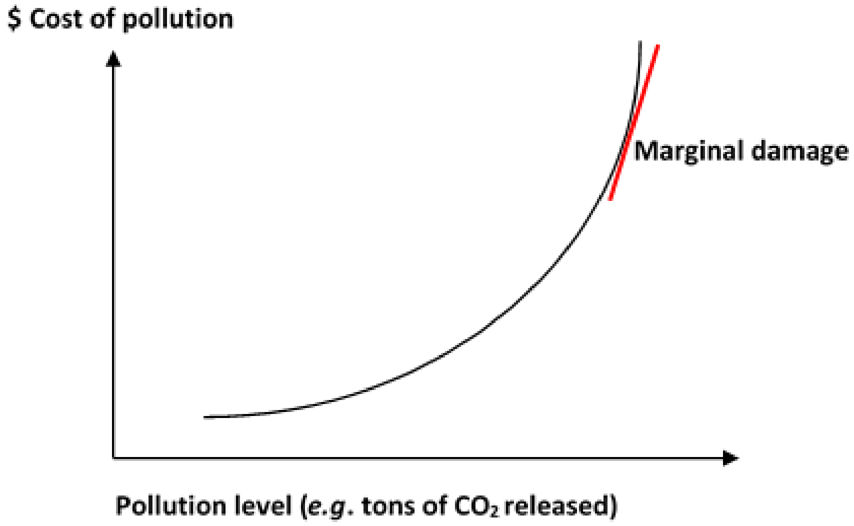

Figure 1.1 Typical marginal damage curve (relationship between pollution level and cost of environmental damages)

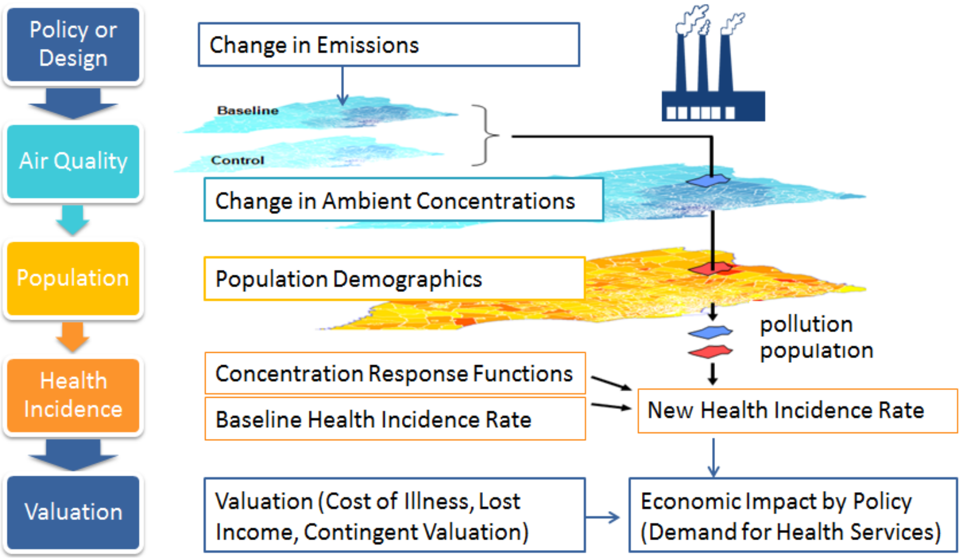

Figure 1.2 Full impact assessment required to calculate damages from atmospheric releases (Saari, 2018)

This process and results of such an impact assessment can vary greatly based on the selection of input parameters for each step in Figure 1.2, and can include additional processes and impacts beyond those affecting human health. The emissions scenario is based on the pollutants of interest for a particular source or region. The choice of atmospheric model requires a trade-off between complexity and computational resources. Atmospheric models can range from state-of-the-art chemical transport models (CTM) which have high resolution and account for the full atmospheric fate and transport of emitted species to low resolution simple dispersion models.

The demographics of the population would be based on the specific time and location for which the assessment is conducted. These factors are significant as they change over time and space. The baseline health incidence rate refers to the baseline rate of a health risk in a population prior to the emissions scenario analyzed in an impact assessment. The change from the baseline incidence rate is used to determine the impacts which can be directly attributed to the emissions scenario. This baseline data also varies over time and space. Converting impacts to economic costs is based on valuations from the economic literature. Valuation is related to the income of a population and varies with income. In addition, valuation requires the selection of a discount rate to discount future damages compared to present ones. The many decisions along these steps can yield many valid but vastly different assessments for the damages of pollution.

The marginal damages literature refers to a growing body of literature which yield estimates for the damages from atmospheric releases based on a variety of techniques that linearize or approximate the full, complex process outlined in Figure 1.2. The estimates from this body of literature present an opportunity for application of marginal damages to infrastructure management without necessitating the time and computational resources of conducting a full impact assessment. These estimates present an opportunity to greatly expand the scope of infrastructure management decisions by incorporating damages from atmospheric releases, thus quantifying damages from climate change and air pollution.

1.3 Pavement Management Systems

Canada has over 1 million km of roads worth over $2 billion (Transportation Association of Canada, 2013). Federal and provincial spending on roadways makes up over 50% of total transportation spending in Canada. In 2016, provincial and territorial spending on roads exceeded $15.9 billion (Transport Canada, 2017). In addition to government spending, trucks are responsible for the majority of freight transportation in Canada (Transportation Association of Canada, 2013). Given the critical role of roadways to Canada’s economy, it is imperative that road networks in Canada be maintained in acceptable conditions.

Pavement management systems (PMS) are a subset of infrastructure management which focus on the long term planning construction, maintenance, and rehabilitation of road networks. In Canada, pavement management systems are used by transportation agencies to design new roads, select appropriate maintenance technologies and maintain existing road networks within acceptable conditions.

Figure 1.3 provides an overview of the general phases involved in pavement management and the environmental impacts of each phase. These environmental impacts can be categorized broadly as: emissions to air, emissions to water, and the use of non-renewable resources. As can be seen from the construction and maintenance phases both include releases to the atmosphere as well as to water sources as well as noise. In addition, the use phase includes vehicle and noise emissions.

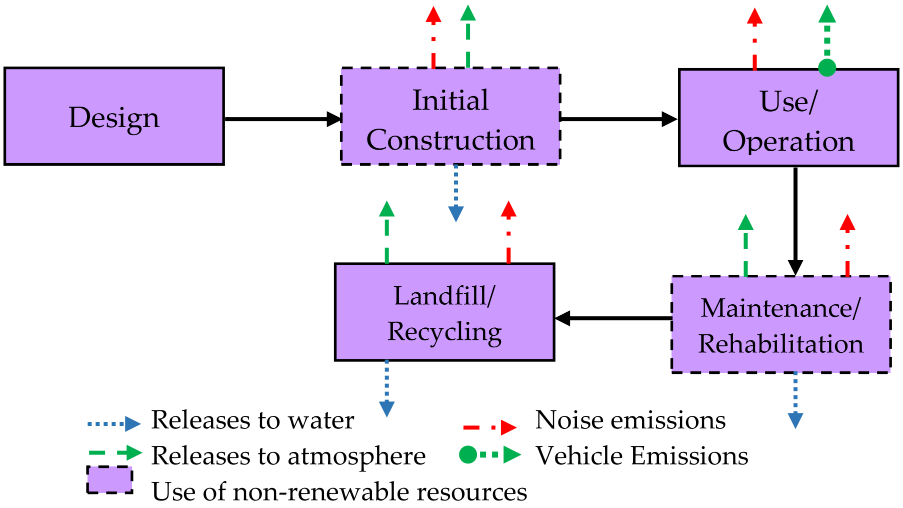

Figure 1.3 General phases of pavement management

Increased awareness of climate change, limited resource availability, as well as stringent environmental regulations have all contributed towards a desire to mitigate the adverse environmental impacts of pavement management. While there are a multitude of tools and practices available and in place by transportation agencies to assess and minimize environmental impacts, it is not common practice for transportation agencies to incorporate environmental impacts in pavement management systems (Transportation Association of Canada, 2013). While no singular answer can provide a full explanation for this discrepancy, infrastructure managers must balance environmental considerations with economic and technical ones, which often leads to complex multi-criteria decision-making. Traditionally, transportation agencies have chosen technically appropriate technologies which minimize agency costs.

Marginal damages provide an economically appropriate methodology for internalizing environmental costs from pavement management systems and incorporating them in existing lifecycle cost analysis to allow for ease of decision-making.

1.4 Objective

In partnership with the Ontario Ministry of Transportation (MTO), this project quantified the economic costs of criteria air contaminants and greenhouse gases resulting from pavement management activities using marginal damages. These environmental costs can be incorporated in existing life cycle cost analyses (LCCA) conducted by the MTO. This thesis reports on the findings of this research and discusses the applicability of these findings for transportation agencies and infrastructure managers.

The overall objective of this study is to integrate environmental costs in MTO's lifecycle cost analysis and develop a framework which allows transportation agencies to easily incorporate environmental costs in pavement management systems.

Chapter 2 will provide a literature review of related work. Chapter 3 details the development of design alternatives and the process by which emissions were determined. Chapter 4 outlines the process of converting emissions to environmental costs and Chapter 5 outlines calculating lifecycle environmental and agency costs. Chapter 6 provides the results of the analysis and Chapter 7 describes the uncertainty of results. Chapter 8 provides conclusions and recommendations for future work.

2 Literature Review

2.1 Methods to Estimate Marginal Damages of Atmospheric Releases

The purpose of this study is to apply marginal damages to atmospheric releases from pavement management activities. Five different methods used to calculate marginal damages from atmospheric releases were reviewed. These are comprehensive methods using state-of-the-art air quality models which provide North American specific MD estimates for atmospheric releases. The goal of the review was to evaluate different MD estimation methods and determine a range of marginal damage estimates for the atmospheric releases of interest in this study (CO_2, NOx, SO_2, CO, $PM_{2.5}$, and, PM_{10}) which are relevant for this application. Table 2.1 provides a summary of the methods reviewed. A brief description of each of the methods reviewed is provided.

2.1.1 CAMx PSAT + BenMAP

Fann et al. (2012) apply the particulate matter source apportionment technology (PSAT) module from the Comprehensive Air Quality Model with Extensions (CAMx) to model air pollution effects of changes in emissions policy and derive marginal costs of emissions using the USEPA's Benefits Mapping and Analysis Program (BenMAP) for ozone as well as fine particulate matter and its precursor emissions. This method models the reduced risk of mortality and morbidity from reducing a ton of emissions determine the environmental damages associated with those emissions. Mortality risk is valued using the US EPA's Value of a Statistical Life (VSL). This method is used in several studies to consider the variability of MD estimates based on the sources of emission and the location of sources. Fann et al. (2009), develop MD estimates for twelve sources of pollutants across 9 US urban areas as well as national US averages. Fann et al. (2012), provides MD estimates for 17 sectors across multiple years based on emissions projections. Fann et al. (2012) estimate the marginal cost of ton of emitted $PM_{2.5}$ from cement kilns at $350,000 (2010 USD).

The CAMx PSAT+ BenMPAP estimates are currently limited to a few urban areas and one national average as well as specific sources. While this method only considers health impacts from primary and secondary $PM_{2.5}$, this is believed to be the largest source of total damages (U.S. Environmental Protection Agency, 2011)

Table 2.1 Review of methods to calculate marginal damages

Method	Atmospheric Representation	Pollutants	Spatial Domain & Resolution	Impact Categories		References
				Health	Non-Health	
CAMx PSAT + BENMAP	Source apportionment of chemical transport model CAMx	Primary $PM_{2.5}$ & secondary $PM_{2.5}$ precursors (NOx, VOC, SO_2);	36-km horizontal domain (148×112); 14 vertical layers; contiguous US	$PM_{2.5}$ mortality[a]; 9 morbidity endpoints	N/A	Fann et al. 2012
APEEP/ AP2	Modified Gaussian plume; Includes some representation of atmospheric chemistry	PM_{10}, Primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors (NOx, SOx, NH_3, VOC)	US county level data for the contiguous US	$PM_{2.5}$ & O_3 mortality[a,b]; 9 morbidity endpoints;	N/A	Muller & Mendelsohn, 2007; Muller et al. 2011; Jaramillo & Muller, 2015;
SCAR	Responses from two chemistry climate composition models	CO_2, CH_4, N_2O, BC, SO_2, OC, CO, NOx, NH_3, Hg, HFC-134a	Input is variable, including worldwide 0.5x0.5° grid. Output is global average values.	$PM_{2.5}$ & O_3 mortality[a]; Additional health effects including mercury and increase in vector-borne diseases from climate change;	Basic climate damages (global mean surface temperature increase & hydrologic cycle changes); Regional precipitation change; Agricultural yield;	Shindell, 2015
EASIUR	Regression model based on CAMx-PSAT simulations	primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors (SO_2, NOx, NH_3)	36x36 km grid; 14 vertical layers (16 km high); Contiguous US & parts of Canada & Mexico	$PM_{2.5}$ mortality[a];	N/A	Heo, Adams, & Gao, 2016a, 2016b;
CMAQ Adjoint	Adjoint of Chemical transport model CMAQ	NOx, VOC, O_3	36x36 km grid; 34 vertical layers; Contiguous US & parts of Canada & Mexico	O_3 mortality[b];	N/A	Pappin & Hakami, 2013;

[a] *Premature mortality caused by chronic exposure;*

[b] *Premature mortality caused by acute exposure;*

2.1.2 APEEP/ AP2

AP2 is the updated version of the Air Pollution and Emissions Experiments and Policy (APEEP) analysis model. APEEP is an integrated assessment model which links a modified air pollution dispersion model to its effects and calculated corresponding damages (Muller & Mendelsohn, 2007; Muller, Mendelsohn, & Nordhaus, 2011). AP2 calculates damages from six pollutants emitted from ten thousand sources for all US counties. 94% of the MD estimates from AP2 comprise of human health damages caused by increase in morbidity and mortality risk. The other 6% of damages are due to reduction in agricultural and timber yields, visibility loss, depreciation of human-made materials and lost recreation usage. The most significant factors in MD estimates include the concentration-response relationship between $PM_{2.5}$ exposure and mortality rates, the use of a uniform vs. age-adjusted VSL, and the location of emission sources in an urban or rural area (Muller et al., 2011).

AP2 results are disaggregated by US counties and are specific to several source heights. The use of a dispersion model which does not include complete atmospheric chemistry may lower total damages (Heo et al., 2016b).

2.1.3 Social Cost of Atmospheric Releases

The Social Cost of Atmospheric Releases (SCAR), is a comprehensive assessment of the marginal damages from atmospheric releases developed by Drew Shindell (2015). SCAR calculates estimates of marginal damages from three major greenhouse gases (carbon dioxide, methane, nitrous oxide), as well as atmospheric pollutants such as black carbon. In total, the emissions of 11 different pollutants and greenhouse gases are accounted for in SCAR. Two-climate composition models as well as an integrated assessment model are used in SCAR to calculate both air pollution and climate related damages across 6 impact categories. Climate damages include health damages from climate change from an increase in tropical diseases as well the increase in air pollution, global mean temperature change, and changes to the hydrologic cycle. Other impact categories include increased mortality risk from $PM_{2.5}$ and O_3, regional precipitation changes, and, agriculture losses. Valuation methods include changes to projected GDP from climate change, global market prices for crops, and the global value of a statistical life (VSL), $3.05 million which is the USEPA VSL adjusted for global GDP. SCAR does not disaggregate damages by source. MD estimates from SCAR can be combined with emissions from any particular source to determine the damages associated with that source. For example, based on the SCAR methodology, damages in the transportation sector are estimated to be $3.80 USD/gallon of diesel fuel (based on a 3% discount rate) (Shindell, 2015).

2.1.4 EASIUR

The Estimating Air pollution Social Impacts Using Regression (EASIUR), like Fann et al. (2012), uses the PSAT tool in the CAMx chemical transport model. From multiple simulations with this tool, they develop a regression model to estimate marginal damages across all sources in their

North American domain. EASIUR provides social costs disaggregated by height, season, and location using a 36-km grid. The increased mortality risk from emissions of $PM_{2.5}$ and its precursors are valued using the US EPA VSL. EASIUR has a 36-km grid and provides location specific results for the contiguous US as well as parts of Canada and Mexico. EASIUR results are disaggregated for ground level and elevated point sources as well as by season.

2.1.5 CMAQ-Adjoint Method

The CMAQ-Adjoint sensitivity analysis is a backward sensitivity analysis developed from the Community Multiscale Air Quality model (Hakami et al., 2007). The adjoint method can estimate the influences of particular sources on individual locations. Pappin and Hakami (2013) used adjoint sensitivity analysis to determine the mortality effects of individual emission sources on specific locations across Canada and the U.S and the estimated marginal damages of those effects. Pappin and Hakami (2013) valued increase mortality risk from short-term exposure to ozone and NO_2 in Canada using the VSL from the Air Quality Benefits Assessment Tool developed by Health Canada (Judek, Stieb, & Jovic, 2006).

2.1.6 Summary of MD Methods Reviewed

Based on the review conducted, MD estimation methods vary greatly in terms of complexity of atmospheric processes represented, range of pollutants and impacts considered, and the valuation methods used. These parameters can have a significant impact on the marginal damage estimate. For e.g. the cost per metric tonne of fine particulate matter ranges from $39,463 to $542,274 in 2010 USD (Fann et al., 2009; Muller et al., 2011). However, each of the different methods also provide very different results for marginal damage estimates when they are disaggregated by factors such as source or location. For e.g. Fann et al. (2010) estimate the cost per ton for fine particulate ranges between $46,000 to $510,000 depending on the source in 2010 USD (Fann et al., 2012).

2.1.7 European MD Methods

This section briefly describes marginal damage estimation methods from Europe available which were reviewed but not applied in this analysis.

Holland, Pye, Watkiss, Droste-Franke, & Bickel (2005) developed marginal damages per ton for ammonia (NH_3), VOCs, SO_2, NOx, and $PM_{2.5}$ for EU25 member states (excluding Cyprus) and surrounding seas as part of the Clean Air for Europe (CAFÉ) Programme. The study used the European Monitoring and Evaluation Program (EMEP) model, a chemical transport model with a 50 x 50 km grid resolution that includes atmospheric chemistry and accounts for some secondary effects. Health damages from $PM_{2.5}$ and O_3, (including mortality and 7 morbidity endpoints) and as well as agricultural yield damages from O_3 were valued. The report provides damages per ton of pollutant for each EU25 member state as well as the surrounding seas. The marginal damage estimates yielded by this study were applied by Tollefsen, Rypdal, Tovanger, and Rive (2009) to determine the benefits of integrating climate effects with air pollution policy in Europe.

Andersen et al. (2008) develop an integrated EVA (economic valuation of air pollution) model to estimate external damages form air pollution. The EVA model was designed to account for atmospheric chemistry and secondary effects of pollutants as they disperse over areas. The air pollution modules of the EVA model comprise a standard Gaussian dispersion model as well as the Danish Eulerian Hemispheric Model (DEHM), a regional Eulerian model. The model values mortality damages for $PM_{2.5}$ (chronic, acute, and infant) and O_3 (acute) and 13 morbidity endpoints from emissions at three different European power plants. Pollutants in the EVA model include, primary $PM_{2.5}$ as well as SO_2, SO_4^-, NO_3, NOx, as well as lead and mercury. The EVA model is able to break down damages by primary and secondary pollutants (e.g. between primary and secondary components of sulphur).

Pietrapertosa et al. (2010) developed marginal damage estimates from emissions of fuel combustion in Italy. The study used the NEEDS-TIME Italy model, developed in the NEEDS Integrated Project as part of the European Union (EU) Sixth Framework Program, for assessment of energy and environmental policies at an EU wide-level with country scale detail. The model yields damages per ton for three greenhouse gases (CO_2, CH_4, N_2O) and 4 pollutants (NOx, SO_2, CO, NMVOC). For air pollutants, damages including human health, crop yield loss, damage to building materials, and loss of biodiversity caused by acidification and eutrophication were valued. For greenhouse gases, climate change damages in terms of CO_2 equivalent were valued based on literature estimates of the damages of CO_2.

The EVA model as well as the studies by Holland et al. (2005) and Pietrapertosa et al. (2010) are valid approaches to computing marginal damages and follow a similar impact pathway approach as the North American studies reviewed. Marginal damage estimates from these two methods were not included in our analysis as they are developed for European baseline data and their applicability for Ontario is limited.

2.2 Applications of Marginal Damages

Marginal damages of atmospheric releases are frequently applied to understand the costs or benefits associated for large-scale national and international policies. For example several studies have applied marginal damages to determine the air quality co-benefits of climate change policies (Shindell, Lee, & Faluvegi, 2016), or for calculating the benefits of emissions reductions in the transportation and energy sectors (Brown, Henze, & Milford, 2017; Jaramillo & Muller, 2016). The specific application of interest to this study is the use of MD estimates to integrate the environmental impacts of atmospheric releases from pavement management activities in Ontario. A review of existing work relevant to this application is provided as well as a discussion on current knowledge gaps.

2.2.1 Applications of Marginal Costs for Transportation Policy

Given the transportation sector's large contribution to overall pollution it is unsurprising that there is interest in developing transportation policy that accounts for environmental impacts. As such, research has evaluated the use of marginal damages as a means to integrate environmental costs from transportation. For example, Levinson & Gillen (1998) calculate the full cost of intercity highway transportation including costs from construction, noise, vehicle emissions, and user costs such as accident and congestion costs. Several studies also apply marginal damage estimates to compare different modes of transportation based on several factors including the costs of air pollution (Litman, 1997; Ortolani, Persona, & Sgarbossa, 2011). Marginal damage estimates have also been applied to internalize the costs of noise emissions from railway and vehicle use (Andersson & Ögren, 2007; Delucchi & Hsu, 1998). While this body of research highlights the application of marginal environmental damages for transportation policies it focuses on environmental impacts from transportation activities *i.e.* the use phase rather than the construction or maintenance of transportation infrastructure.

2.2.2 External Costs of Transportation Facilities and Services

Matthews, Hendrickson, & Horvath (2001) applied marginal damage estimates of atmospheric releases from a literature review by Matthews and Lave (2000) to the construction of materials and equipment for transportation services including roadway construction and maintenance. The study combined MD estimates with data from an economic input-output model of the United States economy in 1992 to calculate environmental costs for each of the direct and indirect services associated with pavement maintenance activities as a percentage of purchase price. The study estimates environmental costs for a 1-km highway are 9% of the direct cost for paving with steel-reinforced concrete and 7.7% for paving with asphalt. The Matthews et al. study (2001) provides a useful starting point for internalizing environmental costs in pavement management across the sector. However, given the use of a dataset from 1992, the study results are outdated, which is problematic as it relies on fixed relationships that will have evolved over time. While the researchers since updated their EIO LCA model for 2002, no further updates are planned. In addition, economic input output models, while well suited to static assessment of broad sectoral impacts, may be less well suited to integration with pavement management systems, where decisions regarding pavement construction and maintenance are less likely to have significant cross-sectoral implications.

2.2.3 Marginal Damage Estimates in Pavement Lifecycle Cost Analysis

Three previous studies have integrated the environmental costs of pavement management activities with a lifecycle cost analysis (LCCA). Yu, Lu, & Xu (2013) and Zhang, Keoleian, Lepech, & Kendall (2010) developed optimization models which included marginal costs of atmospheric releases in lifecycle costs to compare between different pavement overlay options. Chan (2007) integrated MD estimates with lifecycle costs to evaluate asphalt vs. concrete rehabilitation for case studies with the Michigan Department of Transportation. All three studies used a literature review conducted by Tol (1999, 2005) for MD estimates for CO_2. The studies by Chan (2007) and Zhang et al. (2010) both used MD estimates from Banzhaf, Desvousges, & Johnson (1996) and Matthews and Lave (2000) for marginal damages from additional greenhouse gases such as methane, nitrous oxide (N_2O), pollutants such as volatile organic compounds (VOCs), NOx, SOx, and PM_{10}, and lead which is a toxic substance. Chan (2007) also used MD estimates from Deluchhi (1996) for mobile source pollutant emissions, including NOx, SO_2, CO, PM_{10}.

Yu et al. (2013) conducted a literature review of MD estimates to determine the average and probability density functions following advice in Tol (2005) for marginal damages from three GHGs (CO_2, CH_4, N_2O) and four air pollutants (PM10, VOC, NOx, CO, SOx). It should be noted that both Yu et al. and Zhang et al. developed models which optimize pavement maintenance schedules over the lifecycle including emissions from the use phase. This is significant as vehicle emissions during the use phase dominate and this does not allow for direct comparison of project alternatives based on environmental costs from construction and maintenance.

These three studies in addition to Matthews et al. (2001) apply MD estimates available in literature to pavement management LCCA. As described in Section 2.1 MD estimates vary greatly depending on factors such as site and source of emissions, the valuation method used, and the impacts considered. Given this, not all MD estimates available are equally relevant for pavement management activities. There exists a need for an analysis of available MD estimates for their applicability to pavement management systems. In addition, most of the marginal damage estimates applied in these estimates are outdated, many of them from the 1990s. Given the significant advances in air quality modelling as well as changes to other factors in MD calculations (population, income, meteorology) since this time period the estimates these studies provide for environmental costs of pavement management are no longer reliable.

It should also be noted that the studies reviewed do not calculate marginal costs for $PM_{2.5}$ which is one of the most harmful pollutants for human health and therefore has the highest MD estimates associated with it. Given that many activities during pavement construction and maintenance include open sources of dust and particulate emissions the inclusion of $PM_{2.5}$ damages may have a significant effect on the environmental cost of these activities.

2.3 Environmental Cost Integration in Pavement Management Systems

Section 2.1.2 details the state of the current literature on the application of marginal damages estimates to evaluate the environmental cost of transportation infrastructure, specifically in pavement management. However, it is also important to consider the current state of practice by transportation agencies in Canada.

Accounting for the environmental impacts of pavement management has become a priority for transportation agencies as highlighted in the MTO's Sustainability Implementation Plan (MTO, 2013). Traditional efforts to reduce the environmental impacts of pavement management activities include innovative technologies (Santos, Flintsch, & Ferreira, 2017), the use of recycled materials (Chan, Lane, Raymond, Lee, & Kazmierowski, 2009), and efforts to reduce greenhouse gas emissions (Tighe & Gransberg, 2013). There are also many decision-making tools which can be used by transportation agencies to determine or compare the environmental impacts of project alternatives such as Athena (Athena Sustainable Materials Institute, 2018) and PaLATE (Horvath, 2007) which assess the environmental impacts of pavement management over the lifecycle. Several studies have also considered the use of multi-criteria decision making in pavement management to integrate environmental impacts in decision-making (Cafiso, Di Graziano, Kerali, & Odoki, 2002; Torres-Machi, Chamorro, Pellicer, Yepes, & Videla, 2015). However, there are few efforts to integrate the economic costs of adverse environmental impacts in existing lifecycle cost analysis which is used as a primary decision-making tool in PMS' by transportation agencies across Canada (Moges, Ayed, Viecili, & Abd El Halim, 2017).

Transportation agencies use LCCA to decide between project alternatives based on the costs of a proposed project over the estimated lifecycle of the project. There are three main types of costs associated with pavement projects. The first is agency costs which refers to direct costs to transportation agencies from the construction and maintenance of the proposed project over its lifecycle. In addition there are external costs associated with pavement management activities such as user costs and environmental costs. User costs are costs accrued to road users over the life of the project such as cost due to delays from road closures for construction activities or increase in vehicle operating costs due to pavement condition. Environmental costs are the costs of adverse environmental impacts of pavement management activities including air and water pollution, noise, etc. Environmental costs can be difficult to quantify in economic terms and are not often included in LCCA. A review of LCCA practices by provincial transportation agencies in Canada was conducted by Moges et al. (2017) and is summarized in Table 2.2

As

Table 2.2 shows, only the Alberta transportation agency currently considers environmental costs in their LCCA. Alberta Transportation assesses the costs of emissions of six pollutants based on vehicle kilometres, vehicle type, and running speed on each project segment. The costs per tonne of each pollutant emitted are based on the California Life-Cycle Benefit/Cost Analysis Model (Moges et al., 2017). However, this analysis only considers the environmental cost of emissions during the use phase of the pavement lifecycle and does not consider the environmental impacts for the construction and maintenance phases.

Table 2.2 Review of LCCA practices by provincial transportation agencies in Canada (Moges et al., 2017)

Province	Agency Costs	User Costs	Environmental Costs
British Columbia	Capital; operating; residual value	vehicle; traffic delay; collision;	Not included in LCCA; Uses multiple account evaluation
Alberta	Capital; operating; residual value	vehicle; traffic delay; collision;	Use phase vehicle emissions costs
Saskatchewan	Capital; operating;	Not included	Not included in LCCA
Manitoba	Capital; operating; residual value	Not included	Not included in LCCA
Ontario	Capital; operating; residual value	Not included	Not included in LCCA; Uses GreenPave rating system
Quebec	Capital; operating; residual value	Traffic delay costs	Not included in LCCA; uses multi-criteria analysis
Nova Scotia	Capital; operating;	Not included	Not included in LCCA

2.3.1 State of Practice in Ontario

As the analysis conducted in this study is specific to the Ontario Ministry of Transportation (MTO) it is necessary to understand how environmental impacts of pavement management are currently considered in Ontario.

As seen in

Table 2.2, transportation agencies for Ontario, Quebec, and British Columbia consider environmental impacts outside of LCCA. MTO currently uses GreenPave, a credits based rating system which assesses projects based on environmental criteria in four categories: Pavement Technologies, Energy & Atmosphere, Materials & Resources, and Innovation & Design Process. GreenPave assigns credits to projects based on 14 subcriteria under these categories. Projects can earn a maximum of 32 points. Based on the points awarded projects can be certified as bronze, silver, gold, or trillium under the GreenPave program (Chan, Bennett, & Kazmierowski, 2013).

While GreenPave allows MTO to determine if a project mitigates environmental impacts, it does not consider the full cost of those damages and does not allow for environmental costs to be considered alongside agency costs and to contribute to decision-making for project alternatives.

2.4 Summary of Knowledge Gaps

Based on the literature review conducted there are several key gaps of knowledge in the application of marginal damages to integrate environmental costs with LCCA in pavement management. These include:

- analysis of available MD estimates for their applicability to pavement management systems;
- appropriate conversion of environmental impacts to costs with a focus on the construction/maintenance phases;
- Ease-of-integration with LCCA practices at transportation agencies to allow for direct comparison and selection of appropriate maintenance technologies while considering environmental costs.

The research conducted in this study will attempt to address these knowledge gaps.

3 Environmental Impacts of Pavement Management

The overall objective of this study was to integrate environmental costs in MTO's lifecycle cost analysis and develop a framework which allows transportation agencies to easily incorporate environmental costs in pavement management systems. The main steps in this analysis consisted of:

- development of pavement design alternatives to be evaluated;
- determining environmental impacts (emissions) of design alternatives;
- converting environmental impacts to costs using marginal damages;
- calculating lifecycle agency costs of design alternatives;
- combining agency and environmental costs to determine overall lifecycle costs;

The following sections provide detailed the first two steps listed above, with subsequent steps detailed in proceeding chapters.

3.1 Pavement Design Alternatives

A set of pavement design alternatives was developed for a 1-km, 6-lane (3.5 m + 3.75 m + 3.75 m) road in collaboration with MTO based on the Guidelines for LCCA on freeways provided in Table 3.1. These include a typical design used by MTO for both flexible and rigid pavements (M1 & M5, respectively) as well as several designs which use different maintenance technologies available to MTO. The lifecycle cost of these designs, including both environmental and agency costs were calculated to determine the optimal design and allow MTO to integrate with existing pavement management systems.

Table 3.1 Pavement design alternatives assessed for lifecycle environmental and agency costs

ID	Type	Maintenance	Service Life
M1	Asphalt	Traditional Mill & Overlay	Initial: 19; Routine Maintenance: 9,15,27,38,48; Rehabilitation: 12, 11, 10
M2	Asphalt	Cold-in-Place Recycling	Initial: 19; Routine Maintenance: 9,15,27,38,48; Rehabilitation: 12, 11, 10
M3	Asphalt	M&O with 15% RAP	Initial: 19; Routine Maintenance: 9,15,27,38,48; Rehabilitation: 12, 11, 10
M4	Asphalt	M&O with WMA	Initial: 19; Routine Maintenance: 9,15,27,38,48; Rehabilitation: 12, 11, 10
M5	Concrete	Diamond Grinding, Full-Depth Slab Repair, AC Overlay	Initial: 38; Diamond Grinding, Slab Repair: 10; AC Overlay at 38

M1 represents the traditional asphalt pavement design and lifecycle. The main rehabilitation treatment, mill and overlay (M&O) occur at years 19, 31, and 42 after construction of the road. M&O is a traditional pavement rehabilitation technology which involves crushing a predetermined depth of the pavement surface (in this scenario 90 mm) and overlaying the surface with a new layer of hot-mix asphalt (Transportation Association of Canada, 2013).

M2, M3, and M4 have the same initial design as M1, however instead of rehabilitating with traditional M&O, these designs include alternative rehabilitation technologies. M2 uses Cold-in-place Recycling (CIR) as a rehabilitation treatment. The existing pavement surface is typically pulverized to a certain depth (100 mm in this scenario) and the reclaimed asphalt is recycled in place using a train of equipment. CIR requires the use of asphalt emulsified with additives or bitumen which decreases the asphalt viscosity without requiring heating of the asphalt and reducing energy needs. CIR is often followed by a thin hot-mix overlay to add further stability to the pavement (Transportation Association of Canada, 2013).

The M3 design scenario includes M&O with 15% (by mass) of reclaimed asphalt pavement (RAP) in the rehabilitated surface course. The incorporation of RAP reduces the amount of virgin aggregate material used in the rehabilitation process. The quantity of RAP used in pavement surface courses is specified in Chapter 11 of the Ontario Provincial Specification Standards (OPSS) for Roads and Public Works. OPSS 1150, the standard for hot mix asphalt specifies up to 15% RAP may be used in surface course mix designs (Ontario Ministry of Transportation, 2010).

The M4 scenario includes rehabilitation with using warm-mix asphalt instead of the hot-mix asphalt traditionally used in M&O. Warm-mix asphalt is a technology which uses additives or asphalt foaming to reduce the viscosity of the asphalt mix and reduce the compaction temperature by 14 °C to 25 °C thereby reducing energy needs (Van Dam et al., 2015).

The M5 scenario follows a traditional concrete pavement design and lifecycle. At 18 and 28 years after construction the road is repaired with partial and full depth slab repair as well as diamond grinding. Diamond grinding is a concrete pavement rehabilitation technology which uses diamond saw-cut blades to reduce pavement roughness and improve texture of the pavement. At 38 years after initial construction the concrete pavement is overlaid with a 90-mm asphalt layer to improve stability (Transportation Association of Canada, 2013).

3.2 Emissions Quantifications

Emissions were calculated using an adapted version of the Pavement Lifecycle Assessment Tool for Environmental and Economic Effects (PaLATE). PaLATE is an Excel based lifecycle software developed by the Consortium on Green Design and Manufacturing at the University of California, Berkeley (Horvath, 2007). PaLATE contains background environmental, cost, and equipment data which is combined with user inputted data on pavement design to provide environmental impacts including emissions of greenhouse gases (CO_2), criteria air pollutants

(NO_x, SO_2, PM_{10}, and CO), as well as heavy metals (Hg, Pb), leachate to waterbodies and lifecycle costs.

An adapted version of PaLATE 2.0 was developed to calculate emissions for the releases of interest in this study: CO_2, NO_x, SO_2, PM_{10}, $PM_{2.5}$, and CO. The adapted PaLATE tool was developed with updated emissions data, and, depending on availability, emissions factors for Ontario or Canada were used. Adapted PaLATE was used to calculate direct emissions from the construction and maintenance phases of pavement management including material production, transportation, and construction activities.

The Adapted PaLATE tool can be used to calculate emissions of new construction of asphalt and concrete roads as well as maintenance of existing roads. Users provide data on road section design including length, lane width, and number of lanes. Additionally, given the spreadsheet nature of the tool, users can update any default data in the tool such as equipment used for specific projects. The user provided parameters are used as inputs to calculate atmospheric releases from the material production, transportation, and construction activities respectively.

3.3 Emission Factors

The Adapted PaLATE tool uses emissions factors to calculate the total emissions from pavement management activities. An emission factor is the average rate of emissions associated with an activity. Emission factors can be used to determine the total emissions of a specific pollutant from a set activities using Equation 3.1, adapted from Frey (2007). All emission factors used in the Adapted PaLATE tool are provided in Appendix A.

$$EI_j = \sum_i \left(EF_{i,j} \times A_i\right) \qquad (3.1)$$

where:
EI_j = Total emissions for pollutant j in a given geographic area, and time period, units of mass
$EF_{i,j}$ = Emission factor for pollutant j from source activity i, units of mass/ per unit of activity (e.g. grams/ vehicle km)
$A_{i,,j}$ = Total units of activity i, e.g. total vehicle distance travelled in km;

3.4 Material Production Emissions

Materials production include emissions from all activities associated with material production including raw material extraction, as well as processing of raw materials to produce the materials used in roadway construction. The material production emissions were calculated using Equation 3.2.

$$EI_j = \sum_i \left(Material\ Production\ EF_{i,j} \times Quantity\ Produced_i\right) \qquad (3.2)$$

where:
Material production EF = emission factor for pollutant j, from production of material i, kg/ Mg of material produced
Material $Produced_i$ = quantity of material i produced, Mg

3.5 Transportation Emissions

Transportation includes emissions from the transportation of raw materials to processing plants, processed materials to site, recycled materials to recycling facilities, and waste materials to landfills. The Adapted PaLATE tool uses Equation 3.3 to calculate emissions from transportation activities.

$$EI_j = \sum_i \left(Transportation\ EF_{i,j} \times Quantity_i \times Distance \right) \quad (3.3)$$

where:
Transportation EF = emission factor for pollutant j, in kg/ Mg-km of material transported from transportation of material i
Quantity Transported$_i$ = quantity of material i transported (Mg)
Distance = distance material i was transported, km

Transportation emission factors are based on the mode (shipping, rail, or on-road trucks) used to transport freight..

3.6 Construction Emissions

Construction activities include the use of equipment on site in the construction or maintenance of roadways, as well as the use of on-site equipment to process materials (such as for in-place recycling).

$$EI_j = \sum_i \left(Equipment\ EF_{i,j} \times Power_i \times Productivity_i \times Quantity_i \right) \quad (3.4)$$

where:
Equipment EF = emission factor for pollutant j in kg/hp-hr
Power$_i$ = engine power of equipment used to process material in activity i, (hp)
Productivity$_i$ = rate at which materials are processed during activity i, (Mg/hr)
Quantity = quantity of material processed during activity i, (Mg)

Emissions for construction activities are primarily a result of fuel combustion (such as diesel) used to power non-road equipment. To calculate these emissions, a set of emission factors for non-road diesel equipment from Frey, Rasdorf, & Lewis and Gautam (2010) were combined with equipment data such as production rates and power based on specifications from equipment manufacturers. Where equipment data from manufacturers was not available, data from the original PaLATE tool was used (Horvath, 2007).

3.7 Assumptions in Emissions Quantification

Due to lack of available data or limits to the system boundary, several assumptions were made in determining emissions of design alternatives.

Emission factors for the extraction and production of materials were gathered from the US EPA's AP-42 *Compilation of Air Pollutant Emission Factors,* Fifth Edition, Volume I (US EPA, 1995). Chapter 11 of this compilation provides emissions factors for the main materials used in pavement construction activities including sand and gravel, hot-mix asphalt, cement, and concrete. Given the similarity of production systems between Canada and the United States it is assumed that the US EPA's compilation of emission factors are relevant for an Ontario analysis. This assumption is consistent with Canada's National Pollutant Release Inventory emission estimation calculators for hot mix asphalt plants (Environment and Climate Change Canada, 2015a).

As this analysis was conducted for Ontario, it was assumed that all goods were transported via trucks or rail. Emission factors for freight transport by rail were sourced from the Railway Association of Canada (2013) and from Natural Resources Canada (Malzer, 2005) for transport by truck. As most materials used in pavement management are readily produced in Ontario, a distance of 10 km used for all materials except bitumen which is likely produced out of the province and thus 300 km was used for the transportation distance. The assumptions are consistent with previous uses of PaLATE for assessments of emissions for MTO (Chan, 2010). In addition, an average freight carrying capacity of 20 Mg per truck was assumed. The average rail capacity was assumed to be one tonne of freight transported 198 km on one litre of fuel (Railway Association of Canada, 2013).

3.8 Emissions System Boundary

It should be noted that the use of the term "lifecycle assessment" in the name of PaLATE should be qualified as the analysis conducted for this study does not consist of a full lifecycle assessment but a streamlined one. The purpose of the analysis was to capture the major sources of emissions from pavement management activities to yield a sufficiently accurate estimate of their environmental costs and compare between design alternatives. Some sources of emissions for which accurate information was not available and which do not contribute greatly to the overall results (such as the use of additives) were excluded. In addition, indirect sources of emissions, such as increased vehicle emissions from road closures or delays are not included in this analysis. Emissions from other phases of the pavement lifecycle including use phase emissions were not included in this analysis. These emissions are a significant portion of total lifecycle emissions associated with highway infrastructure. However, they are not expected to differ meaningfully across different maintenance strategies.

As emission factors provide an average rate of emissions they do not provide site or project specific results but are useful for comparing alternatives. The Adapted PaLATE tool can be updated with site-specific emission factors if available to provide more accurate results for a project of interest. The uncertainty associated with emission factors is analyzed further in Chapter 7.

4 Application of Marginal Damages

A range of marginal damages (MD) for the atmospheric releases of interest were gathered from the studies reviewed in Chapter 2. These MD methods provide a comprehensive representation of approaches that can estimate sub-national marginal damages for multiple air pollutants and greenhouse gases.

As discussed in Chapter 1, a full impact assessment for converting a unit of emissions to an economic cost requires a multidisciplinary assessment of the impact pathway, involving atmospheric fate and transport, epidemiology, and economics. It is used to estimate changes in atmospheric concentrations, health responses to those concentrations, and economic damages related to those health responses (and other impacts, e.g., from temperature rise). Developing marginal damages means making decisions in each of these analysis steps. The potential methodological choices are reflected across the range of MD methods reviewed for this study.

These methodological choices affect the accuracy and applicability of results. Accuracy refers to how likely the marginal damages reflect the full and true value. Accuracy is affected, for example, by making trade-offs between comprehensiveness and computational costs. Applicability is influenced by the study domain, including its spatial and temporal extent and characteristics of its receptor population.

As described in Chapter 2 there are key differences across these methods which affect their final marginal damage estimates. These decisions also create limitations in the application of marginal damages outside of the domains for which they were developed or for sources and receptor populations other than those directly accounted for in the MD method. This means it is important to select and apply marginal damage estimates with consideration and care for how they were developed. Using estimates without a deep understanding of how they are estimated risks introducing significant errors by applying them incorrectly (Heo et al.). It also risks combining evidence across multiple approaches inappropriately. Yu et al. (2013) attempts to develop a distribution of estimates of marginal damages of atmospheric releases apparently without carefully reviewing the underlying approaches, and consequently confounds unique marginal damage estimates with case study applications.

To address these gaps, in our analysis, we identified unique marginal damage methods. We assessed them based on the underlying factors used in each method to identify the applicability of the damage estimates yielded by each method towards pavement management in Ontario. Based on this assessment, a series of appropriate adjustments of the MD estimates for certain factors were undertaken. The purpose was to develop a set of adjusted marginal damage estimates which could be applied for pavement management in Ontario. These adjustments are described in detail in this chapter.

4.1 Initial Marginal Damage Estimates

Table 4.1 and Table 4.2 provide details of the data used in this study and the specific marginal damages applied. As described in Chapter 2, each marginal damage method with the exception of SCAR provided several estimates for marginal damages distinguished by source or location. From these methods, the set of estimates chosen for this study were the ones deemed most appropriate for pavement management in Ontario. It should be noted that while there are many estimates for CO_2 available in literature, for this analysis only method which consider multipollutant impacts.

Table 4.1 Details of marginal damage data

MD Method	Units	Currency	Source; Details
CAMx PSAT + BenMAP	$/short ton	2010 USD	Fann, Baker, & Fulcher (2012); cement kilns, emission year 2016
AP2	$/short ton	2000 USD	AP2 Online (Muller et al., 2011) Detroit (FIPS code 26163); ground level;
SCAR	$/ton	2007 USD	Shindell, (2015); Median total, 3% discount rate;
EASIUR	$/metric tonne	2010 USD	EASIUR Online (Heo et al., 2016b, 2016a); Toronto (-79.38 °W, 43.65 °N); ground level annual average; Income, population year 2010;
CMAQ-Adjoint	$/metric tonne	2011 CAD	Pappin & Hakami (2013); GTA;

Table 4.2 Marginal damages applied in study ($/metric tonne, 2010 CAD)

	CO_2	NOx	$PM_{2.5}$	SO_2	CO
CAMx PSAT + BenMAP		$4,840	$307,989	$36,959	
AP2[a]		$3,520	$152,308	$39,680	
SCAR	$78	$61,994	$257,229[b]	$37,011	$583
EASIUR		$17,678	$108,606	$31,874	
CMAQ-Adjoint		$19,286			

a: while AP2 includes non-health damages, these estimates represent only health damages;
b: Based on the combined SCAR MD for components of $PM_{2.5}$ (BC+OC);
Note: marginal damages were converted to 2010 CAD; Original values are available in Appendix B;

4.1.1 Source Type

Fann et al. (2012) provides marginal damages from 17 different source types. For this application, the estimates for cement kilns were chosen as cement is used in the construction of concrete roads. As there are several other source of emissions from pavement management activities the effect of source on MD estimates was investigated in the uncertainty analysis is Chapter 7. While EASIUR and AP2 do not provide marginal damages for specific sources they do disaggregate by several source heights. Emissions from pavement activities include a mix of point, mobile and area source emissions which may occur at various heights; ground level MDs were applied in this study.

4.1.2 Location

The effect of location on marginal damages is related to the climate and population density of the location. Higher density increases the size of the receptor population thereby increasing the health damages. Climate affects the formation of secondary pollutants which is dependent on factors such as precipitation and sunlight. Three methods provide estimates disaggregated by location: CMAQ-Adjoint, EASIUR and AP2. EASIUR includes marginal damages for Ontario whereas AP2 includes damages for counties in the contiguous US. While Ontario has a vast road network across the province, there is a higher concentration of roads in the Southern Ontario which is densely populated. In addition, many of the materials are produced in Southern Ontario and shipped to Northern regions. As such, for CMAQ-Adjoint and EASIUR, marginal damages for a location in Toronto were used. As the AP2 model does not include Ontario, damages for Detroit, a location with similar climate and population density for Toronto were chosen. However, as Northern Ontario is very different from Southern Ontario in population density this effect of location on marginal damages was evaluated in the uncertainty analysis in Chapter 7.

4.2 Marginal Damage Adjustments

4.2.1 Value of a Statistical Life

The value of a statistical life (VSL) is a measure of willingness to pay for a small reduction in individual mortality risk, normalized by convention to an expected risk change of 1.0. Equation 4.1 shows the typical calculation of the VSL. Established literature approaches to measuring non-market goods such as mortality risk included stated preference and revealed preference methods. Stated preference methods rely on surveying a representative sample of individuals to determine their willingness to pay for a reduction in mortality risk. The revealed preference method develops models to measure the full economic value of a marginal change in mortality risk based on market activity such as wage premiums on higher risk jobs (the "hedonic wage" approach). VSL is related to income as populations with higher income are able and therefore willing to pay more for risk reductions, though the relationship between preferences for reduced mortality risks and income is not one to one. An income elasticity factor, ϵ, of 0.4 is used by US EPA (Hammitt & Robinson, 2011) which means that a 1% change in income would result in a 0.4% change in VSL.

$$VSL = \frac{Mean\ Willingness\ to\ Pay}{Change\ in\ Mortality\ Risk} \tag{4.1}$$

The US EPA recommends a VSL of $6.2 million (2002 USD) based on a review of 26 VSL studies (Dockins, Maguire, Simon, & Sullivan, 2004). Fann et al. (2012) & Heo et al. (2016b) use this value in their calculation of marginal damages adjusted for income and inflation. The SCAR method also uses the US EPA recommended VSL adjusted for a global income (Shindell, 2015). The CMAQ-Adjoint method uses the US EPA VSL for assessment of benefits in the United States; for benefits in Canada, the CMAQ-Adjoint method uses a VSL from the Air Quality Benefits Assessment Tool developed by Health Canada (Judek et al., 2006).

Equation 4.2 was used to calculate a new VSL for a 2015 Canadian income based on income elasticity, as described by Sarofim, Waldhoff, & Anenberg (2017). The mean income for a population is calculated as total GDP divided by the total population.

$$VSL_{x,t} = VSL_{ref} \left(Income_{x,t} / Income_{ref}\right)^{\epsilon} \tag{4.2}$$

where:

$VSL_{x,t}$ is the VSL in region x, in time period t (2015 Canada for this study)
VSL_{ref} is the VSL of the reference period
$Income_{ref}$ is the income for the reference period, calculated as GDP/Population
$Income_{x,t}$ is the income for region x, in time period t, (2015 Canada for this study)
ϵ is the income elasticity factor, 0.4, based on US EPA practice

Table 4.3 provides the original and new VSLs for each study along with income. GDP and population data for each region was sourced from the World Bank. The 2015 median Canadian income was $43.3 thousand (The World Bank, 2018).

Table 4.3 2015 Reference and updated VSL values for 2015 Canadian income (The World Bank, 2018)

	VSL_{ref} [a] ($million)	Region	Income Year	$Income_{ref}$ ($thousands)	$VSL_{x,t}$ ($million)	%Δ VSL
CAMx PSAT + BenMAP	8.3	US	2005	44.3	8.2	99%
AP2	9.7	US	2002	38.2	10.2	105%
SCAR	2.96	Global	2010	9.5	5.4	183%
EASIUR	8.6	US	2005	44.3	8.5	99%
CMAQ-Adjoint	5.5	Canada	2007	45.0	5.5	99%

a: The stated VSL from each study was converted to 2010 CAD;

The marginal damage estimates were based on the change in VSL. For methods such as EASIUR which only value mortality damages (Heo et al., 2016b), the relationship between VSL and marginal damages is linear. For the BenMAP studies (Fann et al., 2012) & AP2 which consider both morbidity and mortality damages, the relationship between VSL and marginal damages can be approximated as linear because mortalities represent over 90% of damages (Heo et al., 2016a). As such, for both methods, a 1% increase or decrease in VSL would correspond to a 1% increase or decrease in marginal damages. However, for SCAR methods which account for non-health impacts, such as climate damages the relationship between VSL and marginal damages is not linear. For SCAR based results, Shindell found that when using a US specific VSL for health damages, total damages increased by 13-21%. Assuming a similar change when applying a Canadian VSL (which is significantly closer to the US VSL than the global one used in SCAR estimates) the mean of this range (17% increase) was applied to all marginal damage estimates from SCAR to approximate damages for a 2015 Canadian VSL. Table 4.4 shows the marginal damages based on the 2015 Canadian VSL.

Table 4.4 Marginal damages based on VSL for 2015 Canadian income (2010 CAD)

	%Δ VSL	%Δ MD	CO_2	NOx	$PM_{2.5}$	SO_2	CO
CAMx PSAT + BenMAP	-1%	-1%		$4,796	$305,224	$36,627	
AP2	5%	5%		$3,702	$160,223	$41,742	
SCAR	83%	17%	$91	$72,533	$300,958	$43,303	$682
EASIUR	-1%	-1%		$17,520	$107,631	$31,588	
CMAQ-Adjoint	-1%	-1%		$18,998			

4.2.2 Concentration-Response Relationship

As described in Chapter 2, marginal damage studies use a concentration response function to convert concentrations of pollutants to their equivalent impacts. Equation 4.3 shows a typical concentration response function for human health risk and air quality as described by Fann et al. (2012).

$$y = y_0\left(e^{\beta \Delta x} - 1\right)Pop \qquad (4.3)$$

where:

y_0 *= baseline incidence rate;*

ß = risk coefficient;

Δx = change in air quality;

Pop = population of interest;

The risk coefficient value, ß, is typically sourced from epidemiological literature for the pollutant and health effect of interest. For the relationship between concentration of fine particulate matter and mortality, the relative risk value is sourced from two major studies, the Harvard Six Cities study (Laden, Schwartz, Speizer, & Dockery, 2006; Lepeule, Laden, Dockery, & Schwartz, 2012) and the American Cancer Society study (Krewski et al., 2009; Nasari et al., 2016; Pope et al., 2002). While both studies are widely used and accepted in the marginal damages literature and have advantages and disadvantages as described by Fann et al. (2011), they provide mean estimates that differ by about 50%, with the Harvard Six Cities study finding a higher risk coefficient. Given the significant contribution of $PM_{2.5}$ mortality to overall damages, it was deemed appropriate to adjust all marginal damages in this analysis for a single relative risk factor. Here, we chose Krewski et al. (2009), whose relative risk estimate agrees with the mean found by a recent meta-analysis (Hoek et al., 2013). All marginal damages were adjusted for the relative risk value from the Krewski et al. (2009) study which is 1.06 using Equation 4.3 (Heo et al., 2016b). Table 4.5 provides the adjusted marginal damages based on this relative risk value. The adjusted marginal damages were calculated for $PM_{2.5}$ as well as SO_2 and NOx both of which form secondary $PM_{2.5}$ and contribute to overall $PM_{2.5}$ mortalities. It should be noted that Equation 4.4 represents a linear relationship between marginal damages and $PM_{2.5}$ mortality risk. While this is not true for methods which include other damages in their valuation (AP2, SCAR), $PM_{2.5}$ mortalities still comprise the primary source of damages. As such this linear adjustment will represent an over-adjustment for these methods.

$$F_{\beta} = \frac{\beta - 1.0}{\beta_{ref} - 1.0} \tag{4.4}$$

where:
β_{ref} = *the original relative risk value used in the concentration response relationship;*
β = *the new relative risk value (1.06);*
F_{β} = *scaling factor for marginal damages based on ratio of reference and new relative risk;*

Table 4.5 Marginal damages adjusted for relative risk value of 1.06 from Krewski et al. (2009)

				\$2010 CAD /metric tonne		
	CR Study	**β_{ref}**	**F_{β}**	**$PM_{2.5}$**	**SO_2**	**NOx**
CAMx PSAT + BenMAP	Krewski et al. 2009	1.06	1	\$305,224	\$36,627	\$4,796
AP2	Pope et al. 2002	1.04	1.5	\$240,334	\$62,614	\$5,554
SCAR	Pope et al. 2002	1.04	1.5	\$451,436	\$64,955	\$108,799
EASIUR	Krewski et al. 2009	1.06	1	\$107,631	\$31,588	\$17,520

Note: MDs from the CMAQ-Adjoint method are not shown above as CMAQ-Adjoint does not value $PM_{2.5}$ mortalities

4.2.3 NOx Damages

Nitrous oxide (NOx) which is primarily emitted as a product of combustion has both primary and secondary effects on human health. In Canada, NO_2 is considered a primary pollutant and included in the Canadian Air Quality Health Index as described by Pappin & Hakami (2013). In addition to the health effects of NO_2, emissions of NOx undergo secondary chemical reactions in the atmosphere to form both ozone (O_3) and secondary $PM_{2.5}$ (Seinfeld & Pandis, 1998). As such there are three pathways through which NOx emissions affect human health: as NO_2, O_3, and secondary $PM_{2.5}$. However, all of these effects may not be considered in studies valuing NOx damages. For example, EASIUR (which is based on CAMx-PSAT) and the EPA CAMx-PSAT-based marginal damages only value the effects of NOx from secondary $PM_{2.5}$, as the Particulate Source Apportionment Tool only captures these effects (Koo, Wilson, Morris, Dunker, & Yarwood, 2009). Valuation by SCAR includes both secondary $PM_{2.5}$ damages as well as O_3 damages (Muller et al., 2011; Shindell, 2015). While AP2 can determine ozone damages, the AP2 values used in this study only consider $PM_{2.5}$ damages. The CMAQ-Adjoint method values NOx damages from both NO_2 and O_3, but does not consider secondary $PM_{2.5}$ damages (Pappin & Hakami, 2013). As such, it would be appropriate to combine marginal damage value for NOx, from the CMAQ-Adjoint method with methods that only consider secondary $PM_{2.5}$ damages to obtain a valuation which considers all health damages from NOx emissions. As the two methods do not value any of the same health damages, this would not double-count damages. This adjustment is summarized in Table 4.6.

Table 4.6 Damages included in valuation of NOx emissions

	NOx MD ($/ metric tonne)	Pathway to Damages valued	Total NOx MD for all Damages[a]
CAMx PSAT + BenMAP	$4,796	Secondary $PM_{2.5}$	$23,795
AP2	$5,554	Secondary $PM_{2.5}$	$24,552
SCAR	$108,799	O_3; Secondary $PM_{2.5}$	
EASIUR	$17,520	$PM_{2.5}$	$36,518
CMAQ-Adjoint	$18,998	O_3, NO_2	

a: NOx MD from study combined with MD from CMAQ-Adjoint to value all possible health damages

4.2.4 Adjusted Marginal Damages

The final marginal damages after being appropriate adjustments for input parameters are provided in

Table 4.7. The CMAQ-Adjoint value is not included in the calculation of the median to avoid double counting as it was added to the NOx MD for EASIUR and BenMAP. Figure 4.1 shows the range of marginal damages for pollutants for which damages were valued by multiple studies reviewed, $PM_{2.5}$, SO_2, and NOx.

Table 4.7 Final marginal damages ($2010 CAD/ metric tonne); adjusted for inflation, VSL, NOx damages, & relative risk

	CO_2	NOx	$PM_{2.5}$	SO_2	CO
CAMx PSAT + BenMAP		$23,795	$305,224	$36,627	
AP2		$24,552	$240,334	$62,614	
SCAR	$91	$108,799	$451,436	$64,955	$682
EASIUR		$36,518	$107,631	$31,588	
Median Value	*$91*	*$30,535*	*$272,779*	*$49,620*	*$682*

The purpose of adjustments was to create a set of consistent marginal damage estimates which are appropriate for analysis in Ontario and are suitable for applications such as infrastructure management. The adjustments covered underlying factors in marginal damages including: income, mortality risk from $PM_{2.5}$ exposure, and damages from NOx. However, there are many additional underlying parameters required for the estimation of marginal damages; adjustments for these parameters were outside the scope of this study. These non-adjusted parameters and their influence on MD estimates are discussed further below. The application of the adjusted marginal damages in Figure 4.1 to emissions of pavement management activities in Ontario, will be discussed in Chapter 6. The additional uncertainty associated with these estimates based on underlying factors described here will be discussed in Chapter 7.

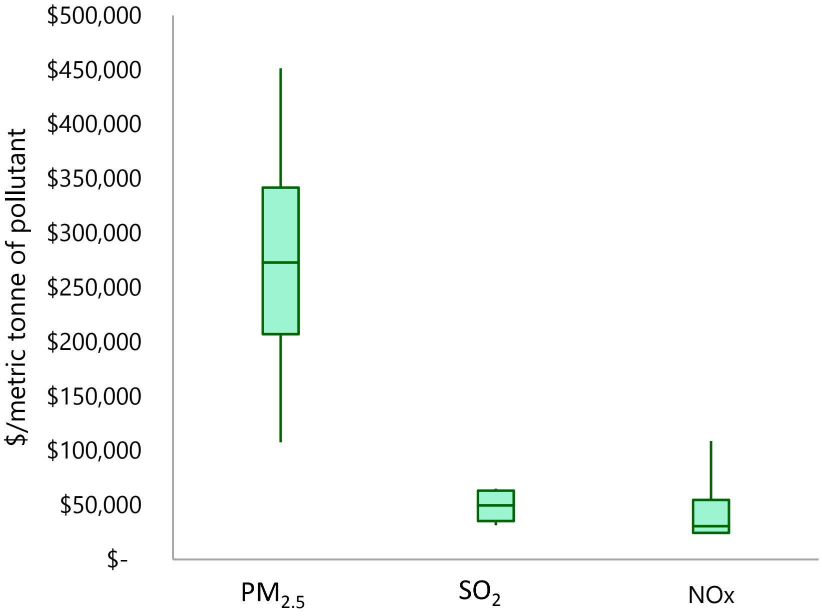

Figure 4.1 Range of adjusted marginal damage values from studies reviewed for $PM_{2.5}$, SO_2, and NOx

4.3 Non-adjusted Factors

Developing marginal damage estimates for atmospheric releases requires baseline conditions for emissions, meteorology, population, and incidence rate. These conditions vary over space and time and each of the marginal damage methods reviewed used baseline conditions for different years and regions. The baseline emission is the "business as usual" emissions scenario which is based on national emissions inventory data for given location and year. Marginal damages are measured through a small change in emissions above or below the baseline and valuing the resulting change in damages. The baseline incidence rate is the rate of incidence of a of a health effect (for e.g. non-fatal heart attacks) in a population prior to pollution exposure. Any change in the incidence rate is thus attributed to the change in pollution exposure from the emission scenario and the damages are valued. The baseline population would also change over space and time. While population is expected to grow in the future, projections of population growth show that these increases are not homogenous as growth is larger in some locations than others. In their supplementary material, Heo et al. (2016b) discuss potential adjustments for population based on projections of population data. For this study, population was not adjusted for. As described, population was accounted for by selecting marginal damages for locations with population density similar to Ontario where possible.

5 Lifecycle Cost Analysis

Lifecycle cost analysis (LCCA) is a financial analysis used by the MTO to compare design alternatives for a predetermined analysis period. The costs of the design alternatives over the design period are converted to a comparable metric using present value analysis, the Life Cycle Cost. This chapter describes the methods used to calculate lifecycle costs for the pavement design alternatives described in Chapter 3. The methods used in this study were based on MTO's *Guidelines for the Use of Life Cycle Cost Analysis for Freeways* (Lane & Kazmierowski, 2005).

5.1 Design Alternatives

This study analyzed design alternatives for a 1-km, 6-lane (3.5 m + 3.75 m + 3.75 m). The specific alternatives and discussed in detail in Chapter 3. Table 5.1 summarizes the design alternatives and provides design measurements including areas and depths.

Table 5.1 Pavement design alternatives evaluated for lifecycle environmental and agency costs

ID	Year	Design / Maintenance	Area (m^2)	Mill (mm)	Surface (mm)	Base (mm)	Subbase (mm)
M1	0	Asphalt Pavement	22000		320	150	450
	9	Mill & Patch 40 mm (5%)	1100	40	40		
	15	Mill & Patch 40 mm (20%)	4400	40	40		
	19	Mill & Overlay	22000	90	90		
	27	Mill & Patch 40 mm (10%)	2200	40	40		
	31	Mill & Overlay	22000	90	90		
	38	Mill & Patch 40 mm (10%)	2200	40	40		
	42	Mill & Overlay	22000	90	90		
	48	Mill & Patch 40 mm (10%)	2200	40	40		
	50	End-of-Analysis					
M2	0	Asphalt Pavement	22000		320	150	450
	9	Mill & Patch 40 mm (5%)	1100	40	40		
	15	Mill & Patch 40 mm (20%)	4400	40	40		
	19	CIR & Overlay	22000	100	50		
	27	Mill & Patch 40 mm (10%)	2200	40	40		
	31	CIR & Overlay	22000	100	50		
	38	Mill & Patch 40 mm (10%)	2200	40	40		
	42	CIR & Overlay	22000	100	50		
	48	Mill & Patch 40 mm (10%)	2200	40	40		
	50	End-of-Analysis					
M3	0	Asphalt Pavement	22000		320	150	450
	9	Mill & Patch 40 mm (5%)	1100	40	40		
	15	Mill & Patch 40 mm (20%)	4400	40	40		

	19	Mill & Overlay (15% RAP)	22000	90	90		
	27	Mill & Patch 40 mm (10%)	2200	40	40		
	31	Mill & Overlay (15% RAP)	22000	90	90		
	38	Mill & Patch 40 mm (10%)	2200	40	40		
	42	Mill & Overlay (15% RAP)	22000	90	90		
	48	Mill & Patch 40 mm (10%)	2200	40	40		
	50	End-of-Analysis					
M4	0	Asphalt Pavement	22000		320	150	450
	9	Mill & Patch 40 mm (5%)	1100	40	40		
	15	Mill & Patch 40 mm (20%)	4400	40	40		
	19	Mill & Overlay (WMA)	22000	90	90		
	27	Mill & Patch 40 mm (10%)	2200	40	40		
	31	Mill & Overlay (WMA)	22000	90	90		
	38	Mill & Patch 40 mm (10%)	2200	40	40		
	42	Mill & Overlay (WMA)	22000	90	90		
	48	Mill & Patch 40 mm (10%)	2200	40	40		
	50	End-of-Analysis					
M5	0	Concrete Pavement	22000		250	100	100
	18	Diamond Grinding	22000				
	18	Partial Depth Slab Repair	64		100		
	18	Full Depth Slab Repair	113		250		
	28	Partial Depth Slab Repair	213		100		
	28	Full Depth Slab Repair	376		250		
	28	Diamond Grinding	22000				
	38	90-mm Asphalt Overlay	22000		90		
	50	End-of-Analysis					

5.2 Agency Costs

As discussed in Chapter 2, at present MTO's LCCA only includes agency costs – user and environmental costs are not included in the analysis. Agency costs, which refer to direct costs to the agency from a proposed project include: capital costs, operation, and salvage value. Capital costs refer to the direct costs for initial construction of a project. Capital costs represent a one-time expense. Operating costs refer to the cost of maintenance and rehabilitation (M&R) costs over the analysis period. Operating costs may occur several times over a project's lifecycle depending on the length of the analysis period. Salvage value refers to the remaining value of the project at the end of the analysis period and is included as a benefit in lifecycle cost analysis. The sum of all three of these costs, (Eq. 5.1) represents the full costs of a project.

$$Project\ Cost = Capital + Operating - Salvage\ Value \qquad (5.1)$$

5.2.1 Present Worth Analysis

In order to sum costs, they must be in fungible units. In MTO's LCCA, all costs are converted to present worth. The present worth conversion is used to account for the time value of money and refers to the present value of a cost which occurs at a future date. The present worth of expenditures tends to decrease over time. In economic analysis of social costs, this decline represents the rate of substitution between consumption now and consumption in the future. In private analysis, it represents the opportunity cost of capital, i.e., the investment rate of return you could secure with those funds (Treasury Board of Canada, 2007). To represent this trade-off and place all expenditures in fungible units, future costs are discounted by a specified rate to be converted into present costs. While MTO recommends a discount rate of 5.3% for their LCCA (Lane & Kazmierowski, 2005), in this analysis a discount rate of 3% was used for consistency with the marginal damages, which use this discount rate in their derivation of damages. Uncertainty due to discount rate is discussed in Chapter 7. Equation 5.2 is used to convert future costs to present worth.

$$P = F \times \left(\frac{1}{1+d}\right)^n \tag{5.2}$$

where:
P = present worth of cost, $
F = future cost, $
d = discount rate, 3%
n = time until future cost, F, occurs

The time at which a cost occurs, n, is based on the service life of a project or the maintenance cost. For capital costs, n = 0, as these costs occur at the initial stages of a project.

Table 5.2 provides the MTO recommended service lives along with standard deviation for the pavement construction and rehabilitation activities analyzed in this study. The service life for the initial pavement represents the years until the first major rehabilitation treatment is required. For asphalt roads this is typically an overlay treatment over the entire pavement surface whereas for concrete roads this may involve slab repairs on a percentage of the road area along with diamond grinding to improve pavement texture.

Table 5.2 Recommended service life and standard deviation for pavement construction and rehabilitation activities (Lane & Kazmierowski, 2005)

	Recommended Service Life & Standard Deviation (Years)
Initial Pavement	
Asphalt Pavement	19±3.0
Concrete Pavement	38±2.5
Rehabilitation Activities	
First Overlay (Mill & Overlay 90 mm)	12±2.8
Second Overlay (Mill & Overlay 90 mm)	11±2.8
Third Overlay (Mill & Overlay 90 mm)	10±2.8
Concrete Pavement Rehabilitation (Diamond Grinding, Slab Repair)	10±2.0
Asphalt Overlay on Concrete Pavement	12±2.3

5.2.2 Salvage Value

In pavement LCCA, salvage value is used to account for the remaining useful life of a pavement at the end of the analysis period. For example, if a road is rehabilitated at year 45, and the expected service life of that rehabilitation is 10 years but the analysis period ends at 50 years, the salvage value is used to include the 5 years of remaining life of that road in the LCCA. Salvage value is calculated based on the cost of the cost of the last major rehabilitation treatment of the pavement and the expected service life of that treatment. Equation 5.3 is used to calculate the salvage value of a project, which is then converted to a present worth using equation 5.2.

$$SV = \left(\frac{L_{rem}}{L_{exp}}\right) \times C_{pvt} \tag{5.3}$$

Where:

SV = salvage value, $

L_{rem} = *remaining service life of the last rehabilitation treatment*

L_{exp} = *expected service life of the last rehabilitation treatment*

C_{pvt} = *cost of the last rehabilitation treatment*

5.3 Agency Cost Calculation

Agency costs were calculated for this study based on cost data provided by the MTO (S. Chan, 2018). Table 5.3 summarizes present costs to MTO for construction, maintenance, and rehabilitation of pavement projects.

Table 5.3 Unit costs used for LCCA ($2018 CAD) (Personal communication, S. Chan, 2018)

	Unit	Costs, $
Asphalt Roads		
Granular A	Mg	$25.39
Granular B	Mg	$16.52
Milling	m^2	$5.32
Overlay 50 mm SP 19	m^2	$12.95
Overlay 50 mm SP 12.5FC2	m^2	$14.68
Overlay 50 mm SP 19 WMA	m^2	$14.53
Cold-in-Place Recycling	m^2	$11.97
Concrete Roads		
PCC Surface	m^2	$76.15
Open Graded Drainage Layer	m^2	$15.38
Full depth slab repair	m^2	$264.92
Partial depth slab repair	m^2	$176.34
Diamond Grinding	m^2	$7

The unit costs were used to calculate total agency costs for the design alternatives in Table 5.1. Sample calculation for total agency costs of design alternative M1 are presented in followed by the present worth of total agency costs for in Table 5.6.

Present worth of all costs in The salvage value calculation for M1, based on the last rehabilitation treatment at year 42 (mill and overlay) was calculated using Equation 5.3. The expected service life of the last rehabilitation was 10 years (from Table 5.2). The salvage value was converted to a present worth cost using n = 50 years as this cost occurs at the end of the analysis period. The salvage value is included in the present worth cost analysis as a negative cost as it represents an unused value of the project.

$$\mathrm{SV} = \left(\frac{\mathrm{L_{rem}}}{\mathrm{L_{exp}}}\right) \times \mathrm{C_{pvt}}$$

$$\mathrm{SV} = \left(\frac{2}{10}\right) \times (\$667920)$$

$$\mathrm{SV} = \$\ 133{,}584$$

Table 5.4 were calculated. The present worth calculation for the first rehabilitation treatment, Mill & Overlay, at year 19 is presented and the present worth of all maintenance and rehabilitation treatments for M1 are summarized in Table 5.5.

$$P = F \times \left(\frac{1}{1+d}\right)^n$$

$$P = (667{,}920)\ \times\ \left(\frac{1}{1+0.03}\right)^{19}$$

$$P = \$\ 380{,}905$$

The salvage value calculation for M1, based on the last rehabilitation treatment at year 42 (mill and overlay) was calculated using Equation 5.3. The expected service life of the last rehabilitation was 10 years (from Table 5.2). The salvage value was converted to a present worth cost using n = 50 years as this cost occurs at the end of the analysis period. The salvage value is included in the present worth cost analysis as a negative cost as it represents an unused value of the project.

$$SV = \left(\frac{L_{rem}}{L_{exp}}\right) \times C_{pvt}$$
$$SV = \left(\frac{2}{10}\right) \times (\$667920)$$
$$SV = \$\ 133{,}584$$

Table 5.4 Agency cost calculations for design M1 ($2018 CAD)

	Unit Cost	Unit	Total Units	Cost
		Initial Construction		
50 mm SP12.5FC2 overlay	$14.68	m² *per 50 mm*	22,000	=$14.68 x 22000 =$322,960
270 mm SP 19.0	$12.95	m² *per 50 mm*	22,000	=$12.95 x 270/50 x 22000 =$1,538,460
150 mm Granular A Base	$25.39	metric tonne	7,260[a]	=$25.39 x 7260 =184,331
450 mm Granular B Subbase	$16.52	metric tonne	19,800[b]	=$16.52 x 19800 =$327,096
		Maintenance		
Mill (5% area)	$5.32	m²	=22,000*0.05 =1,100	=$5.32 x 1,110 =$5852
40mm SP12.5FC2 overlay (5% area)	$14.68	m² *per 50 mm*	=22,000*0.05 =1,100	=$14.68 x (40/50) x 1,100 =12,918
Mill (10% area)	$5.32	m²	=22,000*0.1 =2,200	=$5.32 x 2,200 =$11,704
40mm SP12.5FC2 overlay (5% area)	$14.68	m² *per 50 mm*	=22,000*0.1 =2,200	=$14.68 x (40/50) x 2,200 =25,836
Mill (20% area)	$5.32	m²	=22,000*0.2 =4,400	=$5.32 x 2,200 =$23,408

40mm SP12.5FC2 overlay (5% area)	\$14.68	m^2 *per 50 mm*	=22,000*0.2 =4,400	=\$14.68 x (40/50) x 4,400 =51,673
		Rehabilitation		
90 mm Mill Surface Course	\$5.32	m^2	22,000	=\$5.32 x 22,000 =\$117,040
50 mm SP12.5FC2 Overlay	\$14.68	m^2 *per 50 mm*	22,000	=\$14.68 x 22,000 =\$322,960
40 mm SP19 Overlay	\$12.95	m^2 *per 50 mm*	22,000	=\$12.95 x (40/50) x 22,000 =227,920

[a] *Based on Granular A density of 2.2 tonne/ m*^{3}

[b] *Based on Granular B density of 2.0 tonne/ m*^{3}

Table 5.5 Present worth of costs for design M1 ($2018 CAD)

Year	Design/ Maintenance	Cost	Present Worth
0	Asphalt Pavement	$2,372,847	$2,372,847
9	Mill & Patch 40 mm (5%)	$18,770	$14,386
15	Mill & Patch 40 mm (20%)	$75,082	$48,192
19	Mill & Overlay	$667,920	$380,905
27	Mill & Patch 40 mm (10%)	$37,541	$16,900
31	Mill & Overlay	$168,714	$267,159
38	Mill & Patch 40 mm (10%)	$37,541	$12,209
42	Mill & Overlay	$667,920	$193,002
48	Mill & Patch 40 mm (10%)	$37,541	$9,085
50	End-of-Analysis, Salvage Value	-$133,584	-$30,471
	Lifecycle Agency Cost		**$ 3,284,215**

5.3.1 Lifecycle Agency Costs

The total lifecycle agency costs for all design alternatives are presented in Table 5.6. As can be seen, M5, the concrete road alternative is the most expensive design. The asphalt road alternatives are (M1-M4) have very similar agency costs. M2 has the lowest costs as it requires the lowest raw materials (aggregate and hot-mix asphalt). Presently, M1 & M3 have the same costs as the MTO cost data did not include cost savings for the use of recycled material. In practice, the RAP use in M3 may reduce total agency costs. It is unlikely that this reduction would decrease M3 costs to below M2, as the total use of raw materials in M3 is higher.

Table 5.6 Present worth of total agency costs for each design alternative (2018 CAD)

Design	Total Agency Cost
M1 (Asphalt)	$ 3,284,215
M2 (CIR)	$ 3,185,160
M3 (15% RAP)	$ 3,284,215
M4 (WMA)	$ 3,313,958
M5 (Concrete)	$ 2,557,545

5.4 Environmental Cost LCCA

For this analysis, lifecycle agency costs were combined with lifecycle environmental costs to determine the full cost of pavement construction and maintenance. Environmental costs were calculated using equation 5.4 by combining emissions with marginal damages from Chapter 4.

$$Damages = MD_j \times EI_j \qquad (5.4)$$

where:

MD_j *= marginal damage cost for pollutant j, $/ tonne*

EI_j *= total emissions inventory for pollutant j, from a maintenance activity, tonne*

Table 5.7 Emissions and environmental costs for construction and maintenance practices in design alternative M1, based on marginal damages, $2018 CAD

Emissions (kg)	**CO_2**	**CO**	**NOx**	**SO_2**	**$PM_{2.5}$**
Initial construction (asphalt)	1227385	3085	2254	825	1303
40 mm mill & patch (5% area)	4417	17	8.4	5.1	7.3
40 mm mill & patch (10% area)	8833	35	17	10	15
40 mm mill & patch (20% area)	17666	69	33	21	29
90 mm mill & 100 mm overlay	198744	777	377	231	329
Marginal Damages ($/tonne)[a]	$91	$682	$30,535	$49,620	$272,779
Damages ($2010 CAD)					
Initial construction (asphalt)	$111,692	$2,104	$68,824	$40,942	$355,462
40 mm mill & patch (5% area)	$402	$12	$256	$255	$1,995
40 mm mill & patch (10% area)	$804	$24	$511	$510	$7,980
40 mm mill & patch (20% area)	$1,608	$47	$1,022	$1,020	$3,990
90 mm mill & 100 mm overlay	$18,086	$530	$11,502	$11,472	$89,777

[a] *Median marginal damages from literature review of MD methods, described in Chapter 4*

Each of the environmental costs in Table 5.7 occur at the year of construction or maintenance and were converted to present worth using Equation 5.1 and using a discount rate of 3%. Table 5.8 presents the present worth of environmental costs in design alternative M1. Environmental costs for all design alternatives and a discussion on these costs are provided in Chapter 6.

Table 5.8 Present worth of environmental costs for design alternative M1 ($2018 CAD)

Year	**Design/ Maintenance**	**Cost**	**Present Worth**
0	Asphalt Pavement	$787,863	$787,863
9	Mill & Patch 40 mm (5%)	$3,953	$3,030
15	Mill & Patch 40 mm (20%)	$15,814	$10,150
19	Mill & Overlay	$177,906	$101,458
27	Mill & Patch 40 mm (10%)	$7,907	$3,560
31	Mill & Overlay	$177,906	$71,160
38	Mill & Patch 40 mm (10%)	$7,907	$2,572
42	Mill & Overlay	$177,906	$51,408
48	Mill & Patch 40 mm (10%)	$7,907	$1,913
50	End-of-Analysis		
	Lifecycle Environmental Cost		**$1,033,113**

5.5 Additional Costs

As discussed in Chapter 2, MTO's LCCA current includes only direct agency costs. The purpose of this study is to include environmental costs from atmospheric releases as well as direct agency costs in the MTO's LCCA. However, there are additional costs not currently included in MTO's LCCA which are not accounted for in this study. These include the costs of atmospheric releases not accounted for (increased emissions from user delay and use phase emissions), and additional costs such as noise and user costs. Previous literature has assessed some of these costs such as Yu et al. (2013) who developed an integrated pavement optimization methodology which incorporated user delay and increased vehicle operating costs. Pellecuer et al. (2014) developed the Pavement Environmental Impact Model which assessed costs from noise, air pollution, and greenhouse gas emissions from the construction, maintenance and uses phases of pavement management. While this objective of this analysis was the application of marginal damages to assess environmental costs of atmospheric releases, these results can be incorporated with estimates of additional externalities such as noise and user costs to conduct a comprehensive lifecycle costs analysis of pavement management activities.

6 Results & Discussion

This chapter compares the pavement design alternatives described in detail in Chapter 3 in terms of atmospheric releases, as well as lifecycle environmental and agency costs. These alternatives were designed for a 1-km, 6-lane wide highway in Ontario are summarized in Table 6.1.

Table 6.1 Pavement design alternatives evaluated for lifecycle environmental and agency costs

ID	Type	Maintenance	Service Life
M1	Asphalt	Traditional Mill & Overlay	Initial: 19; Routine Maintenance: 9,15,27,38,48; Rehabilitation: 12, 11, 10
M2	Asphalt	Cold-in-Place Recycling	Initial: 19; Routine Maintenance: 9,15,27,38,48; Rehabilitation: 12, 11, 10
M3	Asphalt	M&O with 15% RAP	Initial: 19; Routine Maintenance: 9,15,27,38,48; Rehabilitation: 12, 11, 10
M4	Asphalt	M&O with WMA	Initial: 19; Routine Maintenance: 9,15,27,38,48; Rehabilitation: 12, 11, 10
M5	Concrete	Diamond Grinding, Full-Depth Slab Repair, AC Overlay	Initial: 38; Diamond Grinding, Slab Repair: 10; AC Overlay at 38

6.1 Emissions Results

Figure 6.1 shows the lifecycle emissions of six atmospheric releases (CO_2, NOx, SO_2,, PM_{10}, $PM_{2.5}$, CO) for each of the design alternatives. These emissions were determined using the Adapted PaLATE tool as described in Chapter 3. The most significant releases in terms of magnitude were found to be carbon dioxide (CO_2) and coarse particulate matter (PM_{10}). Given the high levels of dust involved with construction activities arising from the processing and transportation of materials such as sand and gravel, production of high levels of particulate matter is expected.

Sources of emissions in this analysis included production & processing of material, transportation, and construction. For all design alternatives materials production was the dominant source of emissions, contributing to 90% or of total emissions for all pollutants excepting NOx and CO. NOx is a product of combustion and was emitted primarily in the transportation of materials. For asphalt design alternatives (M1-M4), within material production, hot-mix asphalt production was the greatest source of particulate matter (PM_{10} & $PM_{2.5}$), CO, & SO_2 emissions. Virgin aggregate extraction and processing (for surface course and base courses in new road construction) was the greatest source of emissions for CO_2 emissions. For the concrete design (M5), cement production was the dominant source for all emissions excepting CO and particulate matter. Concrete production was the dominant source for both coarse and fine particulate matter whereas materials transportation was the dominant source for CO.

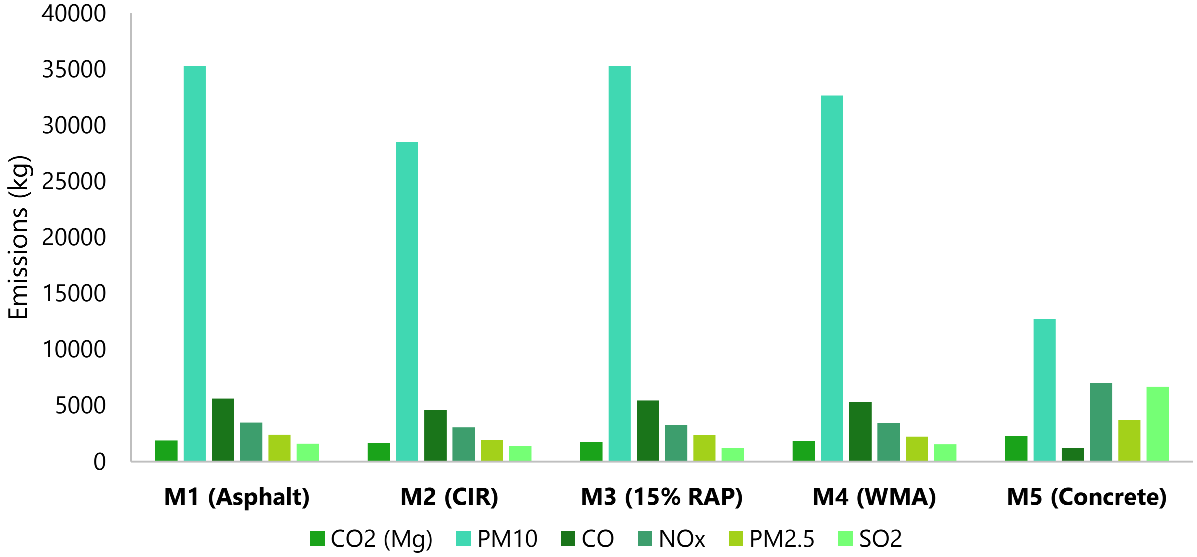

Figure 6.1 Lifecycle emissions of design alternatives described in Table 5.1
Note: emissions of CO2 are in units of Mg while all other emissions are in units of kg;

An interesting result to note is that while emissions were calculated for the lifecycle of the design alternatives, the initial construction was responsible for a majority of emissions as seen in Table 6.2. In particular for M5, the initial construction was responsible for greater than 50% of emissions for 5 out of 6 atmospheric releases quantified and greater than 85% for 4 out of 6 releases. As concrete roads require less maintenance over the lifecycle these results are not surprising. For the asphalt road alternatives (M1-M4), which are known to require higher maintenance, the new construction emissions comprise 50% - 75% of total emissions. For M2, CIR which has the lowest raw material usage in the maintenance processes, new construction comprises 61% - 75% of total emissions, the highest of all the asphalt road alternatives.

Table 6.2 Contribution of initial construction to total lifecycle emissions

	CO_2	CO	NOx	SO_2	PM_{10}	$PM_{2.5}$
M1 (Asphalt)	66%	55%	65%	52%	53%	67%
M2 (CIR)	75%	67%	74%	61%	66%	77%
M3 (15% RAP)	71%	57%	69%	70%	53%	68%
M4 (WMA)	67%	58%	65%	54%	57%	69%
M5 (Concrete)	88%	35%	92%	93%	58%	95%

As seen from Figure 6.1, the concrete road design, M5, has the highest level of CO_2 emissions but the lowest PM_{10} emissions. There is no design which has the lowest emissions for all six atmospheric releases. As such, it is difficult to determine the preferred design alternatives based on these emissions alone without a metric for comparison between the various atmospheric releases. While there are many processes available for environmental decision-making for an accurate analysis, these emissions should be accounted for based on the economic damages they create. As described in Chapter 4, marginal damages provide an opportunity to determine the economic costs of these emissions and use those costs in decision-making. Additional knowledge of these atmospheric releases and their impacts is needed to determine the overall impacts of each design alternative. As this knowledge may not be readily available, this highlights the need to simplify these emissions so they may be easily understood by infrastructure managers and incorporated in decision-making.

6.2 Environmental Costs

Environmental costs for the design alternatives were determined by converting the emissions from Figure 6.1 to costs using the marginal damages from Chapter 4. The median value of the marginal damages for each pollutant was used to calculate the environmental costs of the construction and maintenance and rehabilitation based on the emissions. The environmental costs were converted to a present worth based on the method described in Chapter 3 and using a discount rate of 3%. The present worth of the lifecycle environmental costs are provided in Figure 6.2.

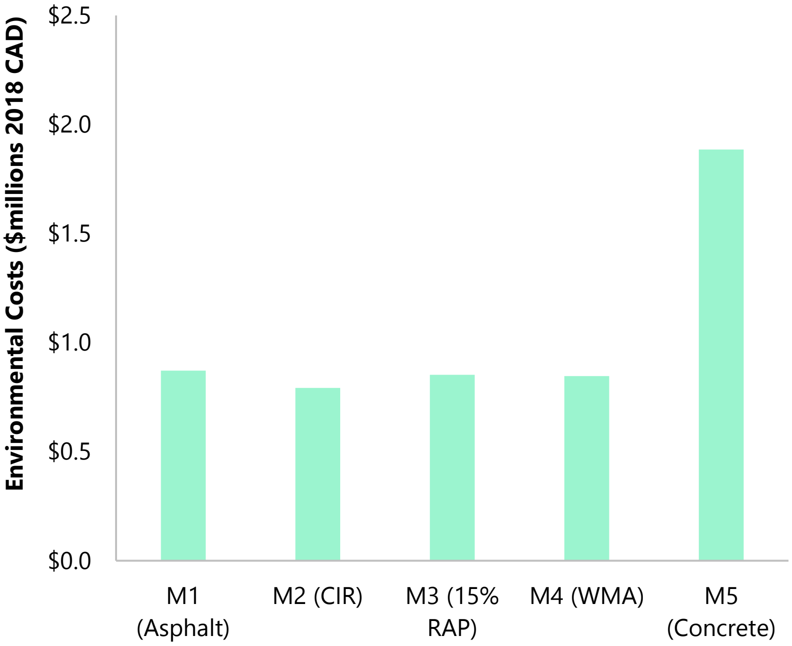

Figure 6.2 Present worth of environmental costs of design alternatives based on median marginal damages of atmospheric releases ($2018 CAD)

Unlike the emissions results in Figure 6.1, the environment costs results are simpler to interpret, and can be directly applied in LCC analysis to select the overall preferred alternative. Figure 6.2 shows that M2, which is a typical asphalt road rehabilitated with cold-in-place recycling (CIR), has the lowest environmental cost. In addition, M5, the concrete road design has the highest environmental cost. While concrete roads require less rehabilitation over the lifecycle, the high emissions of cement and concrete production, result in a much greater environmental impact of concrete roads over the lifecycle. The total environmental costs for M1-M4 are quite similar as the main contributors to environmental costs (production of aggregate and hot mix asphalt) do not change significantly between the 4 alternatives. The low environmental cost for M2 results from the low quantity of hot mix asphalt required when rehabilitating with CIR. As material production represents over 90% of pavement management emissions, the use of recycled material results in significant emissions reductions. In contrast, while warm-mix asphalt is gaining recognition as an environmentally beneficial technology, these results show that the use of this technology alone, without a reduction in virgin material, would not provide significant emission reductions from a full life-cycle perspective.

Total environmental costs of the design alternatives were disaggregated by the contribution of each of the atmospheric releases measured, as seen in Figure 6.3. These disaggregated costs are useful for understanding the total costs and the differences between the design alternatives. For example, while emissions for the concrete design, M5, may not seem significantly different from M1-M4 in Figure 6.1, the environmental costs in in Figure 6.2 are significantly higher. This can be explained by the high emissions of $PM_{2.5}$, SO_2, and NOx, in cement and concrete production. These three pollutants have the have the highest marginal damages associated with them due to their contribution for increased risk of premature mortality.

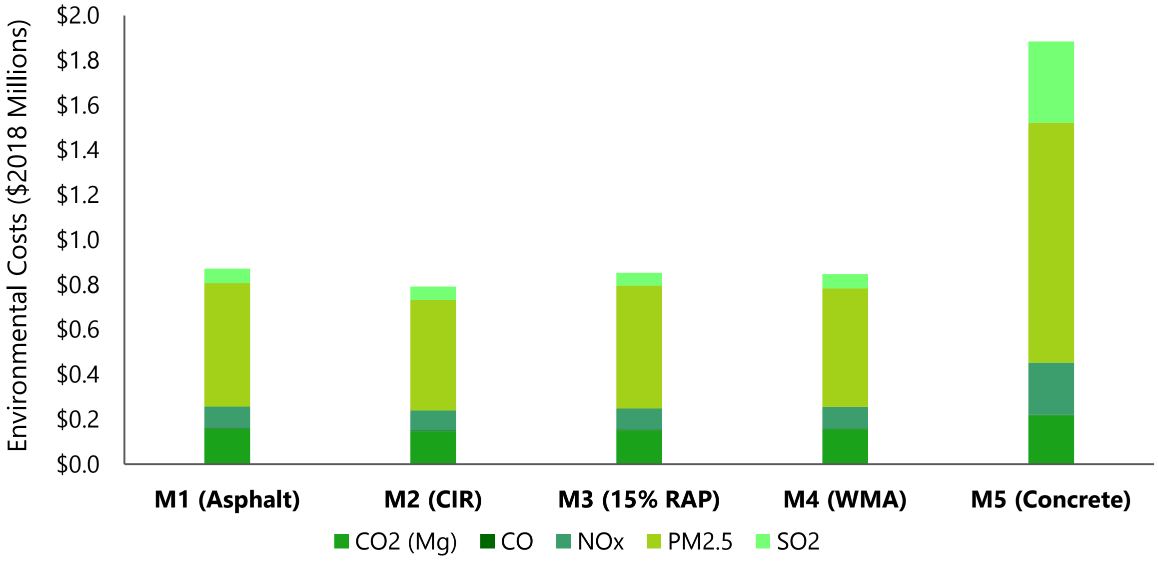

Figure 6.3 Present worth of environmental costs broken down by each atmospheric release ($2018 CAD)

6.3 Lifecycle Environmental & Agency Costs

The environmental costs were combined with the agency costs to create a single lifecycle cost for pavement management that accounts for comprehensive damages due to atmospheric releases. The agency costs represent direct costs to the agency for the construction and maintenance phases of the pavement design as well as the salvage value at the end of the lifecycle. Agency costs were calculated based on data provided by the MTO as described in Chapter 5.

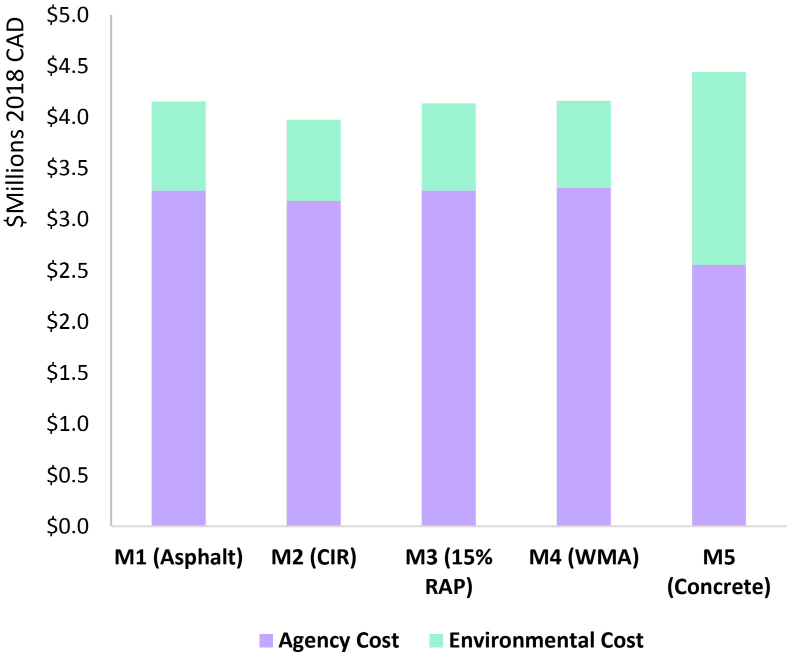

Figure 6.4 Present worth of lifecycle agency and environmental costs for pavement design alternatives ($million 2018 CAD)

Based on these results M2 is the preferred design alternative with the lowest total lifecycle cost. The reduction of virgin material use in M2 reduces direct agency costs (it has the lowest agency costs of the asphalt roads) as well as environmental costs. M5, the concrete road design has the highest total cost, although it has the lowest agency cost. The environmental cost of M5 is significantly higher than all other alternatives, increasing the total lifecycle cost. M5 is also noteworthy as it is the only design for which the environmental cost is higher than the agency cost. For all other designs environmental costs are approximately 35% of agency costs whereas for M5, they are 103% of agency costs.

6.4 Summary

Based on these results, several conclusions can be made. For this scenario, M2, a traditional asphalt road rehabilitated with CIR is the best alternative with lowest lifecycle agency and environmental cost. Despite its longer service life and lower agency cost, a traditional concrete road design has the highest environmental cost due to its high emissions of pollutants which cause high damages ($PM_{2.5}$, SO_2, NOx). The primary source of emissions is the production of materials, as such, reduction of the use of virgin materials is essential to reducing overall environmental cost of any design. The next chapter will provide an uncertainty analysis and discuss the robustness of these recommendations.

7 Uncertainty Analysis

An uncertainty analysis of the results presented in Chapter 6 was conducted. The uncertainty analysis had two objectives: to develop a range of the uncertainty in lifecycle cost; and to assess the sensitivity of the recommended design alternative against the input parameters for emissions, environmental cost, and agency cost.

7.1 Emissions Uncertainty

Emissions uncertainty was evaluated based on two factors: emission rates and particulate matter control. Uncertainty in emissions rates refers to the uncertainty in emissions factors. The use of emission factors imparts uncertainty both due the uncertainty in the measurement and development of those factors, and also in their application as an average to represent conditions that may vary across projects and sites. The magnitude of this uncertainty was determined by developing a range of emissions factors from the literature and calculating the emissions at the maximum and minimum emissions factors for all atmospheric releases except PM_{10} and $PM_{2.5}$ (which is calculated separately, below). As can be seen, the uncertainty due to emission rates is small and represents the smallest source of uncertainty in this analysis. As we do not estimate uncertainty in the underlying measurement, this source of uncertainty is likely underestimated. However, given the relatively small contribution it may be unlikely that more detailed data would make this source of uncertainty more significant than the other sources of uncertainty discussed here.

The uncertainty due to particulate matter controls reflects the range of potential emissions under the range of particulate matter control options used for extracting and processing materials such as gravel and asphalt. As discussed in Chapter 6, hot-mix asphalt is the greatest contributor to particulate matter emissions for asphalt roads. To determine the magnitude of this uncertainty a range of emission factors was obtained for particulate matter in material production. These factors represented the emission rates with different types of pollution control systems (such as fabric filters, or wet scrubbers) as well as an emission rate for uncontrolled particulate matter. For the base case emissions, the median value of emission factors using particulate matter controls was used as the US EPA reports that almost all hot mix plants use some level of emission control (1995). The minimum and maximum values of the emission factor range were used to calculate the magnitude of this uncertainty. The maximum values represent the emission when no particulate matter controls are used. As $PM_{2.5}$ emissions have the highest marginal damages, uncontrolled particulate matter emissions would have a significant impact on overall environmental cost. It should be noted that this represents the full range of possibilities in $PM_{2.5}$ emissions from pavement construction activities and not necessarily the range of these emissions in Ontario specifically. Also, it is a range, not a distribution. In fact, median estimates of emissions factors suggest particulate matter control is frequently applied, which follows our review of practices by Ontario industry groups (Ontario Hot Mix Producers Association, 2015). Further research on the specific practices of Ontario producers and contractors would be required to develop a distribution of particulate matter emissions and environmental costs that reflect current practices in Ontario.

7.2 Marginal Damages Uncertainty

As detailed in Chapter 2, marginal damages represent an estimate of the damages from atmospheric releases, including climate forcers and air pollutants All methods used to determine these estimates need to represent the impact pathway introduced in Chapter1, including the source of emissions, atmospheric fate and transport, the receptors, the damages, and the economic valuation of the damages. Uncertainty in each of these steps results in uncertainty of the final marginal damage estimates. These uncertainties can be broadly categorized as three links of the impact pathway: source-receptor, concentration-response, and economic impacts.

7.2.1 Source Receptor Uncertainty

A source is any activity which produces emissions of pollutants or greenhouse gases. Damages caused by different sources of emissions can vary based on the unique properties of the emitting sources. For e.g. sources which directly emit primary $PM_{2.5}$ tend to have greater damages than those which emit secondary $PM_{2.5}$ precursors such as SO_2 and NOx (Fann et al., 2012). Additionally the damages due to individual sources varies greatly depending on the proximity to receptor populations. In our analysis, this is referred to as "location uncertainty." When measuring health damages, receptor population refers to the population of people living near the emissions source, however, it can also refer to other receptors such as crops when measuring agricultural damages. Emissions which occur near receptor populations tend to have the greatest damages whereas emissions which must travel further to reach receptor populations tend to have lower damages.

Source uncertainty is based on the differences in damages associated with emissions depending on the source of those emissions, e.g., a cement kiln, or exhaust from construction equipment. The characteristics of the sources define their contribution to damages in an area, and thus the importance of reducing those emissions. These characteristics pertain to physical characteristics of the source that affect the fate and transport of its emissions. For example, consider emissions of SO_2 from combustion in a tall industrial stack. The height of the stack, and high temperature of exhaust, both make it easier for those emissions to travel long distances, and to condense into secondary sulfate aerosol (i.e., to form $PM_{2.5}$.) Different marginal damage approaches account for different source characteristics. The most comprehensive we identified was Fann et. al. (2012), which developed marginal damages for 17 different industrial, area, and mobile sectors across the United States for $PM_{2.5}$, NOx, and SO_2. The study found a range of 14% to 159% between the median $PM_{2.5}$ emissions and the smallest and largest source. These results were used to develop the magnitude of source uncertainty in this study.

The location of the source will also affect its marginal damages, both by affecting the fate and transport of its emissions, as well, crucially, as its proximity to receptors. The location of the source will affect factors like the background air pollution levels, topography, weather, and population density, all which affect the relationship between emissions and their impacts. Emissions in densely populated areas will yield much higher damages than those in sparsely populated areas. In addition to receptor proximity, the location of emissions also affects damages through climate as several pollutants yield damages after transforming through atmospheric reactions which are dependent on temperature, precipitation and humidity. This analysis was conducted for Ontario which consists of densely populated urban areas in Southern regions and sparsely populated rural areas in Northern regions. Several MD methods reviewed including AP2, EASIUR, and the CMAQ-Adjoint method disaggregate damages by location. For the base case, when damages disaggregated by source were available they were chosen for a location resembling Toronto, in both population density and climate. It was chosen as the location for the base case because many of Ontario's largest and busiest highways are also located in this region and much of the pavement management activities analyzed in this scenario would take place in the Toronto region. As Toronto is the most densely populated city in Southern Ontario, emissions in this region would yield the greatest damages. The magnitude of the location uncertainty represents the full range of damages for Ontario from densely population regions in Toronto to sparsely population northern regions. This range was developed based on marginal damages from the EASIUR grid which includes Ontario. Damages from a sparsely populated location near a major highway in Northern Ontario were collected and were found to be 31% of marginal damages in Toronto for NOx, 38% of $PM_{2.5}$ damages, and 58% of SO_2 damages.

7.2.2 Concentration-Response Uncertainty

Many, though not all, of the damages of atmospheric releases are due to their harm to human health. Health uncertainty refers to the uncertainty in the concentration response function used to relate pollutant concentrations to resulting health impacts. As described in Chapter 4, concentration response functions are derived from the epidemiological literature which describes the risk of an increase in health incidences such as mortality associated with an increase in pollutant concentration. For this analysis, all marginal damages were adjusted to the relative risk value for $PM_{2.5}$ mortality risk from the American Cancer Society (ACS) (Krewski et al., 2009). The other main epidemiological study from which this relative risk value is used is the Harvard Six Cities study (Lepeule et al., 2012). Heo et al. (2016a) found an effect on marginal damages of -33% to +270% for EASIUR when switching between risks estimated with these two studies . This range was used to determine the magnitude of health uncertainty in the environmental costs for this study. It should be noted that this only considers the uncertainty for $PM_{2.5}$ mortality risk and is likely an underestimate of concentration-to-impact uncertainty for methods which include morbidity and non-health impacts.

7.2.3 Economic Uncertainty

Economic uncertainty relates to the uncertainty in economic valuation of health and environmental damages. The two types of economic uncertainty analyzed in this study include uncertainty in the VSL and discount rate.

The VSL is used to estimate the full economic damages associated with a small increase in mortality risk. It is based on willingness to pay for a small reduction in mortality risk, normalized to a risk increase of 1.0. Given the difficulty in measuring the value of a non-market good, such as mortality risk, there is a high degree of uncertainty associated with the VSL. The US EPA recommends a standard value based on a review of 26 VSL studies. Based on this review Heo et al. (2016a) provide range of -90% to 160% for marginal damages. This range was applied to the damages of $PM_{2.5}$, NOx, and SO_2 to determine the magnitude of VSL uncertainty for this analysis.

There uncertainty due to discount rate refers to the discount rate used in marginal damage studies to discount future damages compared to present damages. For damages due to long-term effects such as climate change, the discount rate can have a significant effect on overall damages as a high discount rate means that future damages are valued much less than present damages, whereas a low discount rate would value future damages much closer to present damages. For the base case in this analysis all marginal damages were calculated using a discount rate of 3%. The uncertainty from discount rates was determined using the SCAR estimates which calculates damages at several discount rates including 1.4%, 3%, 5%, and a declining discount rate (Shindell, 2015). The median total value of these discount rates was used to develop the range of discount rate uncertainty.

7.3 Uncertainty of Environmental Cost

Uncertainty ranges for all factors of uncertainty in marginal damages are presented in Table 7.1. These ranges, along with the emissions uncertainty ranges were used to determine the uncertainty in the environmental cost.

Table 7.1 Uncertainty ranges for marginal damages

	CO_2	CO	NOx	SO_2	$PM_{2.5}$
CR – PM2.5 Mortality[1]				-33% to +270%	
VSL[2]				-90% to +160%	
Location[3]			31%	38%	58%
Source[4]				27% - 932%	28% - 239%
Discount Rate[5]	32% - 179%	65% -130%		95% -102%	81%-113%

[1] *95% confidence interval of two PM2.5 relative risks from Krewski et al. (2009) and Lepeule et al. (2012)* (Heo et al., 2016a)

[2] *95% confidence interval based on literature review of 26 VSL studies by the US EPA* (Heo et al., 2016a)

[3] *Based on the difference between the EASIUR MD for Toronto (-79.38, 43.65) & Northern Ontario (-81.03, 49.03)*

[4] *Based on the difference between the median MD and the largest (iron and steel) and smallest source (marine vessels) from Fann et al. (2012)*

[5] *Based on the median values calculated by Shindell (2015) for discount rates of 1.4%, 3%, 5%.*

The uncertainties in environmental cost due to all factors are provided in Figure 7.1 for the preferred design alternative, M2 (CIR). The base case value is based on the results presented in the results from Chapter 6. As can be seen in Figure 7.1, the greatest source of potential uncertainty in environmental costs is based on particulate matter controls.

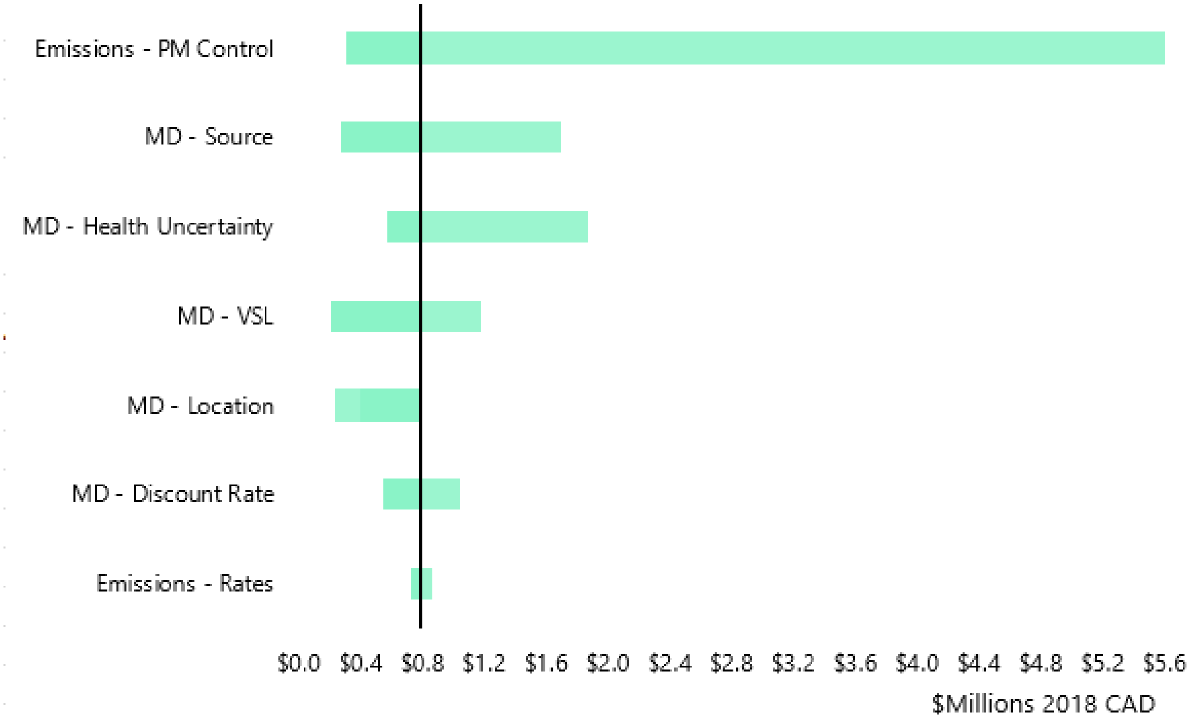

Figure 7.1 Uncertainty of lifecycle environmental cost of preferred design alternative, M2 (CIR)

7.4 Total Uncertainty

Figure 7.2 shows the total uncertainty of lifecycle costs for the preferred design alternative (M2 CIR). The sources of uncertainty investigated were: service life, the discount rate, range of marginal damages from literature, uncertainty in marginal damages, and emissions.

Of the uncertainty sources investigated, service life and discount affect both agency and environmental costs. The magnitude of uncertainty for service was based on the MTO Guidelines for LCCA on freeways which includes recommended standard deviations of service lives and is provided in Chapter 5. For discount rate, both agency and environmental costs were determined at a discount rate of 5%, 3% (base case), and 1.5%. In addition, marginal damages were adjusted for different discount rates based on the analysis by Shindell (2015).

Figure 7.2 Uncertainty in total lifecycle cost of preferred design alternative (M2 CIR) ($2018 CAD)

The environmental cost uncertainty is broken down by uncertainty in marginal damages and emissions. Marginal damages uncertainty is calculated as a cumulative uncertainty based on the cited uncertainties of various factors used to determine damages. The total marginal damages uncertainty was determined by examining the uncertainty around each of the key factors used to calculate marginal damages (such as economic valuation, source of emissions, etc.) and determining their contribution to overall uncertainty. For comparison, the range of estimates cited in the literature (provided in Chapter 4) is much narrower. While the range of literature estimates reflects differences in methodologies and study aims, our estimate reflects underlying uncertainty in the factors, estimated from ranges and sensitivity studies provided within the literature. Although the literature review identified key differences in the methods used to calculate marginal damages, this uncertainty is still much lower than the total uncertainty in marginal damages. This is noteworthy as it shows that a literature review alone does not capture the full uncertainty in the application of marginal damages.

7.5 Sensitivity Analysis

The purpose of the sensitivity analysis was to determine the robustness of the ranking of design alternatives in the study results. Sensitivity of the total lifecycle cost to the agency cost, environmental cost, and discount rate was tested and is shown in Figure 7.3. Since M5 has the highest lowest agency costs and the highest environmental costs, a change in either one of these would affect the total lifecycle cost and the preferred alternative.

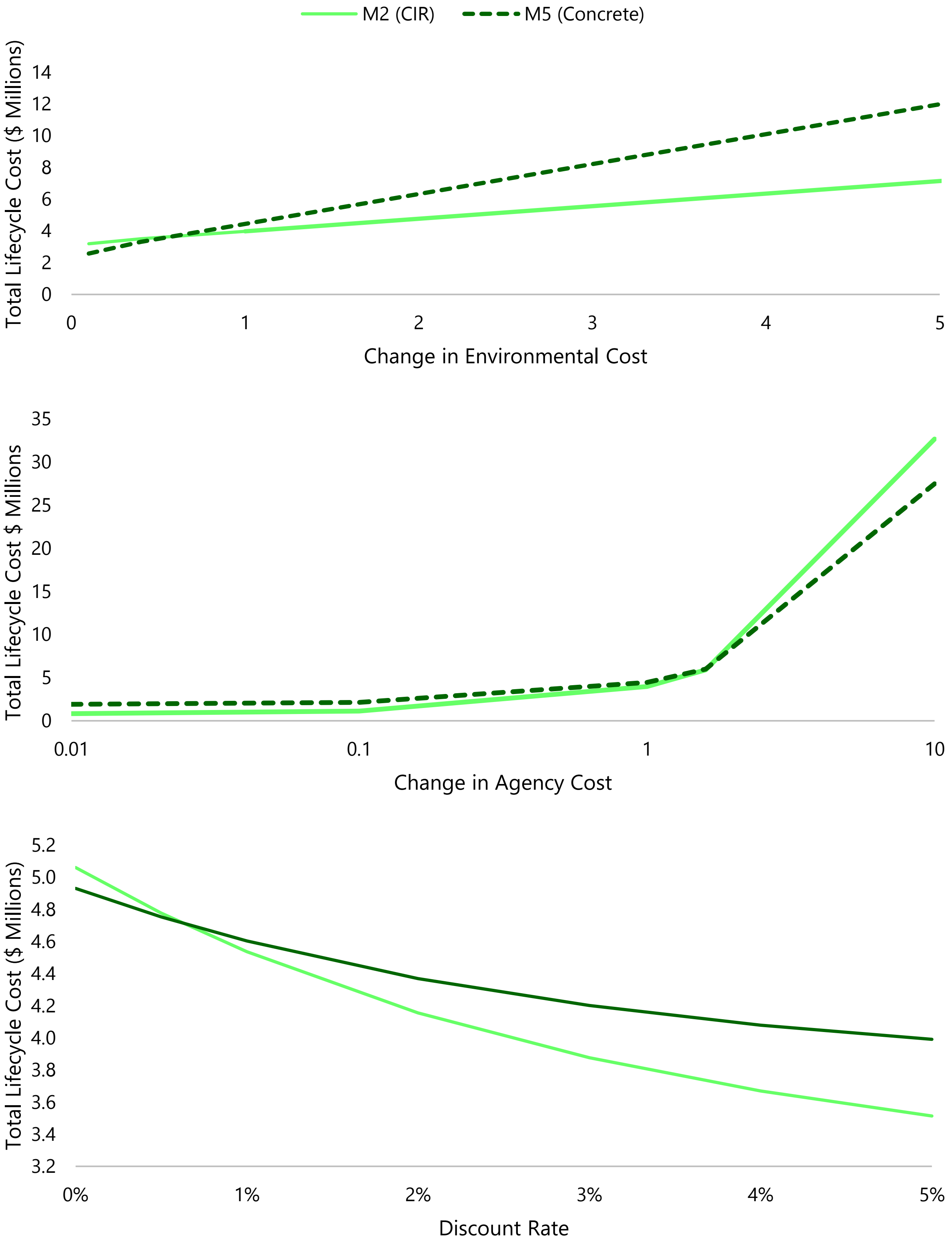

Figure 7.3 Sensitivity of lifecycle cost of all design alternatives to a) environmental cost, b) agency cost c) discount rate

As seen in Figure 7.3, the choice of preferred alternative is highly sensitive to both the agency and environmental cost. If environmental costs were 0.4 times lower than present costs M5 would be the preferred alternative. This is within the total uncertainty of environmental costs described in Section 7.4. Similarly an increase of 1.5 times present in agency costs would also make M5 the preferred alternative. While the uncertainty in agency costs is not known it is possible that costs could increase as materials the scarcity of materials increases.

The discount rate is used to convert future costs to present value. While the asphalt alternatives, have high maintenance costs, the concrete alternative, M5 has high initial costs and low maintenance costs. As such a low discount rate, which would value future costs higher, would favour M5, whereas a high discount rate would favour the asphalt alternatives. As such, sensitivity to the discount rate was tested. It was found that at very low discount rates, 0.4% or lower, M5 is the preferred alternative.

The sensitivity between the asphalt alternatives was tested by keeping the costs of M2, the preferred alternative constant and varying the costs of the other asphalt alternatives as shown in Figure 7.4. The costs were found to be highly sensitive to agency cost. A 5% reduction in agency costs would change the preferred alternative to M3, with 15% RAP which is presently the second lowest alternative. This is noteworthy as the cost data used in this analysis did not include savings for the use of recycled materials, it is possible that the costs of M3 could decrease by 5% thereby making it the preferred alternative.

Similarly, if the environmental costs of M2 stayed constant, but decreased for all other alternatives, M3 would be the preferred alternative at 85% of present costs. While this is within the uncertainty of environmental costs, it is unlikely that the environmental costs would decrease for only this alternative as there are minimal differences in the sources of emissions between the alternatives.

It should be noted that the sensitivity analysis conducted does not represent the full potential of sensitivity of these alternatives in site-specific analyses for which the data might differ greatly. For this study the main contributors to environmental cost were emissions of NOx, SO_2, and $PM_{2.5}$ from materials production. As such, there was very little sensitivity in the total environmental cost. In addition, the system boundaries for this analysis focused on emissions & damages from transportation, material production, and construction activities. As such the sensitivity analysis focused only on these factors. Sensitivity due to the agency costs was not evaluated as agency costs were based on cost data from MTO and no underlying model for agency costs was available. In addition, there are many factors which fall outside the system boundary of this analysis which could change the design alternatives including noise costs and user costs. User costs in particular could change the preferred alternative in favour of M5, as concrete roads require less maintenance resulting in much lower user costs than for asphalt roads.

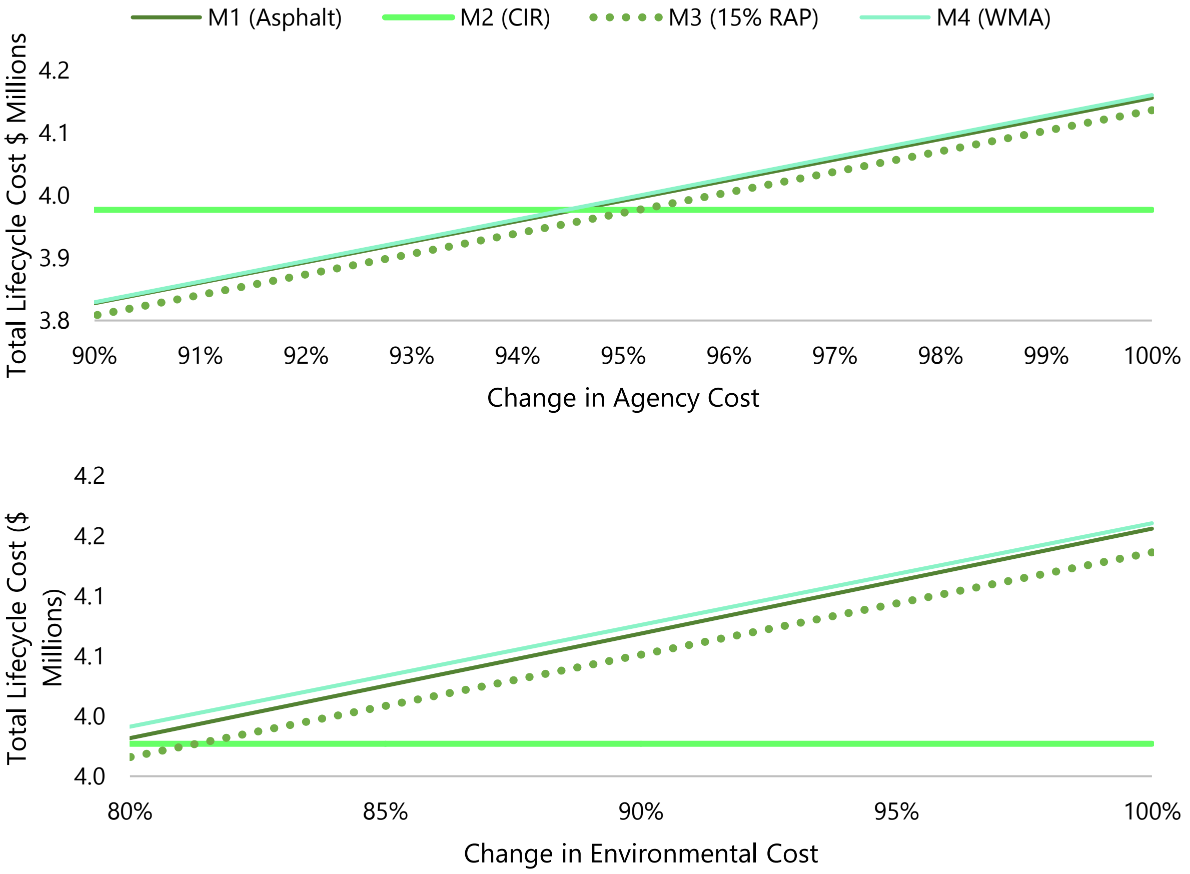

Figure 7.4 Sensitivity of asphalt alternatives to a) agency cost b) environmental cost

7.6 Summary of Uncertainty

There are significant sources of uncertainty in determining environmental costs of pavement management activities. However, some of this uncertainty can be reduced when conducting a specific analysis for which site-specific knowledge about the source and magnitude of emissions is available. Given the sensitivity of the preferred alternative to these areas of uncertainty further research is required to determine a true environmental cost estimate of these alternatives for integration in decision-making.

8 Conclusions & Recommendations

The analysis conducted in this study provides some key insights both towards the process of internalizing environmental costs for transportation agencies as well as for applications of marginal damages by decision-makers. These findings and recommendations for future work in these areas are discussed in this chapter. Key insights from this study include:

- Increased mortality risk from $PM_{2.5}$ emissions is the largest contributor to overall environmental costs of atmospheric releases
- Reduction of $PM_{2.5}$ emissions in the production of asphalt and concrete materials would have the greatest impact in reducing environmental costs of pavement management
- Application of marginal damages provides opportunities for decision-makers such as infrastructure managers to internalize environmental costs

8.1 Pavement Management Systems

Transportation agencies, as with many policy and decision-makers, face an increasing need to account for and mitigate the adverse environmental effects of their work. This need arises from an increased awareness and pressing problem of climate change, as well as due to increasingly stringent environmental regulations. Even when certain activities have known environmental effects such as pollution, decision-makers may not be able to apply research about the damages of that pollution into pavement management decisions. Current decision-making practices which do not account for these environmental impacts result in sub-optimal decisions because they do not consider full social costs of atmospheric releases. The marginal damages literature provides one solution to this problem as it allows transportation agencies to convert known atmospheric releases to an economic cost based on the human health and environmental damages caused by those releases.

This study provided an integrated lifecycle cost analysis for pavement management systems which accounted for both agency and environmental costs of pavement construction and maintenance. Based on the analysis conducted, Cold-in-Place recycling was found to have the lowest environmental damages and lowest agency costs as it uses the highest percentage of recycled materials of the design alternatives evaluated. The reduction of raw materials was found to have the greatest effect on reducing emissions as materials production was the largest contributor to emissions. While warm-mix asphalt, which reduces the temperature at which asphalt is produced and requires less energy also reduces emissions it is not as effective as lowering the quantity of raw materials. Concrete roads were found to have the highest damages, which can mostly be attributed to high emissions in both cement and concrete production. Reducing environmental damages from concrete road construction would require recycled alternatives to cement and concrete and reducing the overall components of these materials used if possible.

However, there were many external costs not accounted for in this analysis including additional environmental costs (such as noise emissions as well as increased vehicle emissions due to road closures) as well as user costs (such as vehicle operating or construction delay costs). User costs in particular could change the preferred alternative in favour of M5, as concrete roads require less maintenance resulting in much lower user costs than for asphalt roads. Continued integration of these external costs into pavement management systems will allow transportation agencies to make truly optimal design and maintenance decisions. The results and insights of this study can provide useful insight for future analyses.

8.2 Application of Marginal Damages

There is a growing body of literature on the estimation of damages from atmospheric releases of greenhouse gases and atmospheric pollutants. Given the increasing sophistication of these techniques, this literature provides new opportunities for understanding and valuing the damages of these atmospheric releases across human health and the environment. The valuation of these damages in economic terms provides opportunities for decision-makers (such as infrastructure managers) to understand the full impacts of their activities and internalize environmental costs in decisions. Marginal damages provide a simpler method for decision-makers and regulators to convert emissions to costs without requiring them to conduct full impact analyses which would fall outside the scope of their work. However, the application of marginal damages towards determining environmental costs requires an understanding of the process by which marginal damages are developed. As discussed in Chapters 4 & 7, marginal damage estimates can vary greatly depending on the input factors (such as complexity of atmospheric model) as well as the site-specific factors for the application (such as population income). The analysis conducted here provides a useful case study on the application of marginal damage estimates in a manner which accounts for both the distinction between different estimates and the needs of the decision-makers who can apply these results towards internalizing environmental costs.

Future work in this area could consider more consistent approaches for adjusting marginal damages available in literature for specific applications such as infrastructure management and beyond. The application of marginal damages provides opportunities for decision-makers looking to internalize environmental damages. This potential should lead to further research on how to conduct such applications in a manner which both accounts for the specificity of marginal damage estimates as well as the unique needs of various stakeholders and decision-makers.

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Appendices

A. Emissions Data

Table A.1 Materials production emission factors

			CO_2	CO	NOx	SO_2	PM_{10}	Total PM	$PM_{2.5}$	Units
HMA (US EPA, 2004)										
Drum-Mix	Natural Gas	FF	33	0.13	0.026	0.034	0.023	0.033	0.0029	lb/ton
Batch-Mix	Natural Gas	FF	37	0.4	0.025	0.046	0.027	0.042	0.0083	lb/ton
Drum-Mix	Natural Gas	Uncontrolled	33	0.13	0.026	0.034	6.5	28	1.5	lb/ton
Batch-Mix	Natural Gas	Uncontrolled	37	0.4	0.025	0.046	4.5	32	0.27	lb/ton
Drum-Mix	Natural Gas	Scrubber	33	0.13	0.026	0.034		0.045		lb/ton
Batch-Mix	Natural Gas	Scrubber	37	0.4	0.025	0.046		0.14		lb/ton
Drum-Mix	#2 Fuel Oil		33	0.13	0.055	0.011				lb/ton
Batch-Mix	#2 Fuel Oil		37	0.4	0.12	0.088				lb/ton
Drum-Mix	Waste Oil		33	0.13	0.055	0.058				lb/ton
Batch-Mix	Waste Oil		37	0.4	0.12	0.088				lb/ton
Drum-Mix	Coal		33			0.019				lb/ton
Batch-Mix	Coal		37			0.043				lb/ton
Concrete (US EPA, 2006)										
	Truck Mix	Controlled					0.03448	0.0612	0.025596	kg/Mg
	Truck Mix	Uncontrolled					1.06381	2.4962	0.449316	kg/Mg
	Central Mix	Controlled					0.02418	0.1042	0.044946	kg/Mg
	Central Mix	Uncontrolled					0.98681	2.2232	0.400176	kg/Mg
Cement (US EPA, 1995)										
	Wet	FF	1100	0.06	3.7	4.1	0.25262	0.298	0.1778	kg/Mg
	Wet	ESP	1100	0.06	3.7	4.1	0.37032	0.428	0.2648	kg/Mg
	Wet	FF+gravel bed	1100	0.06	3.7	4.1	0.2795	0.34	0.1912	kg/Mg
	Wet	ESP+gravel bed	1100	0.06	3.7	4.1	0.414	0.49	0.2872	kg/Mg
	Wet	Uncontrolled+FF	1100	0.06	3.7	4.1	16.05712	65.068	4.5806	kg/Mg
	Wet	Uncontrolled+ESP	1100	0.06	3.7	4.1	16.04032	65.048	4.5716	kg/Mg
	Wet	Uncontrolled+gravel bed	1100	0.06	3.7	4.1	16.084	65.11	4.594	kg/Mg
	Wet	Multiple+FF	1100	0.06	3.7	4.1	0.14212	0.168	0.0946	kg/Mg

	Wet	Multiple+ESP	1100	0.06	3.7	4.1	0.12532	0.148	0.0856	kg/Mg
	Wet	Multiple+Gravel bed	1100	0.06	3.7	4.1	0.169	0.21	0.108	kg/Mg
	Dry	FF	900	0.11	3	4.9	0.14112	0.168	0.0756	kg/Mg
	Dry	ESP	900	0.11	3	4.9	0.46032	0.548	0.2466	kg/Mg
	Dry	FF+Gravel bed	900	0.11	3	4.9	0.168	0.21	0.089	kg/Mg
	Dry	ESP+gravel bed	900	0.11	3	4.9	0.42	0.5	0.225	kg/Mg
Sand & Gravel (US EPA, 1995)										
		FF	14		0.016		0.007632	0.01521	0.001709	kg/Mg
		Scrubber	14		0.016		0.014619	0.02891	0.003764	kg/Mg
		Uncontrolled	14		0.016		0.552866	1.17009	0.162419	kg/Mg
Bitumen (Carnegie Mellon University Green Design Institute, 2018)										
			358.40	0.38	0.36	1.33	0.02		0.002304	kg/Mg

Table A.2 Emissions factors for transportation & equipment

Model	Source	CO_2	CO	NOx	SO_2	PM_{10}	Total PM	Units
Rail	Railway Association of Canada (2013)	13.66	0.035606	0.224293	0.000101		0.005101	g/tonne-km
Trucks	NRCAN, 2006	108.2096	1.203822	1.43386	0.010985		0.045232	g/tonne-km
	CARB, 2004	140.8013	0.144743	0.45426			0.025201	g/tonne-km
Non-road mobile equipment	Frey,Rasdorf, Lewis, (2010)	140.9373	0.462334	1.692739	0.002554	0.014914		g/hp-hr
	Gautam, (2002)	609.9825	2.550294	8.277269		0.633845		g/hp-hr

Table A.3 Emissions of Design Alternatives from Adapted PaLATE

Year	Design / Maintenance	CO_2	CO	NOx	SO_2	PM_{10}	$PM_{2.5}$
	M1 (Asphalt)						
0	Asphalt Pavement	1227385	3085	2254	825	18716	1303
9	Mill & Patch 40 mm (5%)	4417	17	8.4	5.1	114	7.3
15	Mill & Patch 40 mm (20%)	17666	69	33	21	455	29
19	Mill & Overlay	198744	777	377	231	5120	329
27	Mill & Patch 40 mm (10%)	8833	35	17	10	228	15
31	Mill & Overlay	198744	777	377	231	5120	329
38	Mill & Patch 40 mm (10%)	8833	35	17	10	228	15
42	Mill & Overlay	198744	777	377	231	5120	329
48	Mill & Patch 40 mm (10%)	8833	35	17	10	228	15
50	End-of-Analysis						
	Total	1872199	5608	3476	1575	35327	2371
	M2 (CIR)						
0	Asphalt Pavement	1227385	3085	2254	825	18716	1303
9	Mill & Patch 40 mm (5%)	4417	17	8	5	114	7
15	Mill & Patch 40 mm (20%)	17666	69	33	21	455	29
19	CIR & Overlay	119191	446	236	156	2846	183
27	Mill & Patch 40 mm (10%)	8833	35	17	10	228	15
31	CIR & Overlay	119191	446	236	156	2846	183
38	Mill & Patch 40 mm (10%)	8833	35	17	10	228	15
42	CIR & Overlay	119191	446	236	156	2846	183
48	Mill & Patch 40 mm (10%)	8833	35	17	10	228	15
50	End-of-Analysis						
	Total	1633541	4612	3055	1349	28506	1932
	M3 (15% RAP)						
0	Asphalt Pavement	1227385	3085	2254	825	18716	1303
9	Mill & Patch 40 mm (5%)	4417	17	8	5	114	7
15	Mill & Patch 40 mm (20%)	17666	59	24	21	455	29
19	Mill & Overlay (15% RAP)	151999	727	315	100	5107	326
27	Mill & Patch 40 mm (10%)	8833	35	17	10	228	15
31	Mill & Overlay (15% RAP)	151999	727	315	100	5107	326
38	Mill & Patch 40 mm (10%)	8833	35	17	10	228	15
42	Mill & Overlay (15% RAP)	151999	727	315	100	5107	326
48	Mill & Patch 40 mm (10%)	8833	35	17	10	228	15
50	End-of-Analysis						
	Total	1731963	5446	3281	1183	35287	2362
	M4 (WMA)						
0	Asphalt Pavement	1227385	3085	2254	825	18716	1303
9	Mill & Patch 40 mm (5%)	4417	17	8	5	114	7
15	Mill & Patch 40 mm (20%)	17666	69	33	21	455	29

19	Mill & Overlay (WMA)	184944	673	366	214	4227	274
27	Mill & Patch 40 mm (10%)	8833	35	17	10	228	15
31	Mill & Overlay (WMA)	184944	673	366	214	4227	274
38	Mill & Patch 40 mm (10%)	8833	35	17	10	228	15
42	Mill & Overlay (WMA)	184944	673	366	214	4227	274
48	Mill & Patch 40 mm (10%)	8833	35	17	10	228	15
50	End-of-Analysis						
	Total	1830801	5294	3445	1523	32650	2206
	M5 (Concrete)						
0	Concrete Pavement	1996809	410	6407	6199	7413	3271
18	Diamond Grinding	866	3	12	0.01	0.75	0.00
18	Partial Depth Slab Repair	3708	1	13	13	11	5
18	Full Depth Slab Repair	13093	3	45	45	38	17
28	Partial Depth Slab Repair	6546	1	22	22	19	9
28	Full Depth Slab Repair	43566	9	148	148	128	57
28	Diamond Grinding	866	3	12	0.01	0.75	0.00
38	90-mm Asphalt Overlay	195117	747	329	231	5119	329
50	End-of-Analysis						
	Total	260,572	1,178	6,987	6,658	12,729	3,689

B. Environmental Cost Data

Table B.1 Original MD Data Used in Study

	CO_2	NOx	$PM_{2.5}$	SO_2	CO	Currency Year	Units
CAMx PSAT + BenMAP		$5,500	$350,000	$42,000		2010	$/ton
AP2[a]		$24,552	$240,334	$62,614		2000	$/ton
SCAR	$84	$67,000	$278,000[b]	$40,000	$630	2007	$/ton
EASIUR		$18,225	$111,965	$32,860		2010	$/metric tonne
CMAQ-Adjoint		$20,000				2011 CAD	$/metric tonne

a: only includes $PM_{2.5}$ mortality and morbidity damages

b: Based on the SCAR MD for OC+BC

Table B.2 Damages for Design Alternatives ($2010 CAD)

Year	Design / Maintenance	CO_2	CO	NOx	SO_2	$PM_{2.5}$
0	Asphalt Pavement	$111,692	$2,104	$68,824	$40,942	$355,462
9	Mill & Patch 40 mm (5%)	$402	$12	$256	$255	$1,995
15	Mill & Patch 40 mm (20%)	$1,608	$47	$1,022	$1,020	$7,980
19	Mill & Overlay	$18,086	$530	$11,502	$11,472	$89,777
27	Mill & Patch 40 mm (10%)	$804	$24	$511	$510	$3,990
31	Mill & Overlay	$18,086	$530	$11,502	$11,472	$89,777
38	Mill & Patch 40 mm (10%)	$804	$24	$511	$510	$3,990
42	Mill & Overlay	$18,086	$530	$11,502	$11,472	$89,777
48	Mill & Patch 40 mm (10%)	$804	$24	$511	$510	$3,990
50	End-of-Analysis					
0	Asphalt Pavement	$111,692	$2,104	$68,824	$40,942	$355,462
9	Mill & Patch 40 mm (5%)	$402	$12	$256	$255	$1,995
15	Mill & Patch 40 mm (20%)	$1,608	$47	$1,022	$1,020	$7,980
19	CIR & Overlay	$10,846	$304	$7,220	$7,723	$49,889
27	Mill & Patch 40 mm (10%)	$804	$24	$511	$510	$3,990
31	CIR & Overlay	$10,846	$304	$7,220	$7,723	$49,889
38	Mill & Patch 40 mm (10%)	$804	$24	$511	$510	$3,990
42	CIR & Overlay	$10,846	$304	$7,220	$7,723	$49,889
48	Mill & Patch 40 mm (10%)	$804	$24	$511	$510	$3,990
50	End-of-Analysis					
0	Asphalt Pavement	$111,692	$2,104	$68,824	$40,942	$355,462
9	Mill & Patch 40 mm (5%)	$402	$12	$256	$255	$1,995
15	Mill & Patch 40 mm (20%)	$1,608	$40	$733	$1,018	$7,980
19	Mill & Overlay (15% RAP)	$13,832	$496	$9,613	$4,984	$88,941

27	Mill & Patch 40 mm (10%)	$804	$24	$511	$510	$3,990
31	Mill & Overlay (15% RAP)	$13,832	$496	$9,613	$4,984	$88,941
38	Mill & Patch 40 mm (10%)	$804	$24	$511	$510	$3,990
42	Mill & Overlay (15% RAP)	$13,832	$496	$9,613	$4,984	$88,941
48	Mill & Patch 40 mm (10%)	$804	$24	$511	$510	$3,990
50	End-of-Analysis					
0	Asphalt Pavement	$111,692	$2,104	$68,824	$40,942	$355,462
9	Mill & Patch 40 mm (5%)	$402	$12	$256	$255	$1,995
15	Mill & Patch 40 mm (20%)	$1,608	$47	$1,022	$1,020	$7,980
19	Mill & Overlay (WMA)	$16,830	$459	$11,189	$10,602	$74,812
27	Mill & Patch 40 mm (10%)	$804	$24	$511	$510	$3,990
31	Mill & Overlay (WMA)	$16,830	$459	$11,189	$10,602	$74,812
38	Mill & Patch 40 mm (10%)	$804	$24	$511	$510	$3,990
42	Mill & Overlay (WMA)	$16,830	$459	$11,189	$10,602	$74,812
48	Mill & Patch 40 mm (10%)	$804	$24	$511	$510	$3,990
50	End-of-Analysis					
0	Concrete Pavement	$181,710	$280	$195,638	$307,591	$892,367
18	Diamond Grinding	$79	$2	$351	$0	$0
18	Partial Depth Slab Repair	$337	$1	$386	$627	$1,334
18	Full Depth Slab Repai4	$1,191	$2	$1,362	$2,213	$4,711
28	Partial Depth Slab Repair	$596	$1	$681	$1,106	$2,355
28	Full Depth Slab Repair	$3,965	$6	$4,533	$7,363	$15,675
28	Diamond Grinding	$79	$2	$351	$0	$0
38	90-mm Asphalt Overlay	$17,756	$509	$10,033	$11,461	$89,777
50	End-of-Analysis					