Incorporating Environmental Sustainability into Pavement Design and Management

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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

Statement of Contributions

This thesis is partially the product of co-authored publications as follows:

Chapter 2 and Chapter 4 of this thesis contain parts of a final report that was submitted to Ministry of Transportation Ontario and authored by myself and co-authored by my supervisors (Dr. Tighe and Dr. Saari). Dr. Tighe initiated the project. I developed the methodology for the analysis, with inputs from Professor Tighe. Prof. Saari advised on the research methodology and data collection. I wrote the report based on the findings. I documented the findings and the co-authors also provided editing and review during report production.

Chapter 3 of this thesis consists of a paper that will be submitted for publication. The paper is authored by myself and co-authored by my supervisors and several lab members. I developed the research approach for the study. Dr. Saari provided guidance on the research approach and assisted in the compilation of data for the study. Dr. Saari and I analyzed the data and developed the new evaluation framework. I wrote the paper based on my findings. Dr. Saari assisted in manuscript preparation. Drs. Saari and Tighe provided editing and review.

Chapter 6 of this thesis consist of a paper published by the Journal of the Transportation Research Board. The paper is authored by myself, and co-authored by Oluremi Oyediji, Filzah Nasir and by my supervisors. I developed the research methodology. Oluremi, Filzah and I compiled the data for analysis. The analysis in the paper was done by myself under the supervision and guidance of my supervisors.

Chapter 7 and Chapter 8 of this thesis contains parts of a paper that will be submitted for publication. The paper is authored by myself, co-authored by my supervisors and Ushnik Mukherjee. My supervisors provided guidance on the research methodology, I developed the methodology for the analysis, Ushnik and I collected the data, I analyzed the data myself with guidance from my supervisors. I wrote the paper based on the findings and my supervisors provided editing and review during paper writing.

Abstract

Increasing interest in pavement sustainability has led to the development of sustainability assessment tools and a plethora of potential indicators. Well-designed indicators are capable of quantitatively tracking and informing environmental performance of pavement infrastructure systems. Here, we review literature on sustainability assessment, focusing on work relevant to transportation and civil infrastructure. This research considers the context of Ontario, its values, conditions and practices for sustainability assessment in pavement management and proposes a framework, set of indicators and associated measures to assess environmental sustainability of pavements throughout their lifecycle. The framework includes seven factors addressing environmental protection, and four reflecting natural resource management. A combination of input-based, output-based, and outcome-based indicators are provided for each factor. The key environmental performance indicators are selected to be comprehensive, consistent, measurable, context-specific, and informed by values, influence and purpose of Ontario pavement managers. Providing measures of these indicators, where possible, required some novel applications and analysis of existing methods and data for Ontario pavements.

It was observed that climate change continues to be an important environmental issue. Widespread impacts of climate change are expected to affect Canadian infrastructure systems because of changes in precipitation, temperature, winds, sea level rise, and other extreme events. A major cause of climate change, greenhouse gas (GHG) emissions, are increasing because of human influence. Responding to climate change requires action to mitigate anthropogenic greenhouse gas (GHG) emissions and increase climate-resiliency of assets and operations. This study provided a comprehensive list of GHG mitigation measures and an improved selection framework for implementing such measures across roadway design, construction, and maintenance processes. Four approaches to manage GHG emissions to investigate strategies to manage GHG emissions during all highway management phases: Design, Construction, Rehabilitation and Reconstruction and Maintenance. A review of current and emerging best practices and strategies from other jurisdictions for addressing GHG emissions was done, along with surveys and interviews were prepared to enhance this information and yield insights into factors that influence implementation of mitigation measures. Survey and interviews were designed to capture information related to cost of implementing measures, changes to internal resourcing at the agencies, industry's response and evidence of social resistance; as well as strategies to manage these influencing factors. Cost was identified as a major factor for implementing innovations to manage GHG emissions.

Transportation energy consumption and the associated emission from fuel combustion have adverse effects on air quality and healthy living in Canada. Improvement in engine performance and emission control technologies are often considered to improve vehicle fuel economy and reduce the consequent pollution, but past studies have focused on vehicle emissions. This research shows that road surface condition management can be used as a short-term strategy to reduce environmental impact even as the population of Canada continues to grow, and vehicle numbers increase,, especially in densely populated urban areas. A model to predict the impact of road surface condition measured by International Roughness index (IRI) (m/km) on vehicle fuel consumption and associated emissions was developed. Additionally, the relationship between excess damage cost from rougher roads (IRI >1m/km) was estimated for cars and trucks travelling on Ontario Road. When models are implemented into a network-level analysis of Ontario Roads, results show that the vehicles using on Ontario Road network released an excess 2000 tonnes of carbon dioxide (CO_2) emission due to the road condition (IRI >1m/km) in 2014. Also, the environmental damage cost of emissions (2010CAD) of five atmospherics pollutants was found to be about $2.6 Million in 2014. A project level sustainability assessment framework was proposed to incorporate economic, environmental and technical aspects of sustainability into pavement management. Future study can expand the framework to network-level and incorporate the road condition models developed in this research program and documented in this thesis.

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I would like to express sincere gratitude and appreciation to the many people who have supported me during the completion of this research. Firstly, to my supervisors, Dr. Susan Tighe, whose irreplaceable support, and guidance enabled me to undertake the doctoral study and Dr. Rebecca Saari, whose guidance and dedication propelled me to expand my knowledge in this field of research. Their encouragements all through my research study was key to the achievement of this study. Secondly, I would like to thank my husband, Doubra, for his tireless support and patience. Thirdly, thanks to my mother and my sisters, Ijay, Julie, Jennifer and Amaka, for their prayers and support.

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Dedication

I dedicate this thesis to my loving sister of blessed memory, Late Miss Gloria Oyiboka Achebe; to my lovely husband Doubra Ambaiowei, my babies Raphael Ebitari Chukwunonso and Binatari, my mother and my sisters, whose support, patience, and love have made this a possibility; Finally, this work is dedicated in thanksgiving to my God, for what God cannot do, does not exist.

Table of Contents

Examining Committee Membership ii
Author's Declaration iii
Statement of Contributions iv
Abstract v
Acknowledgements vii
Dedication viii
List of Figures xiii
List of Tables xviii
Chapter 1 Introduction 1
  1.1 Research Context 3
  1.2 Research Objective and Questions 5
  1.3 Thesis Structure 5
Chapter 2 Background 8
  2.1 Introduction 8
  2.2 Pavement Management 8
    2.2.1 Overview 8
    2.2.2 Decision Making Approaches in Pavement Management 10
  2.3 Environmental Sustainability of Pavement Systems 11
    2.3.1 Environmental Aspects in Each Phase of the Pavement Life Cycle 12
    2.3.2 Measuring and Assessing Environmental Sustainability 19
  2.4 Sustainability Evaluation in Pavement Management 33
    2.4.1 Overview of State of the Art 33
    2.4.2 Adapting Life Cycle Assessment to Pavement Management System 35
  2.5 Sustainable Pavement and Changing Atmospheric Conditions 36
    2.5.1 Atmospheric Issues 37
    2.5.2 Greenhouse Gas Mitigation in Pavement 39
    2.5.3 Adapting Pavement to Climate Change 42
  2.6 Summary 43
Chapter 3 Environmental Sustainability Measurement in Pavement Asset Management 45
  3.1 Introduction 45
  3.2 Research Approach 49

3.3 Overview of Environmental Sustainability and Pavement Management.................................. 49
3.3.1 Environmental Sustainability and Canadian Roads 49
3.3.2 Environmental Factors Sustainable Pavement Design and Management 56
3.4 Framework for Pavement Environmental Sustainability Evaluation.. 65
3.4.1 Integrating Environmental Sustainability: Evaluation Framework and Key Factors.......... 65
3.4.2 Operationalizing ES: Key Pavement Environmental Performance Evaluation 66
3.5 Discussion and Conclusion 76
Chapter 4 GHG Mitigation Strategies during Highway Design, Construction and Maintenance (HIIFP, 2018)... 79
4.1 Introduction.. 79
4.1.1 Research Objectives 80
4.2 Research Methodology 81
4.2.1 Scoping the Jurisdictional Review 81
4.2.2 Review of Adoption of GHG Mitigation Measures 82
4.2.3 Practitioner Survey and Interviews 85
4.3 Results and Discussion 87
4.3.1 Comparison of Mitigation Strategies 87
4.3.2 Feasibility Evaluation 97
4.3.3 GHG Mitigation Framework... 100
4.4 Recommendations and Conclusion... 104
Chapter 5 GHG Performance of Innovative Technologies 111
5.1 Introduction.. 111
5.2 Research Approach and Data.. 111
5.2.1 Methodology 111
5.2.2 Case Studies 113
5.3 Results and Discussion 122
5.3.1 Case study 1 - Environmental Performance of innovative Pavement Design Mix 122
5.3.2 Case Study 2: New Functional Pavement Design... 128
5.3.3 Case Study 3: Rehabilitation Design.. 130
5.4 Recommendations and Conclusion... 133
Chapter 6 Sustainability Impact of Pavement under Future Climate Conditions (TRB,2020).......... 135
6.1 Introduction.. 135

6.2 Methods and Data 139

6.2.1 Pavement Design and Deterioration Modelling 140

6.2.2 Resilience Assessment 145

6.2.3 Sustainability Analysis 147

6.3 Results and Discussion 151

6.3.1 JPCP Structural Performance 151

6.3.2 Resilience of Flooded JPCP 155

6.3.3 Sustainability Impacts of Flooded JPCP 157

6.4 Recommendations and Conclusion 162

Chapter 7 Effects of Pavement Surface Condition on Environmental Performance of Ontario Roads 164

7.1 Introduction 164

7.2 Literature Review 168

7.2.1 Pavement-Vehicle Interaction (PVI) 168

7.2.2 Measures of Pavement Surface Condition and PVI 170

7.2.3 Pavement Surface Condition and Fuel Consumption 171

7.2.4 Pavement Surface Condition and Vehicle Emissions 175

7.3 Research Methodology 180

7.3.1 Vehicle Energy Use and Emission Simulation 180

7.3.2 Developing Regression Models for Energy Consumption 186

7.3.3 Developing Regression Models for Environmental Damage Cost of Atmospheric Emissions 187

7.4 Results and Discussion 188

7.4.1 Preliminary Output Data Analysis 188

7.4.2 Regression Analysis and Models 203

7.4.3 Discussion of Validation and Comparison to Other Models 214

7.5 Conclusion 216

Chapter 8 Sustainable Pavement Management Evaluation 218

8.1 Introduction 218

8.2 Sustainability Evaluation at Project-Level Management 218

8.2.1 Application of Proposed framework 220

8.2.2 Results and Discussion 225

  8.3 Network-level Sustainability Evaluation 231
    8.3.1 Application of Proposed Models 231
    8.3.2 Results and Discussion 235
  8.4 Recommendations and Conclusion 241
Chapter 9 Conclusions and Recommendations 243
  9.1 Summary of Major Findings and Contributions 243
  9.2 Recommendations for Future Work 245
Bibliography 247
Appendices 270
Appendix A Supplementary Data for Chapter 3 270
Appendix B Supplementary Data for Chapter 4 278
Appendix C Supplementary Data for Chapter 5 298
Appendix D Supplementary Information for Chapter 7 299
Appendix E Supplementary Information for Chapter 8 308

List of Figures

Figure 1.1 Greenhouse Gas Emission by Canadian Economic Sectors in 2015 and the breakdown for Transportation section by use (ECCC - Environment and Climate Change Canada 2017) 1

Figure 1.2 MTO Annual Highway Rehabilitation and Renewal and Expansion Investment (Source: Asset Management at MTO Meeting and Discussion on Jan 18, 2018) 2

Figure 1.3 Research Methodology 7

Figure 2.1 Components of a Pavement Management System (Haas et al. 2015)................................. 9

Figure 2.2 Selected pavement characteristics and their impacts on use-phase objectives (Van Dam et al. 2015).. 18

Figure 2.3 Different System boundary for pavement LCA, arrows represent typical transportation or process paths, dotted lines labelled A, B, C and D represent various system boundaries considered in pavement LCA studies (adapted from FHWA, 2016)... 24

Figure 2.4 LCIA steps with example impact categories and midpoint and endpoint indicators (adapted from (J. T. Harvey et al. 2016))... 25

Figure 2.5 Chronology of Pavement LCA tools.. 28

Figure 2.6 Examples of GHG Mitigation Measures applicable to Four Highway Management Phases 40

Figure 3.1 Stakeholders Involved with Performance Measures for Roads (Haas et al., 2009) 48

Figure 3.2 Pavement Lifecycle Management Activity Classes adopted from TAC 2013................... 59

Figure 3.3 Focus Areas for Environmental Sustainability Evaluation 66

Figure 4.1 Summary of Tasks for This Project 81

Figure 4.2. How to manage GHG Emissions (adapted from MTO Climate Change Value Engineering Study) 82

Figure 4.3. Framework for Implementing GHG mitigation Strategies 101

Figure 5.1 Typical hexagonal ICP shapes, ... 115

Figure 5.2 Cross section of the pavement designs at the test site, (a) Perpetual pavement design with RBM, (b) conventional flexible pavement design for high traffic, (FC2 = Friction Course 2, PG = performance grade) (Source: El-Hakim and Tighe, 2012).. 118

Figure 5.3 IRI performance prediction for the three different sections designed convention method, PP with RM layer and PP without RBM layer.. 118

Figure 5.4 (A) GHG effect (Global Warming potential (kg CO2 eq.) estimates of 5 HMA mixes with varying proportions of CRCA compared to control mix with 0% CRCA, (B) GWP (CO2 [Mg]) of

pavements with 6 different HMA mix designs for PaLATE with base data and PaLATE with updated data 123
Figure 5.5 Energy use for material production (A) and transportation (B) of mix designs in Table 5.2 125
Figure 5.6 Climate change impact of material production and transportation of mix designs in Table 5.2 126
Figure 5.7 Percentage of material production and transportation CO_2 emissions reduction of all mixes in table 1 (Mix 2 – Mix 12) compared to control mix (Mix 1) 127
Figure 5.8 Contributions of each LCA phase to the LCA environmental performance. 132
Figure 5.9 CO_2 contributions by each LCA phase of conventional techniques compared to PCIP... 132
Figure 6.1 Analysis Framework for sustainability and resilience assessment of pavement designs . 139
Figure 6.2 Performance of JPCP designs for Ontario collector road (AADTT-500), including maintenance schedules for a 50-year service life 153
Figure 6.3 Performance of JPCP designs for Manitoba collector road (AADT-500), including maintenance schedules for a 50-year service life 154
Figure 6.4 Damage ratio of JPCP Collector roads in Manitoba and Ontario (AADTT-500) 155
Figure 6.5 Emissions of JPCP Collector roads (AADTT-500) in Ontario (ON) and Manitoba (MB) considering flood impacts and life cycle phases (Const Mat. = Initial construction material production; Mat. Transport1= Initial construction material transportation; Const. Act. = Initial construction processes; M&R Mat. = M&R material production; Mat. Transport2= M&R material transportation; M&R Act. = M&R processes) 157
Figure 6.6 Environmental performance of JPCP Collect roads (AADTT-500) in Ontario (ON) and Manitoba (MB) considering no climate change/flooding scenario and climate change/flooding scenario 158
Figure 6.7 Economic performance of JPCP Collect roads (AADTT-500) in Ontario (ON) and Manitoba (MB) considering no climate change/flooding scenario and climate change/flooding scenario 159
Figure 7.1 Relationship between total power demand, rolling resistance, internal friction, air drag and speed (as referenced in NHRCP report by Chatti and Zaabar 2012) 165
Figure 7.2 Comparison of different road selection strategies for maintenance in terms of emission reduction potential. Selection strategies include random selection, selection based on annual average

daily traffic (AADT), international roughness index (IRI) and CO_2 emissions (source: Loughalam et al., 2017) 166
Figure 7.3 Four components of pavement surface texture and their influences on PVI factors 171
Figure 7.4 Estimated change of CO2 emission with roughness for heavy truck and medium car (Cirilovic et al. 2015) 174
Figure 7.5 The simplified structure of MOVES 181
Figure 7.6 Effect of IRI and MTD on VSP rolling resistance (A) and air-drag (C) coefficient for a Passenger Car and a Heavy-Duty Truck 190
Figure 7.7 Distribution of energy consumption (J/km) by a passenger travel on a freeway with varying road surface conditions, roughness = 1m/km to 4m/km, and macrotexture = 0.5mm to 2mm and at various speed from 4km/h to 100km/h 191
Figure 7.8 Effect of roughness on energy consumption by Passenger car travelling at different speed label on chart) on four road class. 192
Figure 7.9Effect of IRI on Energy consumption by Heavy Duty Truck, at various speed 192
Figure 7.10 Effect of Macrotexture on Energy Consumption per Passenger Car and Heavy Duty Truck travelling at various speed (4km/h, 100km/h) 193
Figure 7.11 Visualization of Urban Freeway for a Passenger car divided into blocks of macrotexture 194
Figure 7.12 Effect of IRI and speed on energy consumption by a passenger on a freeway with macrotexture of 0.5mm 195
Figure 7.13 Distribution of Carbon dioxide (CO2) emissions (g/ km) from passenger car travel on a freeway with varying road surface conditions, roughness = 1m/km to 4m/km, and macrotexture = 0.5mm to 2mm and at various speed from 4km/h to 100km/h 196
Figure 7.14 Effect of roughness on CO2 emissions from Passenger Car and Heavy Duty Trucks 197
Figure 7.15 Effect of macrotexture on CO2 emissions from Passenger Car and Heavy-duty Trucks at 100km/h 197
Figure 7.16 Effect of IRI and MTD on CO2 emissions produced by a passenger car. 198
Figure 7.17Distribution of Methane gas (CH4) emissions (g/ km) from passenger car travel on a freeway with varying road surface conditions, roughness = 1m/km to 4m/km, and macrotexture = 0.5mm to 2mm and at various speed from 4km/h to 100km/h 199
Figure 7.18 Effect of roughness on CH4 emissions from passenger and trucks 200

Figure 7.19 Distribution of Nitrous oxide (N2O) emissions (g/ km) from passenger car travel on a freeway with varying road surface conditions, roughness = 1m/km to 4m/km, and macrotexture = 0.5mm to 2mm and at various speed from 4km/h to 100km/h 200
Figure 7.20 Effect of roughness on N2O emissions from passenger and trucks 201
Figure 7.21 Effect of roughness on different pollutant emission from heavy duty (combination trucks) traveling on 1km of an urban freeway. 203
Figure 7.22 Effort to fit energy consumption rate data to the equation 7.22, the R-squared achieved was less than 0.3. 204
Figure 7.23 Visualization of fitted regression model equation 7.23 on the energy consumption data for urban freeway, four charts represent four levels of macrotexture (MTD = 0.5mm, 1mm, 1.5mm and 2mm) considered as different categories 205
Figure 7.24 Effort to fit output data for GHG emission rates to the equation 7.22 and 7.23............ 207
Figure 7.25 Environmental Damage Cost (EDC) of CO_2 and CO emissions per Km traveled by a Passenger car (A) and a Truck (B)... 210
Figure 7.26 Environmental Damage Cost (EDC) of NOx, SO_2 and $PM_{2.5}$ emissions per Km traveled by a Passenger car (A) and a Truck (B) 211
Figure 7.27Total Environmental Damage Cost (EDC) per Km traveled by a Passenger car (A) and a Truck (B)... 212
Figure 7.28 Percentage change in energy consumption rate with increasing IRI and speed for a Passenger car.. 215
Figure 7.29 Percentage change in energy consumption rate with increasing IRI and speed for a Heavy-duty Truck 215
Figure 8.1 Proposed framework for incorporating sustainability in Project-level pavement management 219
Figure 8.2 Predicted deterioration of IRI for 50 years without any preservation or maintenance treatments.. 222
Figure 8.3 Technical impacts of the two scenarios of maintenance plans for HWY 48, service levels measure based on RCI over a 50-year time period 225
Figure 8.4. Technical impacts of the two scenarios of maintenance plans for HWY 48, service levels measure based on IRI over a 50-year time period 226
Figure 8.5. Material consumed in application of maintenance strategies, CIR and FDR are used in Scenario 2, while M&O techniques are used for Scenario 1 227

Figure 8.6. Environmental impacts of rehabilitation measured by cost of environmental damage ... 227
Figure 8.7. Ranking of maintenance treatment considering five options of allocating over one-third of the importance weights to one or two sub-criteria 229
Figure 8.8 2014 Predicted IRI of road section on Highway 48 232
Figure 8.9 Locations of the Ontario Road network managed by the MTO. 233
Figure 8.10 Presentation of the 2014 Pavement Condition Index (PCI) of all the road sections reported in the MTO public data 233
Figure 8.11Distribution of the road network road roughness data (A) and section length (B) in the four road classes 234
Figure 8.12 Maintenance Timing for HWY48 section for trigger level 1.4m/km (A) and 1.9 (B) 236
Figure 8.13 Potential EDC ($/Km) savings from IRI management and timely implementation of M&R strategies on 1km 1-lane road of HWY48 sections in this study 237
Figure 8.14 Potential CO_2 emissions savings from IRI management and timely implementation of M&R strategies on 1km 1-lane road of HWY48 sections in this study 237
Figure 8.15 Excess CO2 emission from both passenger cars and trucks using Ontario Roads......... 238
Figure 8.16 Excess CO_2 emissions (kg/km) (A) and Excess EDC ($/km) of CO_2 emissions (B) from passenger car and truck traffic using Ontario Roads 239
Figure 8.17 Excess CO_2 emissions (kg/section) due to road surface condition (IRI> 1m/km) of Ontario Roads 240
Figure 8.18 Environmental Damage Cost ($/section) due to road surface condition (IRI> 1m/km) of Ontario Roads 241

List of Tables

Table 2.1Available optimization and prioritization methods can be grouped in three main classes (adapted from (Torres-Machi et al. 2013, 2017)): 11
Table 2.2 Select Environmental aspects and impacts of Pavement Concrete Production 13
Table 2.3 Pavement Construction and Rehabilitation Design to improve Pavement Sustainability (Chan and Tighe 2010; Van Dam et al. 2015) 15
Table 2.4 Sustainable pavements maintenance techniques based on Pavement surface type........ 17
Table 2.5 Impact factors for environmental sustainability of pavements 20
Table 2.6 Sustainability Rating Tools for Road Pavement........ 21
Table 2.7 Limitations of Pavement Sustainability Rating Systems 22
Table 2.8 Variations of LCA approaches........ 27
Table 2.9 Examples of methodological choices discrepancies in LCA studies 29
Table 2.10 Environmental impacts estimates for Asphalt binder production from select studies (adopted from (Yang 2014)) 30
Table 2.11 Summary of studies related to sustainable pavement management 35
Table 2.12 Atmospheric releases examined and their impacts to health and the environment; adapted from Shindell (2015)........ 38
Table 2.13 Level of Adoption of the GHG Mitigation Measures by Different Jurisdictions 41
Table 3.1 Design policy to improve sustainability of pavement and the environmental focus areas affected (FHWA, 2016). 57
Table 3.2 Impact categories and mid-point indicators of LCIA methods........ 62
Table 3.3 Input-based Indicators........ 67
Table 3.4 Output-based Indicators........ 67
Table 3.5 Outcome-based Indicators 68
Table 4.1 Strategies identified by agencies to have cost savings or no additional cost compared to status quo 90
Table 4.2. Strategies with conflicting responses on cost compared to status quo........ 91
Table 4.3 Strategies identified by agencies to require the same or fewer internal resources compared to status quo 93
Table 4.4. Strategies with conflicting responses on internal resource demand compared to status quo 94

Table 4.5. Strategies for which a public response was rated (positive, neutral, or negative) compared to status quo 96
Table 4.6. List of strategies with additional costs compared to status quo alternative measures 98
Table 4.7. List of cost-effective feasible GHG mitigation strategies during Highway Design, Construction and Maintenance 99
Table 4.8. Select GHG mitigation strategies considered most promising 105
Table 5.1 Material content in mix design for HMA-CRCA mixes 114
Table 5.2 Primary mix design for 1m^3 of concrete mix 116
Table 5.3 Maintenance and rehabilitation program for a 70-year design (El-Hakim, 2009) 118
Table 5.4 Energy use and CO2 Emission contributions from material production and transportation 125
Table 5.5 Change in CO2 reductions compared to the control and Sensitivity of results to transportation distance of RCWM used in the mixes 127
Table 5.6 Sensitivity of results to transportation distance of Portland cement used in the mixes 128
Table 5.7 CO2 emission of a perpetual pavement compared to a conventional asphalt pavement 128
Table 5.8 Environmental damages from construction and maintenance of Perpetual pavement compared to conventional pavement. 129
Table 5.9 Lifecycle CO_2 emissions of the Precast Concrete Inlay Panels (PCIP) 130
Table 5.10 Work zone impact for 9 hours of 2370m (M&O) versus 1570m (PCIP) of lane closure 130
Table 5.11 CO_2 estimate for alternative rehabilitation techniques 131
Table 6.1 Input Parameters for PMED Rigid Pavement Design Analysis 140
Table 6.2 Data for Resilience Assessment 147
Table 6.3 Data for Sustainability Assessment 150
Table 6.4 Structural Performance Results 152
Table 6.5 Resilience Assessment Results 156
Table 6.6 Sustainability Assessment Results 161
Table 7.1 MOVES Road Type Distribution Adopted 182
Table 7.2 Vehicle types considered in the simulation and model development 182
Table 7.3 Assigned Average Speed for MOVES Speed Bins 183
Table 7.4 Performance thresholds per functional class 185
Table 7.5 Analysis design matrix for the levels of road surface factors 186

Table 7.6 Proposed parameter values used in predicting energy consumption rate (J/veh-km) of seven vehicle types on urban freeway and their performance measure 205
Table 7.7 Proposed parameter values used in predicting energy consumption rate (J/veh-km) seven vehicle types on urban arterial/collector/local road and their performance measure......................... 205
Table 7.8 EDC-IRI equation for Urban roads in Ontario at speed limits for Freeway (100km/h) and Arterial Roads (80km/h) 208
Table 7.9 Regression Summary Output for Total EDC ($/km) for Passenger car and Truck driving on a Freeway.. 213
Table 8.1 Data from LTPP for test segment on Highway 48 (source (FHWA 1992)) 219
Table 8.2 Two Scenarios of Preservation and Maintenance plans for the Road network.................. 220
Table 8.3. The value system (A) for pairwise comparison of alternatives on each sub-criteria (B).. 223
Table 8.4 The total material consumed in the two maintenance scenarios 1 and 2 226
Table 8.5. The total environmental damage cost for the two scenarios of maintenance plans 227
Table 8.6. The total environmental damage cost for the two scenarios of maintenance plans 228
Table 8.7 Summary Table... 228

Chapter 1

Introduction

Road infrastructure is critical to the quality of life of Canadians. Road pavement is part of the transportation system that provides mobility and access to various users. When paved road networks are in good condition, an adequate level of service is provided and desired efficiencies achieved (Tighe and Gransberg 2011). However, the construction and maintenance of road networks have undeniable impacts on the biophysical environment that sustains human and non-human lives, and supports their wellbeing (Van Dam et al. 2015; J. T. Harvey et al. 2016). Pavement management activities from planning, design and construction to end-of-life material management influence sustainability issues of climate change, biodiversity loss and resource depletion. The GHG emissions associated with pavement management activities span at least four of five defined major GHG emitting sectors; for example, asphalt, which is a product of the oil and gas sector is a major material for pavement construction in Canada. Cement, lime and steel are also vital materials in pavement construction that are part of the heavy industry sector. Pavement construction and maintenance requires electricity generation and produces waste, thus contributes to GHG emitted by those economic sectors. In 2015, the transportation sector was the second largest contributor to Canada's total greenhouse gas (GHG) emissions (Figure 1.1) with over 85% due to on road vehicle operations (ECCC - Environment and Climate Change Canada 2017). Recent studies have shown that carbon management of the pavement during it use and operation phase provides an opportunity to maximize the reduction rate of CO_2 emissions per lane-mile maintained as well as reduce GHG emissions from road transportation as a short-term policy (Louhghalam, Akbarian, and Ulm 2017; Ziyadi et al. 2018).

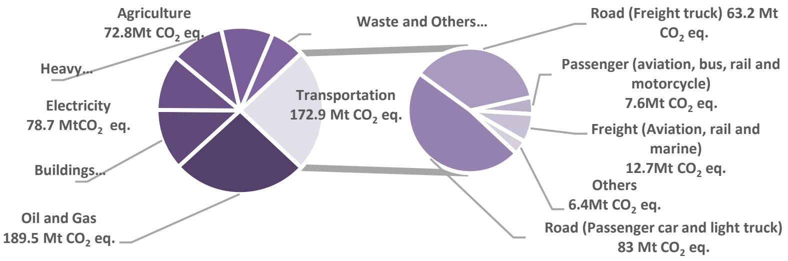

Figure 1.1 Greenhouse Gas Emission by Canadian Economic Sectors in 2015 and the breakdown for Transportation section by use (ECCC - Environment and Climate Change Canada 2017)

Coupled with the environmental sustainability issues in current pavement design, construction and maintenance approaches, road pavements deteriorate over time as the road ages due to growing traffic and exposure to the effects of climate change, resulting in more rapid pavement performance and durability (Mills et al. 2007). As a consequence, substantial rehabilitation and reconstruction are required within a shorter period, resulting in increased costs and environmental problems. The Government of Canada allocates over 25 billion dollars annually to pavement maintenance and capital projects (Thompson 2013; Transport Canada 2012). In Ontario, the annual investment in rehabilitation project has doubled within a decade (see Figure 1.2). Also notable, Canadian municipal infrastructure asset records reveal substantial maintenance backlogs due to funding gaps (CIRC 2016). Such delays in road rehabilitation could mean transferring cost to the road user as fuel consumption could increase spontaneously due to the effects of vehicles travelling over rough road pavements (Pellecuer, Assaf, and St-Jacques 2014; Zaabar and Chatti 2010a, 2010b).

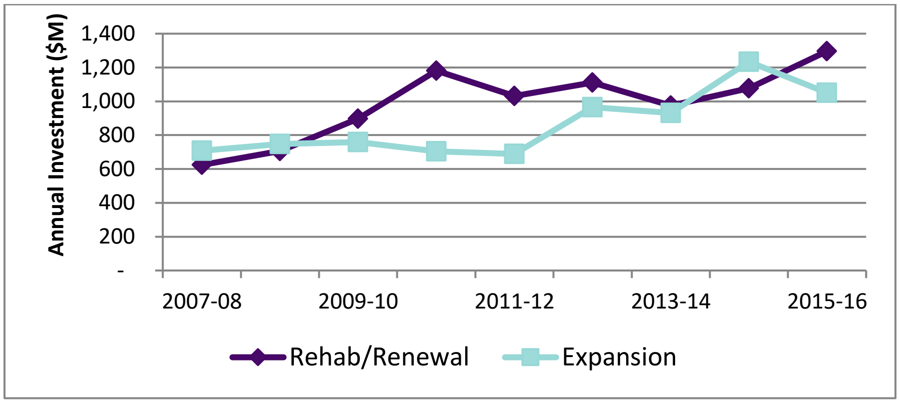

Figure 1.2 MTO Annual Highway Rehabilitation and Renewal and Expansion Investment

(Source: Asset Management at MTO Meeting and Discussion on Jan 18, 2018)

Awareness of the environmental issues related to roadways are well acknowledged across North America, yet these environmental aspects are often overlooked in many highway investment decisions (Gopalakrishnan et al. 2014; Tighe and Gransberg 2011; Varamini and Tighe 2015). There is a need to incorporate environmental sustainability aspects into pavement engineering and management practices to mitigate these impacts (Alkins, Lane, and Kazmierowski 2008; Chan et al. 2009; Chan, Tighe, and Chan 2010; Van Dam et al. 2015).

At the national level, Canada declared an aggressive goal to reduce GHG emissions by 30% below 2005 levels by 2030 at the Conference of the Parties (COP) 21 under the United Nations Framework Convention on Climate Change (UNFCCC) 2015 Paris Agreement (Government of Canada 2017). Canadian transportation agencies have actively tried to mitigate the environmental impacts of road infrastructure.

In Ontario, MTO Road Talk magazine states that the agency "supports conservation by seeking opportunities to mitigate environmental impacts in the highway right-of-way (ROW) during highway planning, design, construction, and maintenance operations" (MTO 2017). Chan et al (2010) (Chan et al. 2010) report that MTO uses numerous innovative pavement preservation practices to foster material conservation, GHG emission reduction and minimization of energy consumption. MTO is committed to incorporating sustainability by using sustainable materials and techniques such as recycled asphalt pavements (RAP), cold in-place recycling with expanded asphalt mix (CIREAM), micro-surfacing and full depth reclamation (FDR) (Chan et al. 2009, 2010). MTO's sustainability strategy is implementing these technologies on a large scale to support a "zero waste" approach and assist in meeting GHG emissions reduction commitments (Chan and Tighe 2010; Olawuyi 2016).

MTO developed its own pavement sustainability rating tool - GreenPave (Kazmierowski and Navarra 2014) to assess sustainability of pavement. Like other available sustainability rating tools, GreenPave is valuable as it encourages incorporation of environmental sustainability principles into infrastructure projects and informs the current practice on sustainability improvement actions such as "use of recycled material" (Lew, Anderson, and Muench 2016; Torres-Machi et al. 2014). However, sustainability rating tools are subjective and reporting standards used in such tools pay little attention to the collective outcomes or potential interactions between the impacts of carrying out these actions. Furthermore, MTO does not use GreenPave for decision making in its Pavement Management System (PMS).

1.1 Research Context

Nowadays, sustainability in pavement engineering and management practices is very important. Resource efficiency, energy conservation and carbon reduction have become key elements of this area. Pavement sustainability is a context–sensitive characteristic of pavement. Thus, to define the most appropriate sustainability practices for a particular pavement system a full accounting of interaction between pavement lifecycle and the surrounding systems is required (Van Dam et al. 2015) . Uddin et al mentioned that defining “quantifiable performance measures tied to realistic policy objectives and implementation targets” is one of the main challenges of environmental sustainability facing modern infrastructure asset management is the 21st century (Uddin, Hudson, and Haas 2013). A critical step towards developing a sustainable pavement management framework is to incorporate all sustainability aspects of pavement into the pavement management decision making process (Bryce et al. 2017; Flintsch and Bryce 2014; Torres-Machí, Chamorro, et al. 2015). This means identifying relevant environmental sustainability impact factors and performance measures for pavement management, and reliable metrics for integration into pavement management systems (PMSs). Selection and integration of objective environmental performance measures and metrics into pavement management systems is challenging, thus environmental aspects are often ignored in pavement management decision making.

Various improvements in pavement material production, construction and maintenance activities are available for more sustainable pavement. Adequate environmental performance measures and metric for analytically accounting of the life cycle environmental performance outcome are required to integrate environmental sustainability into pavement management decision making.

Sustainability rating tools specify indicators in point-based systems that are either subjective or based on limited quantitative assessment. The Life Cycle Assessment (LCA) framework provides a guide to assess the environmental performance of pavement lifecycle considering many environmental impact categories which are broad ranging in the number of indicators admissible. Specifically, LCA environmental performance indicators identified in literature involve impact criteria building on the ISO 14040:2006 (International Organization for Standardization 2006) categories of environmental impact: Damage to natural environment; Damage to human health; and Resources consumption.

Pavement LCA tools to date have utilized limited scope and environmental performance indicators. The use phase of pavement is commonly ignored in pavement lifecycle studies (Azarijafari, Yahia, and Ben Amor 2016; Santero, Masanet, and Horvath 2011). Environmental impacts factors for all relevant environmental aspects of pavement management activities needs to be identified and quantified to inform road network management decisions (Van Dam et al. 2015; J. T. Harvey et al. 2016).

Pavement management must consider sustainability. This includes the particular challenge of climate change, which will demand some level of both mitigation and adaptation; however, more work is needed to guide sustainable pavement management under a changing climate. Questions remain as to how to assess sustainability, evaluate available measures and new techniques (throughout the pavement lifecycle), and guide the adoption of these techniques given the need to adapt to future hazards caused by climate change.

1.2 Research Objective and Questions

This research seeks to answer a series of connected research questions designed to inform sustainable pavement management under climate change. It identifies and fills a set of particularly pressing gaps in the literature. These gaps include the need to better understand how to measure sustainability under climate change, what agencies are doing to mitigate it, how new technologies can help, and how inevitable adaptation affects mitigation measures. The research questions are:

1. What does environmental sustainability mean for pavement, and how can it be measured in the Canadian context under a changing climate?
2. What measures to mitigate the effects of pavement management on climate change are currently in use by transportation agencies, and at what level of technology readiness and adoption?
3. What is the sustainability performance potential of adopting innovative designs for pavement material, construction, and rehabilitation?
4. If pavement managers adapt to climate change, how does this interact with efforts to mitigate?
5. How do pavement surface conditions affect on-road emissions of greenhouse gases and criteria air pollutants?

1.3 Thesis Structure

This thesis describes the studies undertaken to address these questions (listed above). Chapter 2 first lays out the relevant literature on pavement sustainability, pavement management, and the issue of climate change, with a focus on the Canadian context. It also provides a general introduction to the approaches used, with details in individual chapters. The subsequent chapters each address a particular question, as follows:

- Chapter 3: What does environmental sustainability mean for pavement, and how can it be measured in the Canadian context under a changing climate?

- Chapter 4: What measures mitigate the effects of pavement management on climate change are currently in use by transportation agencies, and at what level of technology readiness and adoption?
- Chapter 5: What is the sustainability performance potential of adopting innovative designs for pavement material, construction, and rehabilitation?
- Chapter 6: If pavement managers adapt to climate change, how does this interact with efforts to mitigate?
- Chapter 7: How does pavement surface condition affect on-road emissions of greenhouse gases and criteria air pollutants?

Chapter 8 provides a framework for sustainability evaluation at both project and network level pavement management based on the insight from chapters 2, 4 to 7. Chapter 9 summarizes the overall insights about the readiness of pavement management to tackle the issue of climate change sustainably, with relevant findings to aid this goal. It highlights limitations and future work in this area.

The research methodology involves twelve activities as presented in Figure 1.3

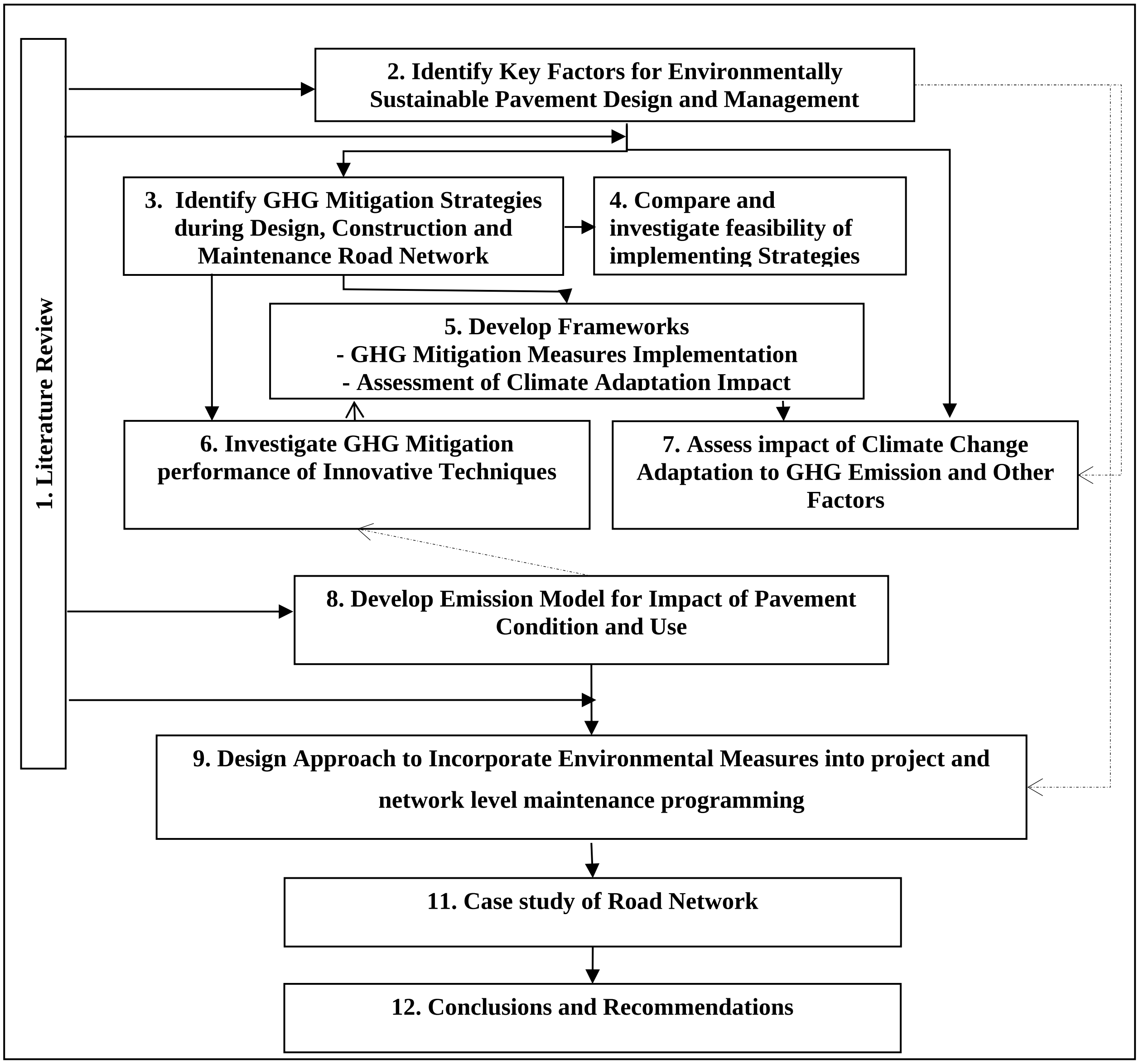

Figure 1.3 Research Methodology

Chapter 2
Background

2.1 Introduction

This chapter provides an overview of pavement management, and the life cycle phases of a pavement system: material production, construction, maintenance, use and operation, and end of life. It also presents approaches for pavement sustainability quantification, key benefits and challenges, and evaluation requirements for pavement environmental sustainability. Then, different quantification tools, models and the methodology are described, and decision analysis technique for pavement maintenance programming are studied. Finally, a review of pavement sustainability in relation to climate change and greenhouse gas mitigation is presented.

2.2 Pavement Management

2.2.1 Overview

Pavement Management involves a coordinated set of activities related to information gathering, planning and programming, design, construction, maintenance, alongside periodic evaluation and research (Haas, Hudson, and Falls 2015). Pavement management is a part of transportation asset management, which operates on two levels: project-level and network-level management. Project-level management deals with the design, construction and maintenance associated with a particular roadway section. Network level management deals with establishing priority programs and schedules of work and developing a final budget.

Over the last six decades, Pavement Management Systems (PMSs) have emerged as a form of mainstream asset management decision support tool widely used among transportation agencies. PMSs link the effects of decisions to various criteria, performance measures, and targets relevant to agency strategic goals. They thus inform decisions about how to best allocate resources and funding to influence desired outcomes like adequate level of service and efficiencies (Haas et al. 2015). A PMS provides the opportunity to achieve the best value possible for available public funds and to provide transportation that is safe, comfortable and economically viable (TAC 2013). The components of a PMS are shown in Figure 2.1.

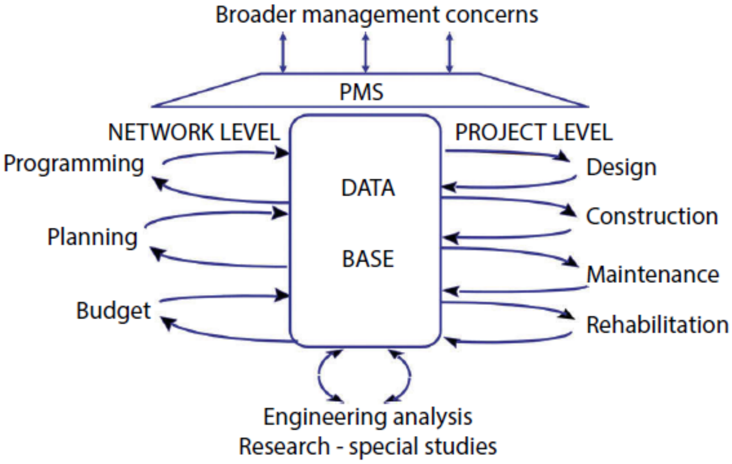

Figure 2.1 Components of a Pavement Management System (Haas et al. 2015)

The idea behind the PMS is to improve efficiency of decision making, expand its scope, provide feedback as to the consequences of decisions, and ensure consistency of decisions made at different levels within the agency (Haas et al. 2015). PMS's rely on the functionality of performance measures to account for different criteria in the decision-making process and assess the level of achievement of management objectives.

Performance measures for infrastructure functional condition, for example, Pavement Condition Index (PCI) or International Roughness Index (IRI), are well established. These metrics are largely standardized across agencies in Canada and the United States (Haas et al. 2015; TAC 2013). Economic viability is often assessed based on lifecycle cost analysis (LCCA). The procedure for LCCA is relatively consistent across the board (TAC 2013). LCCA is frequently used in decision making by most agencies to achieve goals related to optimizing funds within limited budgets (Van Dam et al. 2015).

Traditional approaches to pavement management have focused on economic and technical criteria in their decision-making, neglecting sustainability criteria of environmental impacts (Tighe and Gransberg 2011; Torres-Machi et al. 2017; Torres-Machí, Osorio, et al. 2015). One main challenge seems to be the identification of quantifiable environmental performance measures that can be tied to realistic policy objectives (Uddin et al. 2013).

The role of performance indicators in road asset management has been clearly identified in the transportation infrastructure engineering and management literature (Cornet, Gudmundsson, and Leleur

2016; Dasgupta and Tam 2005; Gudmundsson et al. 2016; Haas et al. 2009). The Transportation Association of Canada Pavement Asset Design and Management Guide describes performance indicators as essential measurable entities for “assessing the current and future state of road infrastructure, as well as agency/institutional efficiency in service and safety provision to users, productivity, cost-effectiveness, environmental protection, preservation of investment and other functions” (Haas et al. 2009). It is imperative that practical and usable performance indicators for a transport agency be linked to realistic policy objectives. Essential features of indicators include the ability to explain, highlight and summarize the enormous complexity of our dynamic environment to less complicated information (Gudmundsson et al. 2016). By observing the phenomena and emphasizing trends, indicators quantify and communicate to all stakeholders a balanced view of the overall efficiency and effectiveness of the transportation system, in terms of a full range of values, in a way that is objective and economical (Haas et al. 2009). As part of an asset management system, performance measures operate at three levels within an agency: strategic-level, network-level and project-level. Performance measures generally fall into three categories: inputs which defines resources dedicated to a program; output, or what is produced; outcome, which represents the impacts of products on the goals of the agency(Haas et al. 2015). Environmental performance measures should be defined in response to the goals and objectives directly aligned with the broad institutional goals of the agency addressing sustainability of transportation systems in which pavements exist (Cornet et al. 2016; Gudmundsson et al. 2016; Uddin et al. 2013).

2.2.2 Decision Making Approaches in Pavement Management

Most efforts to date have focused on defining pavement sustainability and sustainable performance measures. However, a next critical step is implementing sustainability into the pavement management decision-making process. Two main decision analysis techniques or approaches (sequential and holistic) to allow highway agencies to assess the trade-offs and make the feasible solution for optimal allocation of available budget (Torres-Machi et al. 2013). The sequential and holistic approaches vary depending on:

1. Type of information required in the analysis,
2. Time frame over which an analysis is performed.

The sequential approach tackles the budget allocation problem in two phases: treatment and timing selection and section selection. The holistic approach is purely an optimization of the budget allocation problem because it evaluates maintenance programs before any specific section or treatments are defined.

Table 2.1Available optimization and prioritization methods can be grouped in three main classes (adapted from (Torres-Machi et al. 2013, 2017))**:**

Priority Based on Ranking and Multi-criteria Analysis	Near-Optimization or Heuristic Methods	Optimization Methods
1. Subjective Ranking Based on Judgment *2.* Ranking Based on Pavement Condition *3.* Based on a Composite Index *4.* Ranking Based on Economic Analysis. *5.* Multi-criteria Analysis (MCA)	*1.* Incremental Benefit/Cost Analysis *2.* Decision Trees *3.* Local Search Heuristics *4.* Machine Learning including Neural Networks (NN) *5.* Fuzzy Logic	*1.* Linear and Non-Linear Programming *2.* Integer Programming4 *3.* Dynamic Programming

2.3 Environmental Sustainability of Pavement Systems

Pavements exist and function within a transportation system that is responsible for over 25% of anthropogenic greenhouse gases in Canada exacerbating the climate change problems (see Figure 1.1). It is inevitable that sustainable pavement engineering and management practices to minimize greenhouse gases should be a top agenda item to fight a global issue such as climate change.

Sustainable transportation refers to transportation that meets the three aspects of sustainability: (1) economic sustainability - affordable, operates efficiently, offers choice of transport mode, and supports a vibrant economy; (2) social sustainability - allows the basic access needs of individuals and societies to be met safely and in a manner consistent with human and ecosystem health, and with equity within and between generations; (3) environmental sustainability - limits emissions and waste within the planet's ability to absorb them, minimizes consumption of non-renewable resources, limits consumption of renewable resources to the sustainable yield level, reuses and recycles its components, and minimizes the use of land and the production of noise (Cormier and Gilbert 2005). Efforts towards pavement sustainability should take into account the surrounding systems and a pavement's influence on them in order to define appropriate management practices towards more sustainable performance outcomes (Van Dam et al. 2015). On that note, it is important to recognize that roads have environmental sustainability impacts beyond just GHG emissions.

Other major adverse impacts include: energy consumption; habitat loss and fragmentation due to barrier effects, roadkill and dispersion function; water quality impacts from runoff of pavement that is often warmed and may contain pollutants form vehicles on the road; changes in natural hydrologic cycle and greater storm-water runoff due to larger impervious surface area; air quality impacts including fine airborne particulate matter from vehicles that use a pavement facility, as well as the equipment used for materials production and road construction (Van Dam et al. 2015; Li, Qiao, and Yu 2017; Pellecuer 2016). An important element in improving the environmental sustainability of road transportation is the use of new technologies, processes, and products that directly enhance the roadway environmental and economic sustainability through reduced consumption of energy and material (FIDIC 2012; Montgomery, Schirmer, and Hirsch 2015). The role of road pavement in environmental sustainability can be better understood by analysing the pavement lifecycle phases and identifying environmental aspects that enable improvement towards pavement sustainability (Van Dam et al. 2015; Harvey et al. 2016).

2.3.1 Environmental Aspects in Each Phase of the Pavement Life Cycle

2.3.1.1 Material Production

The main materials used in pavement infrastructure include natural aggregates (NA) (gravel/crushed stone, sand), asphalt materials, Portland cement materials, and other mixed materials for example steel and fibres. About 55% of aggregate produced in Ontario are used for road construction and rehabilitation. Over 42 million tonnes of aggregates were consumed between 2005 and 2008 (Kazmierowski 2013; LVM-JEGEL 2010). The entire process of aggregate production including the extraction, crushing, and sieving processes, and aggregate transportation consumes energy, virgin material, and water. It also thus generates emissions from fuel consumed by equipment and vehicles, and impacts the ground water and biodiversity of quarry sites (Van Dam et al. 2015). Energy consumption can influence larger environmental burden depending on energy sources, for example coal, oil, gas, hydro, nuclear, renewables. Asphalt binder used in pavement is a co-product of the crude oil distillation process in the oil and gas industry which is the largest emitter of GHG (Thives and Ghisi 2017). Portland cement is produced from raw material, such as lime and clay, whose mining operations often result in extensive deforestation and topsoil loss. Producing 1 ton of cement clinker releases approximately 1 ton of carbon dioxide into the atmosphere (Damtoft et al. 2008). Asphalt concrete mix and hydraulic cement concrete mix are two types of concrete used for pavement top layers which have significant environmental impacts as shown in Table 2.2.

Table 2.2 Select Environmental aspects and impacts of Pavement Concrete Production

Aspects	Impacts	Asphalt and hydraulic cement concrete production process
• **Use of virgin materials (binder and aggregates)** • **Use of electric power** • **Use of water resources** • **Use of fuel (oil & gas and other sources)** • **Use of solvents and chemical additives**	• Atmosphere– particulate matter, greenhouse gases, sulphur oxides, nitrogen oxide, carbon monoxide and total organic compounds • Noise • Odour • Energy consumption • Waste – sulphur fillers	• Storage and handling of aggregate • Aggregate heating and drying • Combustion in dryer, drum, and hot- oil heaters, burners or generator set • Hot mix storage silos • Material deliver (deliver vehicle), load-out process • Cleaning process • Fan and diesel generators • Other equipment and vehicle operations

The main strategies for reducing the environmental impacts of pavement material and mixtures production are:

- Decrease the negative impact of virgin materials in the mixture by substituting with Recycled, Co-product, or Waste Materials (RCWMs) and alternative materials such as bio-binders (produced from biomass such as trees, plants and animal waste).
- Minimize usage of those additives that may increase the impact of material production (polymers, virgin rubber, or chemical additives[1]) and by changing specifications to permit increased use of locally available but lower quality aggregates.
- Increase performance of the pavement mixtures and optimize the mix design; thus increases the time between future maintenance and rehabilitation treatments.

The recognition of resource criticality and the growing cost of materials have led the global exploration of alternative materials for infrastructure development. Emphasis has been placed on the use of RCWMs and other innovative material in pavement construction and maintenance. Examples

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[1] For example chemical additives used in some warm-mix asphalt technologies often have a greater benefit in maintaining compactibility at lower temperatures than those based on mechanical water foaming, but chemical additives may also have a higher environmental impact during their production.

include (adapted from (Van Dam et al. 2015; Gopalakrishnan et al. 2014; J. T. Harvey et al. 2016; LVM-JEGEL 2010; Tighe and Gransberg 2011)):

- Recycled material: recycled concrete aggregate (RCA), reclaimed asphalt pavement, asphalt singles, crumb rubber, recycled motor oil, recycled glass gravel
- Co-products: fly ash, air-cooled blast furnace slag, bottom ash, crushed slag, steel furnace slag
- Waste materials: baghouse fines, kiln dust, Foundry sand
- Other alternatives: bio-binder, light-weight concrete, interlocking concrete, light-weight concrete

In the road building industry, cost is the major driver for the use of RCWMs (Butler, Tighe, and West 2013). It was estimated that about 1760 truckload (about 16,000 tonnes) of natural aggregate (NA) is consumed to construct one kilometre 4-lane highway, which costs about CAD$ 650,000 (MNRO 2010). Additionally, the potential for successful applications some RCWMs, like RCA, in base layers (Cavalline 2017), concrete pavement (Butler et al. 2013) and asphalt pavement structural layer (Wong, Sun, and Lai 2007) have been reported. Those studies, however, also highlight some performance challenges due to the presence of cement paste on the surface of RCA after the recycling process. This affects the quality of RCA in terms of increasing the porosity, reducing the particle density, and changing the water absorption capacity (Pasandín and Pérez 2014; Tam, Tam, and Le 2007). The properties of RCA can easily be enhanced with a combination of different treatment methods including acid soaking and heat treatment (Al-Bayati, Tighe, and Achebe 2018). Other challenges related to dust control, and presence of undesirable alkaline compounds and heavy metals in the concrete waste can lead to adverse environmental damage and risks of human toxicity. Concerns have been expressed about the long-term effects of arsenic, chromium, lead, and selenium leachate at levels higher than the maximum contaminant level for drinking water standard. Donalson, Curtis, and Najafi (2011) compared the use of RCA to NA from lime rock in highway construction. The authors found the leachability of RCA to be less than that of NA and found that RCA can reduce GHG emissions by 10 tonnes CO2eq. On the other hand, Marinković et al. (2010) showed that environmental impacts of hydraulic concrete with RAC are higher than for concrete with NA, depending on the materials transport distances and hauling vehicle types. The study concluded that RCA transport distances above 20km can increase impacts within a range from 11.3% to 36.6% compared to NA, depending on the environmental impact category.

The use of these approaches should ensure that overall pavement performance is not reduced or compromised. It is important to understand their potential long-term effect on the environment. Van Dam et al., (2015) suggest questions related to the following three themes should be asked to understand the viability of RCWM usage in a pavement construction project:

1. Does the RCWM result in equivalent structural or durability properties to conventional materials? Does the RCWMs change the performance? Does sufficient knowledge regarding performance exist that these questions can be answered with confidence?
2. Does the RCWM have to be processed or transported long distances such that the impact on sustainability of the processing or transportation is greater than the benefits to sustainability of using it?
3. Does the inclusion of the RCWM make the resulting material difficult to recycle in the future?

2.3.1.2 Pavement Construction

There are numerous alternative pavement solutions that can be proposed for developing and maintaining the service levels expected from a pavement structure (Chan 2010). The pavement design process, whether asphalt, concrete, modular, or composite, must begin by defining the owner/agency design and policy objectives as well as any sustainability objectives. Decision should consider the long-term performance and availability of material, equipment/technologies and expertise as well as the whole lifecycle implication in all aspects of sustainability (Van Dam et al. 2015). Economic, environmental and social cost and benefits should all be considered. Examples of the pavement construction and rehabilitation designs commonly used to enhance sustainability performance are shown in Table 2.3.

Table 2.3 Pavement Construction and Rehabilitation Design to improve Pavement Sustainability (Chan and Tighe 2010; Van Dam et al. 2015)

	Flexible Pavement	Rigid Pavement
New Pavement Construction Design	•Perpetual pavement •Porous Asphalt •Warm Asphalt Mix •Quiet Pavements •Cool Pavements	•Pervious Concrete •Permeable Interlocking Concrete •Cool and Quiet Pavements •Two-lift Concrete

Pavement Rehabilitation Design	•Structural asphalt overlay •Bonded concrete overlay •Unbonded concrete overlay	•Bonded Concrete Overlay •Unbonded Concrete Overlay •Structural Asphalt Overlay − Conventional − Crack/Break Seat − Rubblization

It is important to understand the material and energy requirements of these techniques so as to determine their contribution toward sustainability goals. Such consideration has a way of changing overall environmental performance and, in some cases, shifting the impacts to other phases of the pavement life cycle or other supporting environmental systems. For example, chemical additives used in some warm-mix asphalt technologies often have a greater benefit in maintaining compacting ability at lower temperatures than those based on mechanical water foaming, but chemical additives may also have a higher environmental impact during their production. A recent survey of WMA usage by Canadian agencies suggest that a variety of WMA additives have been employed in Canadian road networks, but only about half of those agencies considered sustainability elements (environmental aspects) in the design and management with regards to application of WMA technologies (Varamini and Tighe 2015).

2.3.1.3 Maintenance

The maintenance and operation stage of infrastructure management encompasses decision-making regarding the maintenance and use phases of a pavement life cycle. Decisions have long-tern environmental and sustainability impacts alongside decreasing agency influence and effects on lifecycle cost of a project (Uddin et al. 2013). Preservation, maintenance and rehabilitation (P, M &R) must be carried out for a pavement structure for it to remain in a good and safe condition. Allocated funds for the maintenance of physical assets will be used to delay or prevent infrastructure failure. There is a large range of maintenance and rehabilitation treatments available, widely grouped into preventative and reactive maintenance. Preventive maintenance includes preventive and routine work performed on pavement prior to distress formation to minimize the likelihood and severity of those distresses. Reactive maintenance is typically corrective and unplanned, because distresses have formed and require treatment. Sustainable treatment would be cost-effective, technically effective and not harmful to the environment (Gopalakrishnan et al. 2014). Table 2.4 shows several of these techniques which have been found to have sustainable elements.

Table 2.4 Sustainable pavements maintenance techniques based on Pavement surface type

Techniques	Preventive maintenance	Rehabilitation	Comment
Asphalt Pavement	• Crack sealing • Micro-surfacing • Thin overlay • Hot patches • Slurry seal • Fog seal • Cold patches	• Cold In-place Recycling (CIR) • Cold In-place Recycling with expanded Asphalt Mix (CIREAM) • Full Depth Reclamation (FDR)	In-place recycling techniques reduces the need for virgin materials and material hauling, thus reduces environmental impacts in road rehabilitation such as GHG emission from on- road vehicle.
Concrete Pavement	• Diamond grinding • Joint sealing • Crack sealing • White topping • Shot blasting	• Precast Concrete panels (PCP) • Concrete Overlays	Preventive maintenance such as crack sealing extends the pavement life and reduces the need for high immediate material and energy consuming rehabilitation measures
Gravel Surface	• Dust Control	• Local grading	Dust control is very important to reduce impacts on human health by reducing the amount of particulate matter from the road surface.

A 2010 survey of pavement preservation and maintenance practices by Tighe and Gransberg (2011) found that 4% of the surveyed USA and Canada transportation agencies considered environmental criteria in maintenance selection and programming. Preservation and maintenance can improve sustainability performance of a road network; if the strategy is cost-effective, technically effective and not harmful to the environment (Gopalakrishnan et al. 2014). Material quality, selection, and maintenance timing can influence environmental sustainability in pavement preservation practices. Road condition and characteristics can influence the road vehicle fuel efficiency as well as tire-pavement noise and water quality. The timing of maintenance impacts the overall network condition, which can induce road vehicle emission, noise, and water quality issues. Behaviour of operators, managers or occupiers at the operational/in-use stage of the pavement life can compromise the intended sustainability performance of the development at the design and construction stage (FIDIC 2012).

2.3.1.4 Use/Operation Phase

Back in the 1990s, there was no agreement on the importance of the use phase in sustainable pavement development (Santero, Masanet, and Horvath 2010; Santero et al. 2011). Currently, there is a general consensus that pavement conditions and characteristics have a tangible impact on the environment since they induce nuisances such as noise, air pollution and release of hazardous chemical components (J. T. Harvey et al. 2016; Pellecuer et al. 2014), as shown in Figure 2.2. The key pavement factors include roughness, viscoelastic energy dissipation, deflection and macrotexture defines pavement interactions with vehicle operations and the environment. These factors have large effects on vehicle fuel consumption and vehicle operating costs, so result in increased energy use and GHG emissions. Studies have shown that pavement M&R activities that reduce pavement roughness can affect the energy consumption and GHG emissions from vehicles using the pavement (Lidicker et al. 2013; Loijos, Santero, and Ochsendorf 2013; Santero and Horvath 2009; Wang et al. 2012; Wang, Harvey, and Kendall 2014; Yu and Lu 2012; Zhang, Keoleian, et al. 2010; Zhang, Lepech, et al. 2010). Other environmental aspects such as storm-water disposition, tire-pavement noise, heat capacity and reflectivity of the pavement can also influence other sustainability impacts such as human health, urban heat island effect, and radiative forcing on a global scale (Azarijafari et al. 2016; Van Dam et al. 2015; Santero et al. 2011).

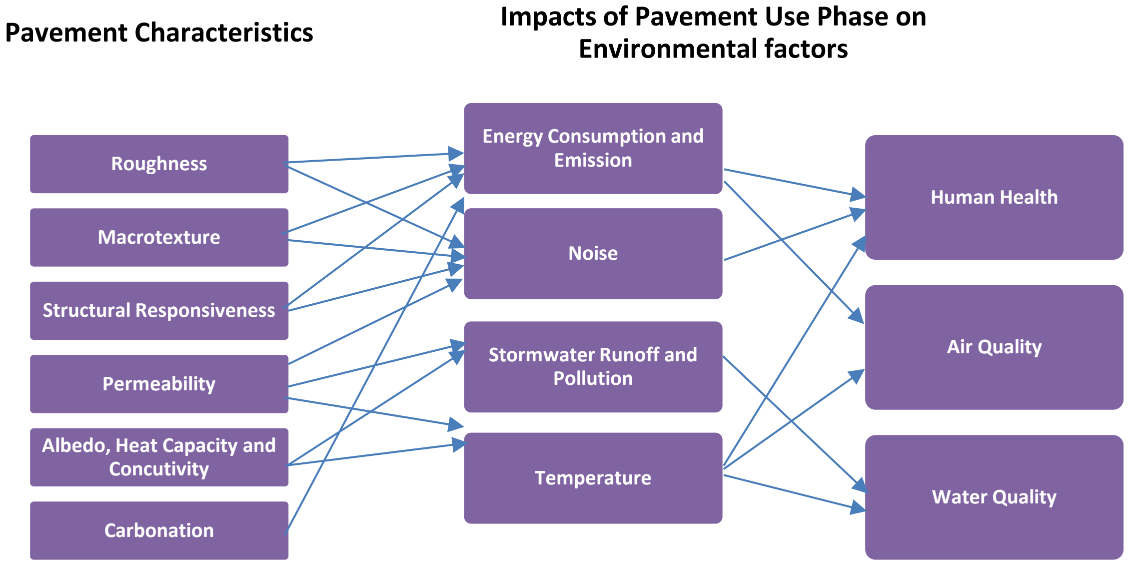


Figure 2.2 Selected pavement characteristics and their impacts on use-phase objectives (Van Dam et al. 2015)

Much of the research pertaining to the impact of the pavement use phase has focused on pavement-vehicle interaction (PVI) or tire-pavement interaction where the excess fuel consumption and emissions, and noise due to rolling resistance effects of pavement properties on vehicles travelling on the pavement are quantified. PVI is the main factor in rolling resistance. It is impacted by several variables, such as: macro-texture, pavement stiffness, roughness, rutting, and the transversal slope of the pavement. Several research projects have quantified the impact of pavement characteristics on vehicle energy consumption. A research project by Izevbekhai (2012) showed that rolling resistance is responsible for 25% of fuel consumption in all driving conditions. Thus, reduction in rolling resistance of a pavement can lead to fuel consumption saving for vehicles driving along that pavement. A study by Evans et al. (2009) found that 1% to 2% fuel consumption savings can be achieved by a vehicle travelling along a pavement with 10% reduction in rolling resistance. Although changes in rolling resistance may seem to provide relatively small changes in fuel consumption, their impact becomes significant when considering high traffic roads, because every vehicle using the pavement is affected.

2.3.1.5 Pavement End of Life

Pavement end-of-life refers to the final disposition and subsequent reuse, processing, or recycling of any portion of a pavement system that has reached the end of its useful life (Van Dam et al. 2015). For a pavement manger, decisions regarding the recycling and reuse of material for reconstruction, land restoration and adopting zero waste management principles are key to improve sustainability of a pavement at a project-level or for a whole road network (TAC 2013). It is important to investigate the recyclability of the materials when designs and construction techniques are selected to better plan for end-of-life treatments and disposition of the material. Such considerations impact sustainability factors such as waste generation and disposition, air and water quality, and materials use.

2.3.2 Measuring and Assessing Environmental Sustainability

Assessing environmental sustainability is an emerging field in the transportation industry, and even more so in pavement management. Focus area, impact factors and measures for environmental sustainability vary depending on approaches and metrics. The Transportation Association of Canada Green Guide for Roads identifies twelve factors to demonstrate environmental stewardship in transportation projects (TAC 2013). The American Association of State Highway and Transportation Officials (AASHTO) Centre for Environmental Excellence identified seven sustainability impact factor areas, as cited in (Tighe and Gransberg 2011). Infrastructure sustainability rating tools (SRT) follow variations of the five focus areas defined in the Leadership in Energy and Environmental Design (LEED®) Green Building Rating System, an internationally recognized third party certification program for green buildings (Montgomery et al. 2015). A number of environmental performance measures have been developed for Life cycle assessment (LCA) defined based on ISO 14040 standard environmental sustainability impact focus areas: natural environment, human health, resources consumption (International Organization for Standardization 2006; Stripple 2001). These environmental sustainability considerations are listed in Table 2.5. Available tools for assessing the environmental sustainability of pavement developed based on sustainability rating approach and life cycle assessment approach are discussed in sections below.

Table 2.5 Impact factors for environmental sustainability of pavements

TAC Green Guide sustainability objectives	CEE Impact factors	LEED green building criteria	Impact categories-based ISO focus areas
•Reduce raw material use •Reduce fossil fuel energy use •Reduce emission to air; •Optimize waste stream; •Maintain biodiversity •Maintain hydrologic regime characteristics •Improve safety, •Improve access and mobility •Improve local economy •Improve lifecycle efficiency •Engage community values and sense of place •Promote innovation	•Virgin material usage; •Alternative material usage; •Program for pavement in-service monitoring and management; •Noise quality; •Air quality; •Water quality; •Energy usage	•Sustainable Sites •Water Efficiency •Energy and Atmosphere •Materials and Resources •Indoor Environmental Quality •Innovation in Design Regional Priority	**•Natural environment** Global warming Ozone depletion Acidification Eutrophication Formation of photochemical oxidants Ecological toxicity Effects on the biodiversity **•Human health** Toxic effects Physical effects Psychological effects Illnesses caused by biological organisms **•Resources consumption** Energy and material use Land use Water use

2.3.2.1 Sustainability Rating Tools

Sustainability rating systems and tools (SRTs) are appraisal mechanisms that are designed based on best practice assessment and to encourage common sustainable choices in infrastructure development projects (Clevenger, Ozbek, and Simpson 2013). Infrastructure SRTs encourage sustainable practice by assessing decisions though a checklist or a questionnaire that may require documentation and verification depending on the tool. The main purpose for this assessment is to provide feedback in support of refining and updating the overall practice, thus projects are scored based on contributions towards the select sustainability criteria and overall sustainability goal defined in rating system (Van Dam et al. 2015). Most of the available SRTs such as Greenroads (Anderson, Anderson, and Muench 2013; J. B. Lew et al. 2016; Soderlund et al. 2008), GreenLITES (Mcvoy et al. n.d.), INVEST tool, and Envision, target general civil engineering infrastructures. So, many of the criteria assessed do not directly relate to pavement systems or paving activities (Bryce et al. 2017; Van Dam et al. 2015). The tools developed specifically for sustainability assessment of roadway projects include the Ministry of Transportation Ontario (MTO) GreenPave (Chan and Tighe 2010; Kazmierowski and Navarra 2014) and BE2ST-in-Highways (Lee et al. 2011). Some tools are developed for general transportation infrastructure. Several other sustainability rating systems are available, including I-LAST for the Illinois Department of Transportation (DOT) and CEEQUAL tool for the UK. An overview of some tools more pertinent to pavement are provided in Table 2.6. A discussion of challenges in applying sustainability rating tools to measurements of environmental performance is presented in Section 2.1.3.3.

Table 2.6 Sustainability Rating Tools for Road Pavement

Tools	Owner	Major categories	Year Developed	Max Points (scale)	Points relevant to Pavement
GreenPave	MTO	Pavement technologies, material resources, energy & atmosphere, innovation & design process	2008	31 (1-5)	100%
Greenroad	Greenroads Foundation	Environment and Water, Access and Equity, Construction Activities, Materials and Resources, Pavement Technologies and Custom Credits	2009	118 (1-5)	49%
GreenLITE	New York State DOT	Sustainable Sites, Water Quality, Material and Resources, Energy and Atmosphere, Innovation /Unlisted	2008	60 (1-10)	10%
INVEST	Federal Highway Administration	Air Quality, Behavioural change & capacity building, Biodiversity, Cultural heritage, Energy, Noise management, Resource management, Road design, Stakeholder engagement, Urban design, Waterway and Water management	2011	118(1-15)	41%
BE2ST-In-Highway	Recycled Materials Resource Center	Greenhouse gas emission, Energy use, Waste reduction, Water consumption, Social carbon Cost saving, Life cycle cost, Traffic noise, and Hazardous waste	2010	10 (0-1)	100%
Envision	Institute for Sustainable Infrastructure	Quality of life, Leadership, Resource Allocation, Natural world, Climate change &risk	2011	809 (1-25)	31%

2.3.2.2 Challenges in Sustainability Rating Tools

Sustainability rating tools for infrastructure have similarities and differences that highlight the challenges in each tool (Torres-Machi et al. 2014). Specifically, each tool evaluates select sustainability objectives related to infrastructure development projects. Studies have shown that the application of rating tools influences the sustainability of projects when different tools (Griffiths et al. 2015) or combinations of tools (Brodie et al. n.d.) are applied to a specific project, or a specific tool is applied to multiple projects (Anderson et al. 2013; Lew et al. 2016). Differences in tool content (Curz et al. 2012); sustainability objectives (Clevenger et al. 2013); appraisal process, implementation requirements and sustainability factors (Bueno, Vassallo, and Cheung n.d.); reporting standards and indicators (Griffiths et al. 2015); and credit weights assigned to each factor and indicators for reporting standards (Veeravigrom 2015); highlight the shortcomings of indicators used in current sustainability rating tools (Bryce et al. 2017) for use in pavement sustainability performance measurement.

A major drawback is the scope and definition of reporting standards in SRT. These standards are widely based on activity measures, not the performance outcome that defines the impacts of carrying out those activities. For example, measures based on the use of 20% recycled material (GreenPave) or conducting a lifecycle assessment (Greenroads), do not communicate nor account for resulting impacts. Further, the high level of subjectivity in SRS often leads to different ratings awarded to same project by different investigators using the same tool and scoring method (Veeravigrom 2015). The sustainability scopes of projects evaluated by a SRT usually reflects a status quo of the specific sustainability values of the tool, implying that a project team will unlikely pursue a subset of goals outside sustainability scope of the SRT (Anderson et al. 2013; Lew et al. 2016). A recent review of SRTs for paving activities by Bryce et al. (2017) discussed these shortcomings of SRT indicators and their inadequacy to provide analytical sustainability performance measures for pavement management activities. These limitations of the sustainability rating tools and their defined indicators are highlighted in Table 2.7.

Table 2.7 Limitations of Pavement Sustainability Rating Systems

Limitations	Comment
Assume certain activity directly leads to sustainability	Use of recycled material might not lead reveal long-term environmental benefit throughout the pavement lifecycle, activity measures are not outcome measures
High subjectivity in procedure and implementation	Points awarded for most indicators are based on analyst perspective of the project being assed

Limited activity focus of pavement management	Focusing on select activities indicates biases in the opportunities identified to extend pavement sustainability
Indicators based on non-generalizable approaches and project/location-specific practices	Specifying benchmarks for indicators like 20% of recycled material limits innovative thinking and discredits long term sustainability consideration
Indicators do not define performance outcome	Indicator such as conducting an LCA shows no evidence of a sustainable outcome
Assessment are based on select objectives	Each tool accentuate the element of sustainability the developer thinks is more important and measurable
Criteria weight not well aligned to objectives	Rating systems provide an overall relative rating of the project but not precise values associated with environmental sustainability.

2.3.2.3 Life Cycle Assessment

Life Cycle Assessment (LCA) is a comprehensive method for quantifying the environmental impacts of a product, service or product system over its whole life cycle from extraction and production of raw material, production of product, distribution and use/operation, maintenance to its end of life and final disposal in a cradle to grave perspective or recycling in a cradle to cradle circular economy view (International Organization for Standardization 2006). LCA can be used for a variety of purposes, including quantifying environmental performance and identifying opportunities for improvement; selecting relevant indicators of environmental performance from a system-wide perspective; and informing decision makers in many purposes such as strategic planning, setting priorities, product or system design selection (J. T. Harvey et al. 2016). Since the early 1990s, ISO has started publishing series' of standards in their 14000 family of standards to ensure consistency of the procedure for an LCA. The most recent updates regarding LCA requirements and guidelines in ISO 14040 standards was published in 2006, which specifies a four stage LCA methodological framework, described in the next sections.

1. **<u>Goal and Scope Definition</u>:** involves key steps including defining the goal, product system investigated, scope and system boundary, relevant environmental impacts to be quantified; essentially, what is tracked and measured. The conceptual construct of the goal and scope sets the frame for LCA assessment and the direction for the other three stages of LCA. In this phase, the product system to be investigated is defined by a functional unit and its study scope. The functional unit is a unique feature of LCA. It reflects the function a system delivers at a product unit level. This will essentially allow the analyst to set the boundaries, identify the right data/database and characterization models for evaluating and interpreting environmental impact inventory from LCI modelling outcome and impact assessment LCIA results. An example of a pavement system boundary is shown in Figure 2.3

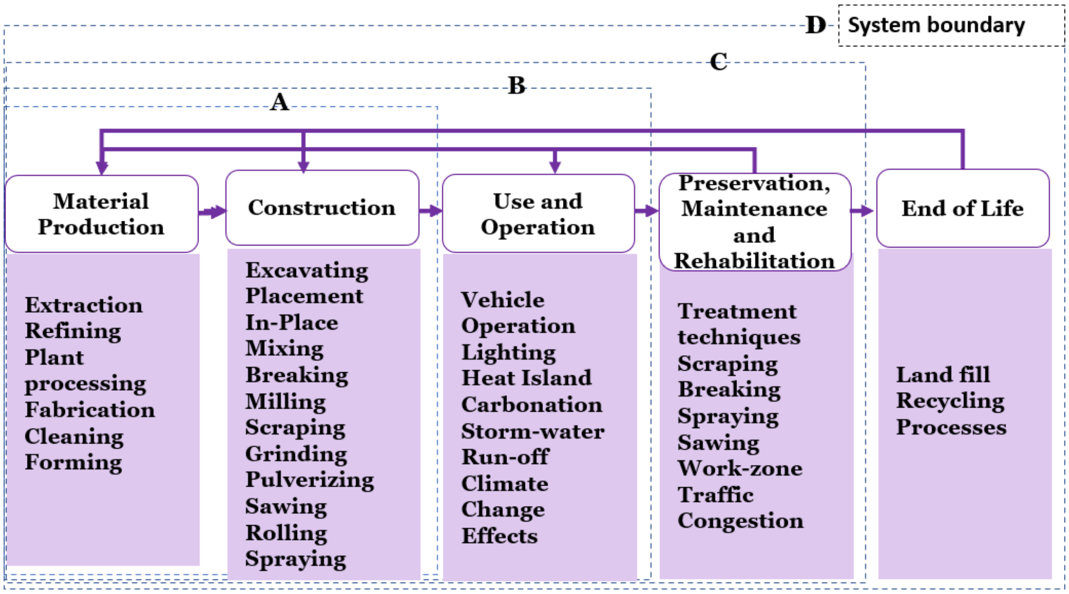


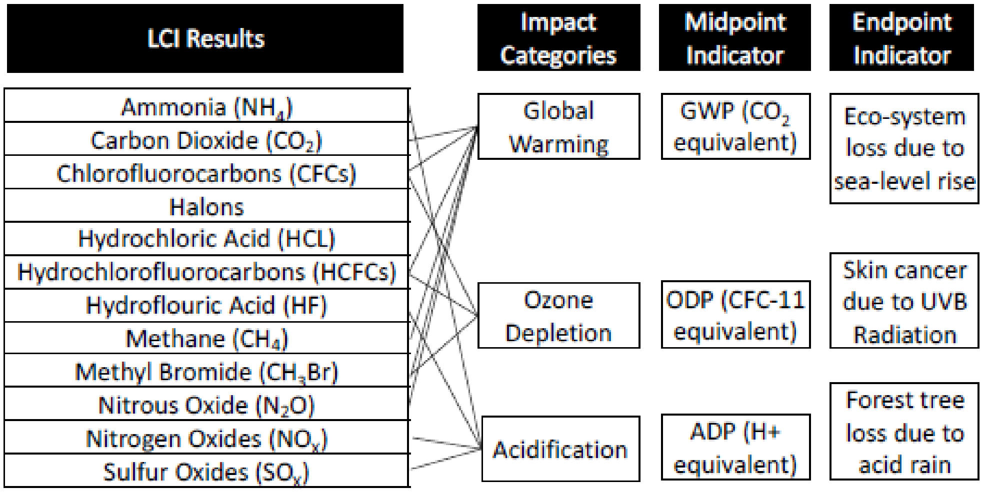
Figure 2.3 Different System boundary for pavement LCA, arrows represent typical transportation or process paths, dotted lines labelled A, B, C and D represent various system boundaries considered in pavement LCA studies (adapted from FHWA, 2016)

2. **<u>Life Cycle Inventory (LCI):</u>** is the accounting stage of inputs and outputs based on data collection approaches necessary to satisfy the goal and scope. The types of inputs (raw materials, auxiliary materials, energy) and outputs in terms of products (including intermediate and co-products) and emissions and waste that are expected are described (International Organization for Standardization 2006). The inventory data collected are generally classified into two groups: primary (also known as specific) data and secondary (also known as generic) data. Primary data refer to data collected from specific processes to model the life cycle, and these represent the production and construction of the studied product. Primary data can be collected from Environmental Product Declarations (EPDs). These data are controlled by the owner of the EPD and reported according to their product category rule (PCR) (Minkov et al. 2015). A PCR is being developed for asphalt mixtures EPDs (Mukherjee 2016; Mukherjee and Dylla 2017). EPD are based on a cradle to gate framework to provide LCI data for specific products. EPDs for various cement and concrete mix products have been developed. Secondary data are often obtained from existing commercially or publicly available databases and literature. Secondary data might not have the same quality as primary data. Their data quality needs to be reviewed to justify that data-quality requirements are met to satisfy the goal and scope. Inconsistencies frequently occur between different data sources, which may be the result of

inconsistent system boundaries, different geographic coverage, completeness, etc. These uncertainties in LCA procedures can skew results of a study. Harvey et al. (J. T. Harvey et al. 2016) suggested that LCA tools for pavement management system applications should include multiple data sources for each material to make-up for the temporal and regional uncertainty of various LCI data sources. Data collection should be carried out for the following key parameters:

- Process parameters: includes energy usage data for each production equipment, storage equipment, paving and construction machines
- Pavement parameters – LCI for pavement constituents and materials recipe, pavement condition models and design data and model
- Emission factors – for all process and pavement materials
- Transportation data – for material hauling

3. **Life Cycle Impact Assessment (LCIA):** is the stage to categorize LCI results into meaningful environmental and health indicators. Three steps are important in the LCIA stage: selection of impact categories, classification of LCI outputs, characterization with appropriate characterization factors and model. LCIA should be done for a complete LCA and should show the resulting impacts from the LCI outputs. This is important for interpretation and to inform decision makers on environmental performance of any product system. Two indicator points are considered in LCIA as shown in **Figure 2.4.**



GWP = Global Warming Potential, ODP = Ozone Depletion Potential, ADP = Acidification Potential

Figure 2.4 LCIA steps with example impact categories and midpoint and endpoint indicators (adapted from (J. T. Harvey et al. 2016)**)**

Mid-point characterization models and factors are well established in many available LCIA modelling approaches. On the other hand, end-points are usually avoided due to the uncertainty presented in existing models. Generally, for civil engineering infrastructures, reporting mid-point impacts are acceptable.

A number of LCIA methods exist, including the US EPA's TRACI, Centre for Milieukunde Leiden (CML), IMPACT 2002+ and ReCiPe (Herrmann and Moltesen 2015; Rosenbaum 2017). The important LCIA parameters to consider for selecting an approach that can be adopted in an LCA tool are:

1. Impact category
2. Category indicators
3. Characterization models and factors

Rosenbaum (Rosenbaum 2017) recommends that an LCA practitioner and tool developer should consider the following factors when choices are made regarding the key LCIA parameters:

- the impact categories, category indicators and characterization models should be internationally accepted, i.e. based on an international agreement or approved by a competent international body
- value-choices and assumptions made during the selection of impact categories, category indicators and characterization models should be minimized
- the characterization model for each category indicator should be scientifically and technically valid and based upon a distinct identifiable environmental mechanism and reproducible empirical observation

the category indicators should be environmentally relevant

4. **Interpretation:** is the final phase of LCA procedure where the results of an LCI and/or an LCIA, or both, are summarized and discussed as a basis for conclusions, recommendations and decision-making in relation to the study goal and scope (International Organization for Standardization 2006).

The interpretation of the results will depend on the type of LCA approach taken. Comprehensive LCAs involve extensive data sets related to materials quantities, emission rates, environmental responses, different levels of detail (temporal and spatial), and other factors. Completing a holistic LCA is very challenging and ISO guidelines do not specify the exact approach to carry out this task. As a consequence, LCAs tend to be time consuming and expensive to complete. Alternative procedures, termed "streamlined life-cycle assessments", seek to preserve the power of and confidence in the LCA approach in demonstrating environmentally-problematic attributes of a product system more quickly and cheaply but with some compromise (International Organization for Standardization 2006; Rosenbaum 2017).

Streamlining within the existing LCA framework can be accomplished by streamlining the methodology (what to do) or the process (how to do) for conducting an LCA. This can be done by limiting the scope of the study or simplifying the modelling procedures, thereby limiting the amount of data or information needed for the assessment. Depending on the purpose of study, there are multiple commonly used LCA approach for assessing environmental impacts, as shown in Table 2.8.

Table 2.8 Variations of LCA approaches

LCA Approaches	Orientation	Purpose
Attributional vs consequential	Defining boundary conditions	Intended to estimate impacts of a specific product system versus to assess impacts of changes to the evaluated system
Single vs comparative	Scenario building	Intended for disclosure of single product performance versus for comparison of alternative products
Static vs. Dynamic	Modelling approach	Differentiates an assessment of impacts at a point in time versus one that looks that impacts that evolves over time
Process vs Input-Output vs Hybrid	Data computation	A top-down data aggregation versus bottom-up process data aggregation
Substitution vs Allocation vs System expansion	Multi-functionality procedure	Differentiates how the environmental burdens should be assigned between co-products or systems
Mass vs economic	Allocation procedure	Differentiates how the environmental burdens can be allocation between co-products or systems

The differences between the approaches influences the inconsistencies in methodological choices and resulting outcomes of LCA studies. On the other hand, developing more readily available life-cycle data or tools, such as software with embedded databases, can enable streamlining the process of conducting LCA. A number of pavement LCA tools (see Figure 2.5) have been developed to ease the rigorous task of pavement LCA modelling. Some major challenges exist including considering only select pavement lifecycle phases, pavement type, materials and processes (see section 2.1.3.4). Commercial LCA tools, such as SimaPro and GaBi are also available for conducting LCA of pavement. Challenges such as the financial requirements for licensing and purchasing databases along with the limited models and data for specific paving activity often limits their use to modelling the material production phase of pavement lifecycle (J Santos et al. 2017; M. O. Santos et al. 2017). Differences between GaBi and Simapro exist, which were reported to originate primarily from errors in the software databases for both inventory and impact assessment methods (Herrmann and Moltesen 2015).

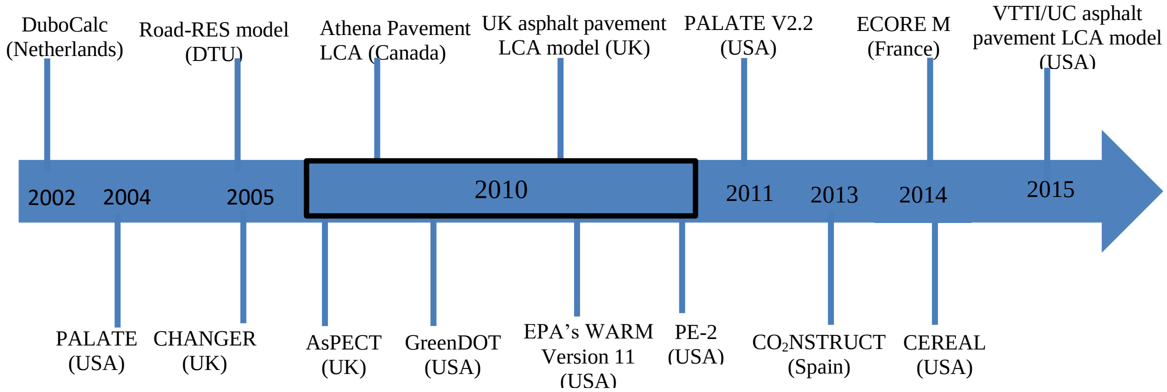


Figure 2.5 Chronology of Pavement LCA tools

2.3.2.4 Challenges Pavement LCA Studies and LCA Tools

LCA study of pavements is a fairly new practice in evaluating the environmental performance of pavements. The first LCA of pavement was conducted in 1996 by Häkkinen and Mäkelä. Attention to assessing the lifecycle impacts of pavement grew in last decade. A review by Santero et al (Santero et al. 2010) reveal, that prior to 2010, only 15 studies were published on pavement LCA. The number of pavement LCA studies quadrupled in the past few years and currently over 300 studies have been published (Azarijafari et al. 2016). Earlier studies have focused on comparing the impacts of the two main types of pavement (concrete and asphalt), ignoring important aspects that promote achieving sustainability goals. The sustainability factors such as those related to material selection, mix designs, constructability, maintenance operation and development of management policies, have not been accurately studied, which makes it challenging to incorporate LCA results into network-level pavement management (Torres-Machi et al. 2013, 2014). This is evident in the consistencies of the methodological attributes of pavement LCA studies (see Table 2.9), which also limits aggregation of the existing literature for comparison and contrasting purposes (Azarijafari et al. 2016; Santero et al. 2010, 2011). A review of the recent studies shown in Table 2.9 reveal issues of limited scope, limited environmental categories, and inconsistences in functional units and boundary definitions. There is a call for standardized functional units and system boundaries, and common set of guidelines for data collection and analysis to unify pavement LCA procedures (Azarijafari et al. 2016; Huang, Bird, and Heidrich 2009; Santero et al. 2011).

Table 2.9 Examples of methodological choices discrepancies in LCA studies

Study	Functional Unit	Lifecycle phase	LCA modeling Tool/ database	Indicators
Butt et al. (Butt, Birgisson, and Kringos 2015)	1 km per lane for a nominal design life	MP, C, T	Modelled with data from Stripple (2001)	GWP and total energy consumption
Celauro et al. (Celauro et al. 2017)	1-km long section in embankment	MP, C, M, T	PaLATE	Energy and water consumption, GWP, HTP and other emission reported by PaLATE
Anastasiou et al. (Anastasiou, Liapis, and Papayianni 2015)	1km of two lane urban road of low traffic load, 20 year design life	MP, C, T, E	Literature data	GWP
Santos et al. (João Santos, Flintsch, and Ferreira 2017)	1 km long one-way road pavement section with 2 lanes, analysis period 50 years	MP,C, M, U, WZ, T and E	LCC-LCA model developed by (Santos, Ferreira, and Flintsch 2015)	GWP, Acidification Potential, HH Particulate, Eutrophication Potential, Ozone Depletion Potential, Smog Potential, Energy Consumption
Huang et al (Huang, Hakim, and Zammataro 2013)	28 km long two-lane dual carriageway, with 8 grade-separated junctions and 13 over/under bridges.	MP, C , T	CHANGER	GWP
Jullien et al. (Jullien, Dauvergne, and Cerezo 2014)	the level of service for ‘‘a traffic of 25 x 10^6 trucks/year/lane for a 1-km, 2-lane road offering the same level of service for 30 years’’	MP, C, M, T	ECORCE M	Energy consumption, GWP, Eutrophication potential
Chen et al. (Chen et al. 2017)	four-lane interstate highway with a length of 1 km	MP, T	GaBi	GWP
Ahammed et al	Road length of 11.02 km, ADDT 3,900 and 50 year design life	MP, C, M and U	Athena Highway Impact Estimator	GWP, Acidification Potential, HH Particulate, Eutrophication Potential, Ozone Depletion Potential, Smog Potential, Energy Consumption

<u>Note:</u> MP – Material Production phase; C – Construction phase; M – Maintenance phase; T – Transportation; WZ – Work zone traffic; U – Use phase; E – End-of-life phase; GWP – Global Warming Potential, HTP – Human Toxicity Potential.

Many discrepancies in data aggregation have resulted in incomparable results in pavement LCAs. One major point of discussion is the allocation procedure for co-products or products from other product systems, for example, using recycled concrete aggregate from a demolished residential building. Asphalt binder is a co-product of crude oil distillation, which also has a large amount of feedstock energy which is not used as an energy resource when binder is used in pavement systems. Some authors have considered this feedstock energy in addition to the primary energy expended in the material production and pavement construction process, which results in inconsistency in the estimates for indicators such as GWP for greenhouse emissions as shown in Table 2.10.

Table 2.10 Environmental impacts estimates for Asphalt binder production from select studies (adopted from (Yang 2014)**)**

Authors	**Data year**	**Region**	**Processes**	**Allocation**	**Indictors per tonne** Kg CO_2 eq.	MJ
Stripple (2001)	1990s	Sweden	• Crude oil production and transportation • Refining process • Refined product transportation • Blending and product storage	Mass	157	3298
Athena Institute (2006)	1999	Canada	• Crude oil production and transportation • Refining process	Mass	477	4993
Eurobitime (2011)	2011	Europe	• Crude oil production and transportation • Refining process • Refined product transportation • Blending and product storage	Economic	172	2627
Ecoinvent (2002)	1990s	Europe	• Crude oil production and transportation • Refining process	Mass	340	4507

There is also limited knowledge of the environmental impacts due to post-construction activities, especially the use phase impacts from pavement operation and the effects of timing and traffic delay from maintenance strategies (Azarijafari et al. 2016). A few studies have shown that emissions due to traffic congestion during maintenance vary considerably when comparing different pavement designs, and conclude that their inclusion is necessary for comparison of pavement life cycle impacts of different designs (Inti, Martin, and Tandon 2016; Inti, Sharma, and Tandon 2016). This indicates the starting point for research on the pavement use phase, benefits of maintenance, and the influence of management decisions on the environmental performance of pavement networks (Azarijafari et al. 2016). More studies have focused on the impact of pavement characteristics on vehicle fuel consumption and emissions, which often referred to as pavement-vehicle interaction (PVI). PVI models quantitatively assess these impacts by considering the effect of different pavement characteristics, and climatic and traffic conditions on the energy dissipation For example, excess energy consumption due to rolling resistance can be estimated with recent fuel consumption models developed by (Zaabar and Chatti 2010b, 2010a) based on a US calibrated version of the world bank HDM4 model. These models are important components in evaluating pavement sustainability performance; however, most models adopted in pavement LCA studies and tools generally account for only discrete vehicle speeds and are limited to only energy consumption. The HDM4 model output measure is the fuel usage and the carbon emission is estimated from CO_2 content of fuel reported. Alternatively, simulation methods like EPA's MOVES (motor vehicle emission simulator) (EPA, 2015) can be used to evaluate moving vehicles' environmental impacts. Recent efforts to incorporate HDM4 modes and MOVES models have helped to develop emission models that consider vehicle speed effects in models to investigate effects of road surface on other environmental factors based on traffic-related air pollution such as: nitrogen oxides, carbon monoxide, fine particulate matter, volatile organic compounds (Ziyadi et al. 2018).

Other models are also available from other regions (Akbarian et al. 2012; Li et al. 2017; Wills, Robbins, and Thompson 2015). The context-related factors, such as traffic level, climate and location, are also important elements influencing use phase impact and the performance outcome may differ depending on pavement type; thus these context-related factors need to be clearly presented, as well as assumptions guiding models identified (Trupia et al. 2017). A number of studies (Araújo, Oliveira, and Silva 2014; Bryce et al. 2014; Pellecuer 2016; Pellecuer, Assaf, and St-jacques 2015; Trupia et al. 2017; Wang et al. 2012, 2014) have adopted these models for both pavement segment and road network analysis to investigate the environmental impacts of pavement characteristics and conditions.

IRI is usually used to represent pavement condition to capture the effects of use phase in terms of roughness to report the environment performance of roads. Some authors do not consider these pavement interactions in the use phase, arguing that available models do not correctly represent the mechanism, since IRI does not represent the overall condition of the road, so its application in estimating environmental impacts of road usage and condition, i.e. pavement use phase, may overestimate or underestimate impacts (Torres-Machi et al. 2017). A recent study by Loprencipe et al (Loprencipe, Pantuso, and Di Mascio 2017) adopted a written regression for PCI and IRI to estimate Vehicle Operating Cost (VOC) using the calibrated HDM4 model.

Although the available pavement LCA tools were developed starting in the early 2000s, most of these tools cannot be used to assess innovative techniques and materials used in practice since the 1980s, for example, CIREAM. Some studies have tried to address these limitations in LCA tools such as PaLATE by considering CIR and replacing the bitumen emulsion with water to represent for the CIREAM technique. Apparently, this will skew the results in favor of CIREAM as opposed to assessing the technique based on practical knowledge that the expanded asphalt can be done using different reagents, not only water, that can be harmful to the environment.

The limited scope of the pavement LCA tools limits pavement managers' ability to account for the whole lifecycle impacts of pavement systems and improve pavement sustainability. Pavement LCA tools cater mostly to the conditions in specific regions where they were developed (Azarijafari et al. 2016; Huang, Spray, and Parry 2013; Santero et al. 2011). Considering that the standards of practice in roadway development differ, there are variations in primary data sources and indicators measured by the tools. Use phase of the pavement lifecycle is rarely included in available tools.

Haung et al (2009) suggest that tools developed prior to 2007 (e.g PaLATE2 and DuboCalc3**)** are currently not suitable for conducting LCAs mainly because these tools use outdated data. However, PaLATE presents some important features relevant for any new, improved LCA tool development. Evidently, it is still in use by some recent pavement LCA studies (Celauro et al. 2017). PaLATE is based on an easy-to-use Microsoft Excel workbook. It has information regarding recycled materials and on-site recycling processes. Also, users can adjust all detailed information such as characteristics, emissions, equipment, and activities in the data worksheets according to the actual conditions (Nathman, McNeil, and Van Dam 2009). Many LCA tools do not provide these features (Santos et al. 2017; Santos et al. 2017). The Athena Highway Impact Estimator developed by the Canadian Athena Institute is considered the most comprehensive North American LCA tool; however, the tool still relies on outdated or less relevant data sources such as Athena Institute data (Athena Sustainable Materials Institute 2006) for materials production and United States Life Cycle Inventory database (US LCI) for transportation. Only the impact of roughness in the use phase is assessed and impact factors such as noise and water quality, water consumption or land use are not evaluated. Thus, tools might not accurately present environmental performance measures for innovations in pavement mix designs, construction or maintenance practices. All pavement LCA tools were built based on an attributional approach and are for project-level decision support. Nonetheless, these tools and their databases provide a rich platform for pavement LCA resources including, for example, inventory data for road and roofing asphalt, and aggregate production has been published by the Athena Institute (Ahammed et al. 2016). It is important to recognize the limitation of these data, as well as the databases in available LCA tools, including limited applicability in certain region. This reflects conclusions of previous pavement LCA

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2 PaLATE Stands for "Pavement Life Cycle Assessment Tool for Environmental and Economic Effects", free tool available 2011, http://www.rmrc.unh.edu/Resources/CD/PaLATE/PaLATE.htm.

3 Developed by Rijkswaterstaat (RWS) is part of the Dutch Ministry for Transport and Waterworks, LCA tool can be obtained from RWS upon request: https://staticresources.rijkswaterstaat.nl/binaries/Application%20Form%20DuboCalc_tcm21-36757.pdf

reviews that there is a need to consider pavement management practices and the importance of localized region-specific databases for pavement environmental sustainability assessments.

A pattern in most road LCA tools is to consider the energy and airborne emissions. Very few included impacts on other factors such as noise and water quality. Considerable variability exists in environmental performance estimated. Santos et al (Santos et al. 2017) found that the different tools reported divergent environmental impacts and different impact categories were considered by these tools. Considering that sustainability is context specific, different impact factors will be of concern for different agencies depending on the institutional sustainability objectives. Thus, a suitable tool for agencies should address the important impact categories which can be characterized into a select set of relevant indicators. Finally, many of the environmental indicators (for example, noise and land use factors) currently not considered can be modelled based on detailed impact assessment methodologies such as IMPACT 2002+ and ReCiPe (Herrmann and Moltesen 2015; Rosenbaum 2017), which can be incorporated into any pavement LCA tool.

2.4 Sustainability Evaluation in Pavement Management

2.4.1 Overview of State of the Art

Sustainability in pavement management is about considering environmental and societal needs and at the same time maintaining economic vitality while making pavement management decisions both at the network-level and project-level. Sustainable pavement management practices for road networks extend the useful life of pavement assets, ensure timely monitoring, repair and replacement by optimizing the sustainability characteristics of the pavement throughout its lifetime. The challenge lies in how to measure and quantify improvements towards more sustainable pavement management practices. Recent studies have focused on two objectives for optimizing and programming M&R in pavement management: minimizing energy consumption and GHG emissions as shown in Table 2.11 , including examples in Lidicker et al. 2013; Loijos et al. 2013; Santero and Horvath 2009; Wang et al. 2012, 2014; Yu and Lu 2012; Zhang, Keoleian, et al. 2010; Zhang, Lepech, et al. 2010). As highlighted in Chapter 1 and Section 2.3of this thesis, pavement management activities can have other impacts on the environment beyond these commonly used proxies for environmental sustainability. These impacts need to be understood and integrated into decision-support tools to enable pavement managers to make more sustainable choices. Quantifying the environmental performance of pavement operation and maintenance activities will assist pavement managers in determining optimum pavement preservation policies for enhancing environmental sustainability and cost-effectiveness.

Efforts have been made to incorporate LCA results into network-level maintenance programming (Bryce et al. 2014; Chong and Wang 2017; Harvey, Wang, and Lea 2014; Loijos et al. 2013; Torres-Machi et al. 2017; Torres-Machí, Chamorro, et al. 2015; Wang et al. 2014); however, these studies are often limited in scope, particularly the life-cycle use phase is often excluded in their analysis. One reason for this practice commonly mentioned by most authors is the limited knowledge of interactions between the use phase and the environmental aspects; for example, regionalized estimate or localized models are needed to reflect the impact of the road condition on the environment (Torres-Machí, Osorio, et al. 2015). A major limitation of the available LCA tools for environmental evaluation is that they are mostly focused on the analysis of a specific road segment at the project level. It thus becomes difficult to apply these tools to evaluate network level environmental performance and therefore to incorporate current PMSs. A sustainable pavement management operation requires the network and project levels to work together efficiently and effectively.

In Ontario, earlier efforts to incorporate environmental performance into pavement management systems include the research collaboration between the MTO and the Centre for Pavement Technology and Transportation (CPATT) at the University of Waterloo (Chan 2010; Chan and Tighe 2010). This research developed a framework for sustainable pavement practices at project and network levels which suggests the sequence of activities that MTO should do to promote pavement sustainability. The study also led to the development of an indicator called the green discounted life cycle cost (GDLCC) for project level and network level decision making. Such efforts are important as they provide a basis for integrating measures of environmental sustainability into pavement management practices by prioritizing more sustainable alternatives. However, the indicators suggested and integrated were developed based on GreenPave reporting standards and life cycle cost (LCC) is limited in measurement of environmental sustainability as sustainability rating tools such as GreenPave do not measure environmental performance outcomes and consider limited factors as discussed in Section 2.3.2. Two recent research collaborations in 2016 (Nasir 2018) and 2018 (Achebe, Saari, and Tighe 2021; Min et al. 2021) came close to addressing the challenge but their final outcomes were more relevant for project-level for specific project assessment and strategic-level for reporting impacts and benefits of all MTO activities on highway infrastructures, which includes pavement and other assets. This work built on that previous work and ventured to address the need for an analytical approach to measure environmental sustainability performance outcomes and inform decision makers on progress towards more sustainable pavement asset management. The limitation is indeed echoed by pavement managers across the country (Achebe et al. 2021).

Table 2.11 Summary of studies related to sustainable pavement management

Related Literatures	**Environmental Factors**	**Level ^{a}**	**Method**	**Pavement lifecycle phase**
Chan & Tighe (Chan and Tighe 2010)	Material use	PL and NL	Greenpave and LCCA	Construction and Maintenance
(Zhang, Keoleian, Lepech, & Kendall, 2010)	GHG emissions	PL	LCA-LCCA model	All phases
Wang et al (2012) (Wang et al. 2012)	Energy consumption and GHG emission	PL	LCA model	Use
Wang et al (2014) (Wang et al. 2014)	GHG emission	PL	LCA model	Use
(Giustozzi, Crispino, & Flintsch, 2012) (Giustozzi, Crispino, and Flintsch 2012)	Energy consumption and GHG emission	PL	Multi-attribute analysis and LCA result	Maintenance
(Gosse, Smith, & Clarens, 2013)	GHG emission	PL	General Algorithm and LCA result	Maintenance
(Loijos, Santero, & Ochsendorf, 2013)	GHG emission	NL	LCA model	All phases
(Lidicker, Sathaye, Madanat, & Horvath, 2013)	GHG emission	NL	Multi-objective optimization	All phases
(Reger, Madanat, & Horvath, 2014)	GHG emission	PL	Multi-objective optimization	Maintenance
(Reger, Madanat, & Horvath, 2015)	GHG emission	PL	Multi-objective optimization (MOO)	Maintenance
(Pellecuer, Assaf, & St-Jacques, 2014; Pellecuer, Assaf, & St-jacques, 2015)	Air and water pollutants, noise	PL	PEIM tool	Maintenance and Use
(Bryce, Katicha, Flintsch, Sivaneswaran, & Santos, 2014)	Energy consumption	NL	Multi-criteria optimization and probabilistic-LCA result	Construction, maintenance and use
(Torres-Machí, Chamorro, Pellicer, Yepes, & Videla, 2015)	GHG emission	NL	Iterative MOO	Maintenance
(Torres-Machi, Pellicer, Yepes, & Chamorro, 2017)	GHG emission	NL	Heuristic MOO algorithm	Maintenance

Note: a – PL and NL represents project level and network-level respectively.

2.4.2 Adapting Life Cycle Assessment to Pavement Management System

LCA can be integrated into PMS, either directly through: integration of inventory data, impact models and assessment reporting; or indirectly through inclusion of LCA results into programming platform in

PMS, such as decision trees (Harvey et al. 2014), but challenges exist. Harvey et al identified three key issues for application of LCA to pavements by road agencies (Harvey et al. 2014):

- Availability of analysis input data that reflects regional differences in materials, construction, maintenance, use and other important variables that determine environmental impact,
- Availability of LCA based decision support tools that meet the time and resource constraints of agencies,
- Information regarding how to apply LCA principles and thinking in light of the first two issues.

Harvey et al (Harvey et al. 2014) concluded that these challenges need to be addressed before a formal and proper integration of LCA in pavement management systems can be achieved. More importantly, interpretation of results from LCI and LCIA is desired to provide information/metrics that can be inform decision making. Limitations and uncertainties in the analysis should be made clear so that any interpretation will reflect the context for which the study scope, LCI and LCIA applies. There are time-dependent variables that affect the results of an LCA. For example, long-life pavements included many of these variables. Technology, risk, environmental capacity, and resource availability are all elements that change over time, yet there is no system in place to quantitatively account for their fluctuations. Previous reviews have highlighted that LCA studies lack sensitivity analysis of uncertain variables that may skew LCA results. Indeed, a new tool with such functionality will improve current practice of LCA and provide decision makers with an understanding of factors that may influence results (Huang, Spray, et al. 2013). Another factor that should be considered when interpreting LCA results is that one indicator can reflect many concerns (Harvey et al. 2016; Rosenbaum 2017). For example, climate change can be linked to several ecosystem and human health concerns. Another example is that energy resource depletion can lead towards more costly energy in the future. These two examples are indicative of the fact that no indicator can represent single objectives without also impacting other objectives.

2.5 Sustainable Pavement and Changing Atmospheric Conditions

Considering all aspects of environmental sustainability of pavement, atmospheric-related issues are among the most pressing, with the highest potential to influence pavement performance and pavement management. The urgency of climate change demands both mitigation and adaptation by pavement systems. Previous sections of the literature review have described how pavement systems emit greenhouse gases throughout their life cycle. Many of the atmospheric emissions from pavement systems affect both the climate system and air quality. Air pollution is the leading environmental risk factor leading to premature death worldwide, according to the Global Burden of Disease Study (Cohen et al., 2017). This section focuses on these atmospheric issues, and their relation to sustainable pavement management.

2.5.1 Atmospheric Issues

Global warming is the consequence of the long-term accumulation of GHGs in the upper layers of the atmosphere. The emission of these gases is caused by human activities that are intensely harmful to the environment (such as land use changes, deforestation, and burning of fossil fuels).

There are two related definitions for carbon footprint, for some researchers carbon footprint a measure of only carbon dioxide emissions that are directly and indirectly caused by an activity or are accumulated over the life stages of a product system; while others consider a definition that encompasses the total mass of greenhouse gases emission (Al-Qadi, Ozer, and Harvey 2017). In both definitions, carbon dioxide (CO_2) is considered a dominant factor of climate change, and CO_2 gas emissions account for nearly 75% of the global emissions of greenhouse gases (GHGs) (Lo Presti and D’Angelo 2017). The climate-related impacts of these GHG emissions can be summed into one single metric called CO_2 equivalent using their Global Warming Potential (GWP). In atmospheric science, GWP is the 100-year Global Warming Potential of an emission relative to CO_2. It is the ratio of the radiative forcing of an instantaneous pulse of one tonne a given emission, integrated over 100 years, compared to that of CO_2. The total CO_2 equivalent can be calculated by multiplying the mass of each emission by its respective GWP.

In LCA, GWP is used interchangeably with CO_2 equivalent emissions. In the UK, the Publicly Available Specification (PAS) 2050:2008, specification for the assessment of the life cycle greenhouse gas emissions of goods and services, addresses the single –impact category of Global Worming Potential – to provide a standardized and simplified implementation of process-based LCA methods for assessing greenhouse gas (GHG) emissions from products. The use of PAS 2050 to simplify existing LCA methods and standards has resulted in specific tools for GHG assessment being developed e.g. CHANGER4 (Huang, Hakim, et al. 2013), asPECT5 (TRL 2011), CEREAL (Spriensma, van Gurp, and Larsen 2014). In North America, similar carbon estimation tools have been developed. AASHTO

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4 Web-based application can be accessed at http://www.irfghg.org/index.php.

5 Web-based application can be accessed at http://www.sustainabilityofhighways.org.uk/

has also released a tool, GreenDOT6. Also, the EPA's waste reduction model (WARM) is used to estimate impacts carbon footprint of different waste materials. The recent WARM version 11 tool released in 2014 includes carbon estimates of road construction materials (Lo Presti and D'Angelo 2017). More recently, the Project Emissions Estimator (PE-2)7 was developed for GHG emissions modelling of construction, maintenance, and use of pavements (J. T. Harvey et al. 2016).

The release of any given substance into the atmosphere is called an "atmospheric emission". Many types of atmospheric emissions can be harmful, contributing to air pollution, climate change, or both. Table 2.12 depicts the effects of five different emissions on the climate (temperature and hydrologic system) and air pollution (levels of $PM_{2.5}$, ozone, and NO_2). The air pollutants 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). A fifth emission, carbon dioxide (CO_2), is the major greenhouse gas which contributing to climate change.

Table 2.12 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*(ECCC, 2020)

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6 Excel based tool downloaded from https://environment.transportation.org/environmental_topics/energy_greenhouse/overview.aspx#bookmarksubInfrastructureCarbonEstimatorGreenDOT

7 Author cites broken link - http://www.construction.mtu.edu/cass_reports/webpage/plca_estimator.php

The contribution of the pollutants to climate change depends on their effect on the global mean surface temperature and the subsequent impacts such as changes to weather patterns and an increase in tropical diseases (ECCC, 2019). At the regional scale, the effect of atmospheric releases on precipitation can affect hydrologic cycles, which would affect agricultural yields and impact human health. Ground-level ozone and fine particulate matter are the most harmful pollutants with direct adverse impact on human health. Ground level ozone is formed through atmospheric reactions between NOx and volatile organic compounds (VOCs). $PM_{2.5}$ is formed through chemical reaction of pollutants such as NOx and SO_2 (known as secondary $PM_{2.5}$); or emitted directly into the atmosphere (known as primary $PM_{2.5}$). 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 (ECCC, 2020; NRCan, 2020). (Nasir 2018) evaluated the effects of these atmospheric releases and their contribution to environmental and health damages from various pavement management activities.

2.5.2 Greenhouse Gas Mitigation in Pavement

Highway management phases are planning and design, new construction, rehabilitation / reconstruction, maintenance, and policy development. The major work types include Paving – Asphalt & Concrete, Structural, Removals, Grading, Landscaping, Culverts, Drainage, In-water operations, and Electrical (MTO, 2018). GHG emissions mitigation measures in the highway management sector encompass a variety of possible activities ranging from administrative programs and policies to engineered techniques, technologies and practices. It may include the use of novel materials or technologies and renewable energy, retrofitting old equipment, increasing energy efficiency, or changing management practices in design, construction, rehabilitation and maintenance activities.

Over 100 GHG mitigation strategies have been identified and reported by (Achebe et al. 2021) as part of the project report for “Greenhouse Gas Mitigation in Highway Design, Construction and Maintenance - Jurisdictional Scan. Final Report, HIIFP Project #2018-02”. Part of this report is presented in this thesis as Chapter 4. The list of the mitigation strategies can be found in Appendix B of this thesis. The report provides comprehensive description of the mitigation practices organized by four main highway management phases as shown in Figure 2.6.

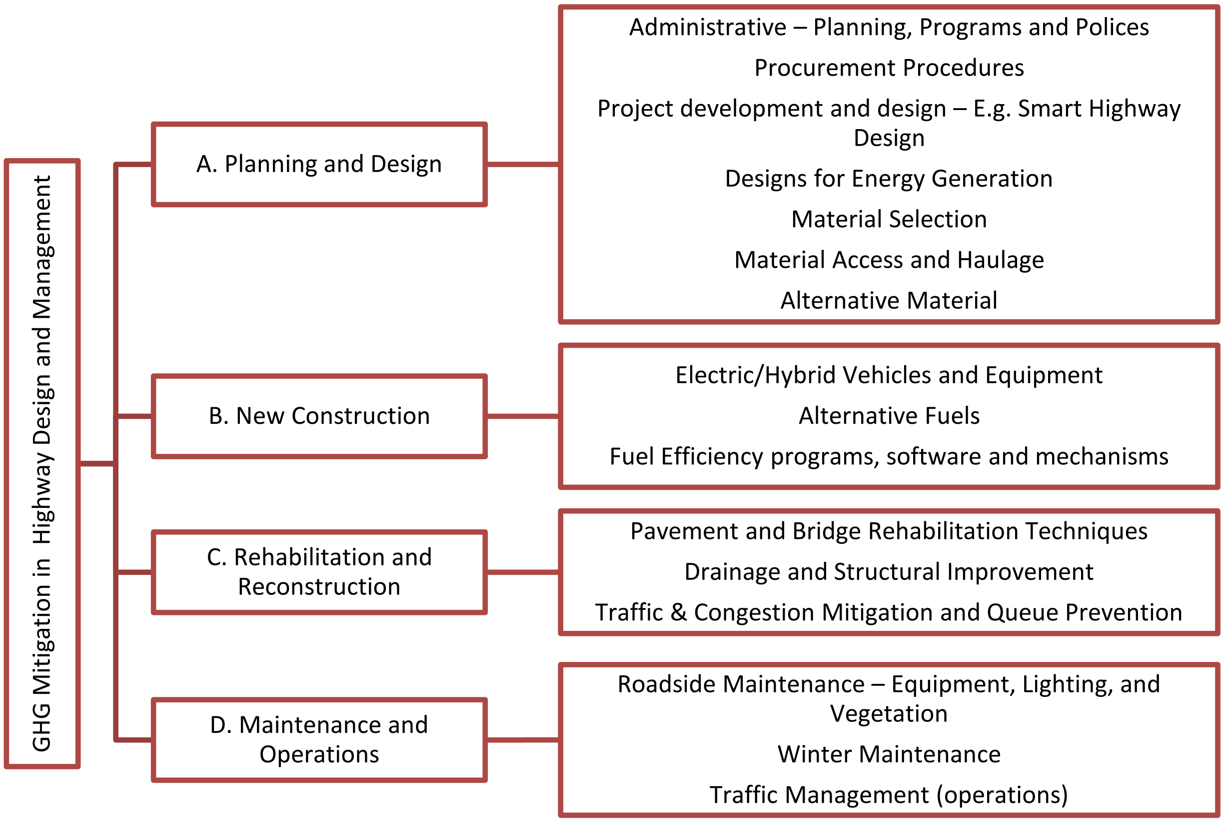

Figure 2.6 Examples of GHG Mitigation Measures applicable to Four Highway Management Phases

Given that the list was collated from different sources, including various reports from transportation agencies, it shows that rate implementation/ level of adoption and type of measures adopted differ by jurisdictions and transportation agencies. The list of GHG mitigation measures are mapped into the three levels of adoption- "currently in use", "use occasionally/pilot project,", "not in-use", "Unsure/NA" for nine countries and regions as shown in Table 2.13 .

Table 2.13 Level of Adoption of the GHG Mitigation Measures by Different Jurisdictions

Category	# of GHG Mitigation Measure	ONT	CAN	USA	UK	NTL	SCA	Other EU	AUS	ROW
Planning and Design	97	🟥 39	▨ 59	▨ 44	▨ 49	🟩 48	▨ 49	🟩 47	▨ 64	▨ 80
Policies, Programs and Technologies	70	🟩 33	🟩 31	🟩 43	🟩 41	▨ 45	🟩 47	▨ 45	🟩 30	🟩 15
Alternative materials	27	▨ 15	🟨 4	🟨 7	🟨 5	🟨 3	🟥 1	🟨 4	🟨 2	🟨 2
		🟨 10	🟥 3	🟥 3	🟥 2	🟥 1		🟥 1	🟥 1	
New Construction	19	▨ 9	🟨 11	▨ 10	▨ 12	▨ 12	▨ 12	▨ 12	▨ 13	
		🟩 6	🟩 7	🟩 9	🟩 7	🟩 7	🟩 7	🟩 7	🟩 6	
		🟥 4	▨ 1							
Rehabilitation and Reconstruction	19	🟩 11	▨ 13	▨ 11	▨ 5	▨ 15	▨ 15	▨ 14	▨ 17	▨ 17
		🟥 5	🟩 6	🟩 8	🟩 14	🟩 4	🟩 4	🟩 5	🟩 2	🟩 2
		2								
		🟨 1								
Maintenance and Operations	28	▨ 18	▨ 19	▨ 20	🟩 12	🟩 14	🟩 13	🟩 14	▨ 22	
		🟩 7	🟨 5	🟩 6	🟨 10	🟨 8	🟨 9	🟨 9	🟩 6	
		🟨 2	🟩 4	🟨 2	▨ 6	▨ 6	▨ 6	▨ 5		
		🟥 1								

🟩 **Currently in Use**	🟥 **Not in Use**
🟨 **Used Occasionally/Pilot Project**	▨ **Unsure/NA**

2.5.3 Adapting Pavement to Climate Change

The phenomena of changing climate conditions may produce variations in temperature and average rainfall resulting in more frequency freeze-thaw cycle and flooding which have both direct and indirect impacts on pavement condition (Bles et al. 2016; Hyman, Kafalenos, and Beucler 2014). Climate change mitigation are actions to permanently eliminate or reduce the long-term risk of climate change. Studies have found that mitigation alone cannot meet these requirements and avert consequences, thus the ability of living with, avoiding, and minimizing negative impacts of climate change consequences is very critical now.

The pressures of climate change on paved roads modify pavement exposure in a positive or negative way depending on the location. For example, in Canada, magnitudes of impacts predicted to 36% increase in pavement rutting and 3% reduced roughness for pavements in Manitoba and British Columbia respectively (Mills et al. 2007; Tighe et al. 2008).

It is becoming increasingly clear that actions must be taken not only to reduce generation of the greenhouse gases, but also to address the present and future adverse impacts of climate change through adaptation. The Intergovernmental Panel on Climate Change (IPCC) defines adaptation as “The ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions.” (IPCC, 2014). Adaptation involves processes and actions to reduce the adverse consequences which are in-effect now or expected in the near future. The goals of adaptation in infrastructure asset management could include the effective management of risks of extreme events and structural change in design and planning to preserve and improve resilience of the assets such that the level of serviceability, safety, and sustainability will not be reduced (Li, Mills, and McNeil 2012).

Adaptation to climate change may have direct and indirect impact on other sustainability objectives such as on road safety and traffic noise (Enríquez-de-Salamanca 2017). An example of an effect of climate change is flooding or increased precipitation, which is expected to increase the need for substantial investments in road networks through pavement preservation and maintenance. Adaptation strategies such as replacing porous pavement type with concrete pavement to adapt to effects of temperature change or increased precipitation in the pavement structure can have rebound effects on road noise performance. (Enríquez-de-Salamanca 2017) suggest possible ways to mitigate the impacts includes using more resilient materials, pavement recycling techniques, materials with lower emissions and processing-equipment with greater energy efficiency. Integrating noise performance measures in decision-making for road pavement adaptation can avoid unintended indirect impacts.

2.6 Summary

In this chapter, an overview of pavement asset management is provided highlighting its framework components and advantages. A review of environmental sustainability in the context of pavement system is presented. Pavement sustainability represents a very important concept underpinning the complexity of pavement asset management. Successful and sustainable pavement asset management requires performance measures that are objectively based, consistent, quantifiable and responsive to all aspects of sustainability. Specifically, pavement management and decision support tools PMS should incorporate institutional objectives for economic, environmental, safety, technical and functional considerations. Pavement management decision making is guided by its performance measures and the associated targets or thresholds. Therefore, this research addresses the importance of properly identifying required environmental performance measures and the associated assessment tools for integrating environmental sustainability into pavement management frameworks. In addition, a review of environmental assessment tools and their application to measuring environmental performance of pavement systems and management activities as a means of studying the feasibility of different tool is conducted. LCA modelling is of particular importance to this research as it is used as a basis to develop and evaluate the environmental performance measures of the pavement life cycle as well as their integration into the development of optimized sustainable maintenance and rehabilitation policies.

There are various LCA tools that can be utilized to estimate impacts of pavement systems. Each method requires different sets of data, investigates selected measures and results in different estimates. It is recognized that there is no universally accepted LCA approach. However, it is noted that adopting localized databases and impact factors that comprehensively consider the environmental aspects of pavement engineering and management practice in a region is important for applicability of the LCA results in decision making. Several variations of environmental sustainability performance measures have been developed with many uncertainties and there is no standardized metric that can be applied to pavement management decision support (Flintsch and Bryce 2014; Gopalakrishnan et al. 2014). There is a need to assess environmental impacts of pavement management decisions and define measures that inform progress towards pavement sustainability. Pavement sustainability is a context–sensitive characteristic of pavement which exist and functions within the transportation system and environmental system. An accounting of interactions between the pavement lifecycle and the surrounding systems is required to ascertain claims of strategies that profess sustainable practices for a particular pavement system (Van Dam et al. 2015). The use of RCWM pose a question in this regard, so should be investigated.

Another point of system interactions that can influence sustainability is related to the PVI effect of pavement characteristics given their impacts on vehicle fuel consumption and it associated emissions. There is limited understanding of the PVI effect and models to reflect the regional practice and road condition to account for these interactions are not available. There is a need to inform pavement management strategies and reduce the effects on transportation emissions which are considered the main source of traffic related health challenges.

Limited research has been introduced to incorporate pavement LCA into pavement management systems; however, there is no comprehensive work done to incorporate environmental aspects and impacts from all phases of the pavement life-cycle into pavement management systems. The research efforts presented herein seeks to address gaps identified in this literature review, developing sustainability metrics specific to Ontario, reviewing its GHG mitigation practices, evaluating the sustainability of innovative technologies, addressing adaptation, and, finally, project and network-level evaluation of PVI-related energy and emissions in Ontario.

Chapter 3

Environmental Sustainability Measurement in Pavement Asset Management

3.1 Introduction

Environmental sustainability of transportation is the subject of a rich and growing body of literature and practice. However, the inclusion of sustainability assessment in pavement management remains inconsistent (Tighe and Gransberg 2011). One major challenge is defining one general set of indicators that is effective and resonate with a broad array of stakeholders and contexts in the case of pavement assets (Gudmundsson et al. 2016). This is in part because relevant indicators may vary with the context, influence, and purpose of pavement managers and their stakeholders. Further, credible and practical means of measuring progress against these indicators need to reflect new knowledge and be adapted to local conditions. Here, we describe theories and practice for defining and evaluating environmental sustainability for the pavement lifecycle. We focus on the Canadian context and the case of pavement managers in Ontario to develop a systematic framework and accompanying indicators and measurement methods for environmentally sustainable pavement management.

Canada provides an example of a Northern, developed nation with a decades-long history of environmental sustainability assessment practice in pavement management. Federally, Canada has relied on environmental performance indicators for three decades (Environment Canada 1991). Canada was the source of a widely used sustainability framework, the pressure-state-response framework (Cormier and Gilbert 2005). The Transportation Association of Canada (TAC) presented principles and framing indicators for sustainable transportation in 1999 (TAC, 1999).

The important role of performance measurements and indicators in pavement asset management has been clearly identified in literature (Cornet et al. 2016; Dasgupta and Tam 2005; Gudmundsson et al. 2016; Haas et al. 2009). The TAC Pavement Asset Design and Management Guide describes performance indicators as essential measurable entities for “accessing the current and future state of road infrastructure, as well as agency/institutional efficiency in service and safety provision to users, productivity, cost-effectiveness, environmental protection, preservation of investment and other functions” (TAC 2013). Essential features of indicators include their ability to explain, highlight, and summarize the enormous complexity of our dynamic environment to less complicated information (Gudmundsson et al. 2016). Performance measures for infrastructure functional condition, for example, Pavement Condition Index (PCI) or International Roughness Index (IRI), are well established. These metrics are largely standardized across agencies in Canada (Haas et al. 2015).

Indicators of environmental performance differ from conventional performance measures in their linkage to sustainability goals and objectives. Environmental indicators developed based on quantitative measurements or statistics of environmental conditions allow for a comparison of states of the environment across time or space (Ebert and Welsch, 2004).

Previous work provides guidance in the selection of environmental indicators. Radermacher (2005) defined statistical measurability, political/societal relevance, and scientific consistency, as the three important characteristics that should be considered during the indicator selection process. Moreover, there are two significant factors in identifying and selecting the relevant set of indicators for monitoring environmental performance in transportation infrastructure management. First, the measurement framework needs to be sufficiently consistent to make meaningful comparisons between technology alternatives, but it also needs to recognize the significance of diversity of application, i.e., context-specificity. Second, the tool needs to be comprehensive enough to be meaningful, but there is also broad agreement that indicators should reflect the values and priorities of relevant stakeholders, context, and intend use (Cambridge Systematics Inc. 2008; Zietsman et al. 2011).

A comprehensive set of environmental indicators will reflect the many environmental issues can be related to road development and management, from energy use, air and water pollution to biodiversity loss. It is evident that certain issues such as climate change can no longer be neglected in transportation infrastructure management decisions. In Canada, the transportation sector is the second largest contributor to Canada’s total greenhouse gases (GHG) emissions with over 85% (Figure 4.1) due to on-road vehicle operations (ECCC - Environment and Climate Change Canada 2017). The pavement lifecycle can equally have other adverse impacts on the environment and human health, such as: noise from tire-pavement interactions; pollution affecting water, soil and air quality; impacts on biodiversity, flora and fauna (Enríquez-de-Salamanca 2017; Loijos et al. 2013). These issues are acknowledged across North America, yet these environmental aspects are often overlooked in many roadway investment decisions (Tighe and Gransberg 2011; Varamini and Tighe 2015).

When evaluating environmental performance, different classes of environmental indicators are used. One class includes system activity-based (input, process and output) indicators, such as quantity of material used, or air pollutants emitted (e.g. GHG emissions) (Santero, Loijos, and Ochsendorf 2013). Others consider outcome-based indicators, at midpoint (e.g. global warming potential) (Huang et al.

and end point (e.g. human health effects) (Nathman et al. 2009), and others evaluate the economic costs of impacts (e.g. using the social marginal damage cost of carbon emissions) (Nasir 2018; Yu and Lu 2012). Further, different lifecycle phases may be included in the assessment scope (Santos et al. 2015). They may include material production and construction activities, use phase or the impacts from selected maintenance treatments. Inconsistency in the scope and set of indicators makes it difficult to compare the performance of different designs and management approaches, which may reduce the influence of environmental aspects considerations in investment decisions. While indicators should be comprehensive, they should also be context-specific. Pavement sustainability is a context–sensitive characteristic of pavement, whose impact factors and their measurement varies depending on objectives and goals of main road authorities and key stakeholders. Context is also a function of the location, characteristics of the pavement, pavement-related activities, and the conditions within which the pavement system is developed and managed. Environmental conditions, as well as the characteristics and values of receptor populations can affect the potential for and severity of harm related to environmental issues.

Indicators should consider not only the goals of stakeholders, but also their influence. Selection of performance measures is not merely a technical issue, there is also a question of who to take responsibility for certain impacts. For this reason, transportation authorities, like Transport Canada, have developed tiered indicators within influence-oriented frameworks that acknowledge the agency's level of influence and control over different factors (Jeon and Amekudzi 2005). Four major groups of stakeholders, as shown in Figure 3.1, are involved in the performance measure of roads, so a balance application of performance measures depends on their involvement and interest or requirements. Moreover, the level of influence on activities to reduce to environmental impacts of road development is shared between the agencies and industry partners including consultants and contractors who can recommend designs and ultimately control activities at the site that cause the environmental problems (U.S.EPA 2009).

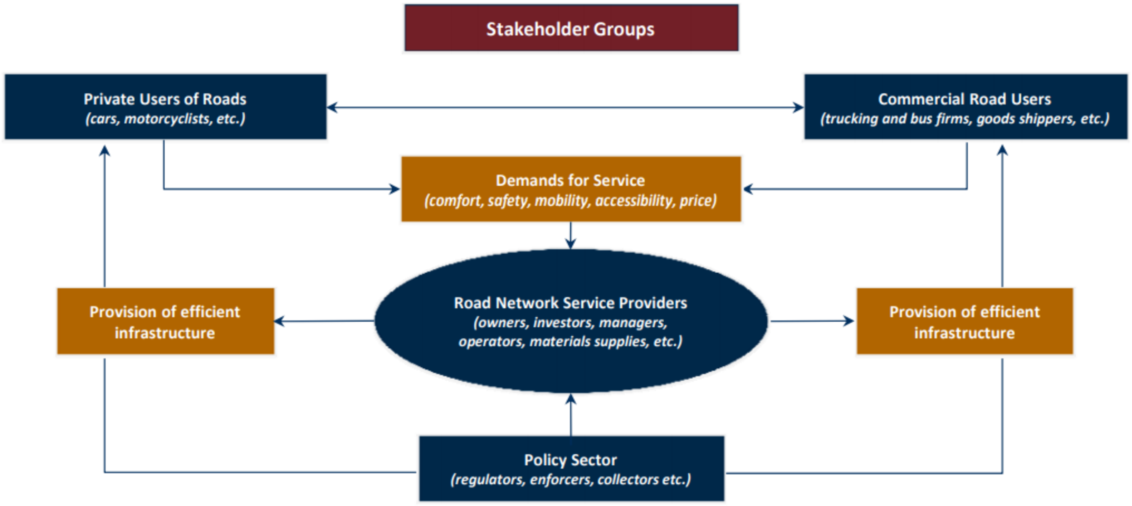

Figure 3.1 Stakeholders Involved with Performance Measures for Roads (Haas et al., 2009)

The choice of indicators should be driven by their intended use. The rationale for sustainability measurement can be grouped broadly into: accounting, decision support and process improvement (FHWA, 2015). Accounting refers to measurement mainly for the purpose of quantitative tracking, usually for reporting purposes. Decision support refers to qualitative or quantitative measures that inform organizational or project decisions. Process improvement measurements provide feedback to refine methods. From the perspective of pavement managers, there are two broad decisions to make: which sustainability performance measures to recommend and promote to industry partners, and which measures to collect to assist in planning, programming, accounting, and decision making.

The main objective of this research is to develop and implement an environmental sustainability evaluation framework suitable for assessing the pavement lifecycle. This includes selecting relevant environmental factors, associated indicators, and measurement methods relevant for sustainable pavement management at project and network-levels. The purpose is to enable environmental sustainability performance evaluation of road pavement management decisions, to understand the environmental impacts of road networks, and establish links between pavement management activities and environmental components throughout the pavement life cycle. Factors, indicators, and measures are selected to be comprehensive and context-specific. The chosen context is Canadian, focusing on pavement managers in Ontario, with the aim of providing measures reflecting their values, aims and purposes.

3.2 Research Approach

This study adapts a top-down, or issue-based, approach to environmental performance indicator selection for quantifying sustainability in pavement management (Oltean-Dumbrava, Watts, and Miah 2014). This is achieved primarily through a review and application of academic literature and national and provincial frameworks and guides for environmental management in the transportation sector. First, environmental sustainability is conceptualized in the domain of pavement management. Types of indicators are reviewed, as are applications of such indicators in the context of Canadian road management. Methods for employing such indicators in sustainable pavement management are discussed, along with applications in the literature and practice in Canadian provinces and territories. This review is used to identify potential environmental performance indicators and select a number of indicators that could make the framework operational for pavement management in Ontario.

3.3 Overview of Environmental Sustainability and Pavement Management

3.3.1 Environmental Sustainability and Canadian Roads

3.3.1.1 Conceptualizing Environmental Sustainability

A common touchstone for conceptualizing sustainability is the widely cited definition of sustainable development in the “Our Common Future” report (Brundtland Commission, 1987); and the “triple bottom line” incorporating environmental sustainability, economic sustainability, and social sustainability. Historically, however, the concept of sustainability was broadly understood only as environmental sustainability. A principal idea was to limit economic growth within the carrying capacity of the environment (Goodland, 1995; Moldan et al, 2012); but the definition and relevance of the term sustainable, and what should be sustained, remained a source of debate (Kates, Parris, and Leiserowitz 2005).

One reason for debate is centred in the differing worldviews, values, and theories that can underlie concepts of sustainability. Sustainability science has been shaped by numerous interdisciplinary research fields. These have helped to identify critical elements and interactions for assessing sustainability in some contexts but have yet to inform a single generalizable theory of sustainability (Clark and Harley 2020). Sustainability frameworks are largely built on an understanding of guiding principles and a system of values (Sala et al. 2015).

One early debate on sustainability worldviews, centred on weak versus strong sustainability, expressed several principles related to environmental protection, including: integrity; regeneration; assimilative capacity; resilience; precautionary principle; irreversibility and criticality of natural capital; substitutability; assimilation; the polluter pays principle; and constraints of resources and waste generation (Hopwood et al. 2005). Such concepts have been applied to define sustainability and address environmental problems related to individual biotic or abiotic species, or entire ecosystems (Cornet, Gudmundsson, and Leleur 2016).

Hopwood et al. (2005) analyzed and mapped the sustainability discourses on the social and environmental aspects from weak to strong sustainability. The authors believed that achieving strong sustainability requires two systems of values: the eco-centric, prioritizing environmental protection; and the anthropocentric, prioritizing justice and well-being. More recent discourses on what these theories mean for sustainability can be found in Cornet et al. 2016, Moldan, 2012; Morelli, 2011) (Cornet, Gudmundsson, and Leleur 2016).

An earlier conceptualization of environmental sustainability (ES) by Goodland (1995,), based on the biological law, defined ES simply as "maintenance of natural capital". The biological law posits three rules on input, output and operational efficiency. The first rule points out the importance of the balance between waste flows and the assimilative capacity of the environment. The second rule explains how to renewable and non-renewable resource exploitation should maintain regenerative capacity. The third rule says that the improvement of efficiency takes precedence over the capacity.

Natural capital refers to assets derived from nature that provide goods or services for protecting human life. Along with “anthropogenic capital”, it comprises the resource stocks that constitute the productive base for human wellbeing (Clark and Harley 2020). It includes renewable or non-renewable natural assets such as soil, atmosphere, forests, water, wetlands and ocean bodies.

Goodland (1995) described ES as a set of constraints on major anthropogenic activities affecting natural capital: resource use, ecosystem pollution and waste. Ecological economics distinguishes the following four types of natural capital: renewable resources (e.g. forests) from within the biosphere; non-renewable resources (e.g. fossil fuels) from the lithosphere; eco-systems and the services they produce (e.g. biodiversity or the ozone layer); and natural sinks (e.g. land, the air and the water bodies).

Recent approaches have attempted to incorporate all capital stocks, including natural capital, into an inclusive wealth framework. Under this framework, sustainability is achieved by conserving per capita inclusive wealth. In theory, this framework provides a significant advance in sustainability assessment by offering a specific and consistent definition for sustainability (Clark and Harley 2020). In practice, measuring inclusive wealth remains challenging, requiring a deep scientific understanding of dynamics of the earth system and its nature-society interactions, with most applications at the national scale.

Other approaches address the measurement of environmental sustainability from a biophysical basis. Holdren et al. (1995) defined biophysical sustainability as maintaining or improving the integrity of the life support systems of the Earth, comprising the atmosphere, hydrosphere, lithosphere and biosphere. The authors posit that any economic activity will lead to some environmental damage except in cases where the susceptibility factor, which is the damage per unit of stress, is zero. This underscores the relevance of economic principles (such as the valuation of natural capital) to environmental protection, and the anthropocentric approach to environmental problems.

Morelli (2011) revisited the biophysical foundations of ES with a focus on health of the ecosystems. He then set out to provide an ES definition for environmental professionals in the first edition of the Journal of Environmental Sustainability. The work contextualized “environmental” as a subset of the broader concept of “ecological,” i.e., the intersection of human activities and ecological systems. He then contextualized ES as a facet of sustainable development that is a subset of ecological sustainability. It defined ES as “a condition of balance, resilience and interconnectedness that allows human society to satisfy its needs while neither exceeding the capacity of its supporting ecosystems to continue to regenerate the services necessary to meet those needs nor by our actions diminishing biological diversity” (pg. 6). A set of 15 principles were suggested to guide the operationalization of environmental sustainability. In general terms, these principles highlight valuing ecological services and recognizing systems’ interconnectedness.

A comparison of the environmental sustainability definitions proposed by Goodland (1995), Holdren et al. (1995) and Morelli (2011) reflects the importance of the output rule, the input rule, and the operational principles in ES. In short, the work underscores the need to develop our communities while ensuring responsible use of resources and mitigation of environmental pollution. These principles of environmental sustainability should guide the definition of ES objectives in pavement design and management, thus informing the selection of suitable measures and indicators to track performance towards desired outcomes.

In the realm of Canadian transportation, environmental sustainability has been conceptualized by the Centre for Sustainable Transportation as: limiting emissions and waste within the planet’s ability to absorb them; minimizing consumption of non-renewable resources; limiting consumption of renewable resources to the sustainable yield level; reusing and recycling its components; and minimizing the use of land and the production of noise (Cormier and Gilbert 2005). In practice, definitions of sustainability in transportation vary across practitioners and research initiatives (Jeon and Amekudzi 2005).

3.3.1.2 Categories of Environmental Indicators

The indicator approach to environmental sustainability can provide a basis for prioritizing environmental factors, encourage attention to mitigation and restoration efforts, and enable agencies to address legislative mandates and public concerns regarding environmental protection and quality. Indicators are an important measurement of what is valued and should be protected or maintained. Technically, indicators are drawn from values and they build values (Meadows 1998).

An indicator is a key informational device that enables navigation from planning and decision-making to implementation, to monitoring and evaluation of pavement management activities. This involves integrating sustainability priorities and values.

The international standard organization ISO 14031 defines an Environmental Performance Indicator (EPI) as an indicator that provides information about an organization's environmental performance, focusing on either management/strategy or operations. Gudmundsson et al. (2016) defined a transportation environmental sustainability indicator as a "variable, based on measurements, which represents potential or actual impacts on the environment - or factors that may cause such impacts - due to transport, as accurately as possible and necessary".

Environmental indicators are used to define the environmental impact of interest. For example, climate change impacts may be measured by global warming potential (GWP). Indicators are usually defined along the cause - effect chain by relating effects on the environmental to potential impacts.

Generally, performance indicators are characterized into strategic (or managerial) and operational categories. Strategic measures are better suited for decisions regarding a transportation authority's expression of environmental responsibility at the strategic level of management which covers all transportation infrastructure assets. The numerous facets of an indicator are often formulated based on dimensions of time and space, intended use, timeframe and an organization's operational functions which combines factors of other categories with the overall level and scale indicator applicability.

Operational measures can be grouped into four casually linked subcategories: input, process, output, and outcome. In this study, three of these categories are included: input-based indicators, output-based indicators, and outcome indicators. Process-based indicators do not evaluate performance or effect of an activity to the environment, so they were not included in this study. Instead, we consider operational measures such as inputs of energy and materials, and outputs of emissions, concentration, or outcomes for ecosystems and wellbeing.

Both input-based and output-based indicators are a function of processes and activities of the system under investigation. They provide information on the amount of resources consumed (input-based) and the pollution released (output-based). These do not estimate the actual environmental damage but can eventually be used to estimate the effects on the environment and outcomes for receptors. Examples of outputs include noise levels, hazardous spills, or emissions released (such as air pollutants, toxic substances, and greenhouse gases).

Outcome-based indicators estimate the impacts of activities on human and natural receptors. Examples of outcomes include damage to human health and infrastructure and biodiversity loss. However, connecting an output to an outcome indicator is rarely straightforward. It requires tracing outputs through their effects on environmental factors and relevant receptors. For example, it would require tracing the effect of material used (recycled asphalt material content: an input-based indicator) during construction of pavement to air pollutant emissions (GHG emissions: an output-based indicator), to the resulting concentrations that affect levels of health risk, and the associated economic cost (outcome-based indicator) (Achebe et al. 2021).

3.3.1.3 Environmental Sustainability in Context for Canadian roads

Pavements exist and function within a transportation system that is responsible for over 25% of anthropogenic greenhouse gas emissions causing climate change (see Figure 1.1). The Government of Canada declared a goal to reduce GHG emissions by 30% below 2005 levels by 2030 at the Conference of the Parties (COP) 21 under the United Nations Framework Convention on Climate Change (UNFCCC) 2015 Paris Agreement (Government of Canada, 2017). This declaration put action on climate change atop the Federal Sustainable Development Strategy (Government of Canada, 2021).

Environment and Climate Change Canada developed the Canadian Environmental Sustainability Indicators (CESI) program (ECCC, 2019) to report on the current state of the environment and track progress of the Federal Sustainable Development Strategy. CESI provides data and indicators on air, climate, water, nature, and human influence. They track Canada's performance on key environmental sustainability issues such as air and water pollution, waste management, climate change and greenhouse gasses emissions, noise, natural resource protection and use, biodiversity and habitat loss, ecosystem and human health, pressures on water quality, air quality and biological resources.

The CESI program provides a framework to identify the main factors of focus for quantifying pavement environmental sustainability performance in Canada. However, the federal government in Canada typically legislates transboundary aspects and issues. The regulation of environmental protection largely falls to provinces and territories, each having its own legislation with respect to environmental factors of concern and priority. Moreover, highways and road networks in Canada generally fall within the purview of provincial/territorial jurisdictions. Exceptions include the highways through national parks and a portion of the Alaska Highway, which are managed by federal departments and agencies. Therefore, the planning, design, construction, operation, maintenance and financing of highways are the responsibilities of provincial/territorial governments within their jurisdiction (Government of Canada 2021).

Effective analytical inclusion of environmental impacts in pavement management decisions are thus highly dependent on (1) the values of the province or territory and its road authorities (2) how these values are prioritized and (3) the plan to operationalize those values and prioritize them. Environmental performance measures should be defined in response to the goals and objectives directly aligned with the broad institutional goals of the agency addressing sustainability of transportation systems in which pavements exist (Cornet, Gudmundsson, and Leleur 2016; Gudmundsson et al. 2016; Uddin, Hudson, and Haas 2013).

In Ontario, the Ministry of Transportation Ontario (MTO) has established its statement of environmental values (SEV) in response to the provincial environmental bill of right (EBR). The EBR is based on three principles: valuing the natural environment, the right to a healthy environment, and environmental protection. One of the MTO's SEV priorities is to integrate environmental concerns into decision making.

The MTO stated hierarchy of environmental protection, in order of decreasing preference, is: avoidance / prevention; control / mitigation; and compensation / enhancement. The Ministry has made efforts to establish to establish procedures for mitigating impacts on the environment. These documents include:

- Environmental Protection Requirements (EPRs): are a list of statements that provide a clear and organized list of environmental legislative and policy requirements. The EPRs are a synthesis of the requirements in over sixty statutes, supporting regulations and formal government policies applicable to environmental aspects of transportation projects. For example, each statement of the Environmental Protection Requirements for Transportation Planning and Highway Design, Construction, Operation and Maintenance (MTO, 2014) is an interpretation of these requirements as they apply to transportation planning and highway design, construction, operation and maintenance activities.

- MTO's Class EA document is an approved planning document that defines groups of projects and activities and the environmental assessment (EA) processes which MTO commits to following for each of these undertakings. The Environmental Assessment Act provides for the preparation at Class Environmental Assessments (Class EA). The Class EA is a principle-based document which defines the groups of projects, what must be achieved, and the processes that could be followed. Four main stages of focus in the Class EA process are planning, preliminary design, detail design and construction.

- The Environmental Standards and User Guides contain an overview of significant environmental impacts associated with transportation projects for each environmental factor. It contains design considerations in managing those impacts and list of applicable policies, guides, and references.

- Other documents include environmental references such as the Environmental Reference for Highway Design (ERD) and Environmental Guide for Fish and Fish Habitat, Noise, Wildlife and other factors. The ERD addresses environmental assessment issues relating to preliminary design and detailed design of transportation projects. The Environmental Guide documents environmental assessment and mitigation processes and technical details for individual environmental factors as may be applicable on a project-specific basis.

Under the Canadian Environmental Act, environmental factors are grouped into natural, social, economic, and cultural environment factors. In transportation projects, the environmental factors addressed depend on the project objective and study area conditions. Decisions on how the hierarchy of environmental factors is applied to specific provincial transportation projects and activities are made through the Ontario Environmental Assessment permits, approvals, and authorizations. This is reflected in the EPRs. According to the Environmental Protection Requirements for Transportation Planning and Highway Design, Construction, Operation and Maintenance, the following factors should be considered:

- Air quality impacts and greenhouse gas emissions

- Water resources (groundwater, surface water)
- Noise
- Species at risk
- Fish and fish habitat
- Terrestrial ecosystems (wildlife, wetland, and vegetation)
- Land use factors
- Contaminated property, waste and excess material management
- Built heritage and cultural heritage landscape
- Archaeological resources

3.3.2 Environmental Factors Sustainable Pavement Design and Management

Sustainability issues of a pavement system can often be understood by how each system component affects sustainability, and by which outcomes are most desirable given the priorities of the organization and other stakeholders responsible for design and management of the system (Van Dam et al. 2015). Engineering design and management of a pavement system influence interactions between the system unit processes of pavements and the environment. Pavement design refers to the process of identifying the structural and functional requirements of a pavement for given site conditions (subgrade, climate, existing pavement structure, traffic loadings) and then determining the pavement structural composition and accompanying materials. The design process is applied not only to new pavement designs but also to rehabilitation technologies used in maintenance and preservation treatments. Pavement sustainability is a context–sensitive characteristic of pavement, so, to define the most appropriate sustainability practices for a particular pavement system, a context-specific accounting of interactions between pavement lifecycle and the surrounding systems is required (Van Dam et al. 2015). Decisions made regarding pavement design influence interactions between the pavement lifecycle and the surrounding systems. The US Federal Highway Administration recently published a comprehensive report on sustainability goals for each phase of the pavement life cycle (FHWA, 2016). Table 3.1 provides examples of design or policy objectives, approaches that potentially improve sustainability over common status quo methods, and accompanying negative and positive environmental implications throughout the pavement lifecycle.

Table 3.1 Design policy to improve sustainability of pavement and the environmental focus areas affected (FHWA, 2016).

Design/Policy Objective	Sustainability Improving Approach	Positive Environmental Impact	Negative Environmental impact
Achieve longer life or same life for reduced thickness	• Use of higher quality materials and construction quality; • Use selected recycled materials to improve structural characteristics; • Improved construction specifications	• Reduced environmental effects of construction and materials use due to less frequent maintenance or reduced thickness • Increased pavement quality may decrease user emissions	• Increase environmental impact during material production
Maximize use of recycled and local materials	• Replace virgin materials with recycled pavement materials • Minimize transportation distances for materials	• Reduce use of scare materials •	• Recycled material may contain toxic substances that can affect nearby water body • May increase the need for resurfacing if material do not meet performance standard,
Minimize impact of utility construction	• Minimize utility cuts in pavements •	• Reduce impacts due to long pavement life • Less frequent maintenance and its impacts •	• Potential increased initial material and construction impacts of utility corridor •
Minimize impact of construction	• Use accelerated construction approaches	• Reduce effect of work zone traffic	• Possibility of shorter performance life may increase impacts
Achieve/ maintain pavement smoothness	• Consider smoothness over the pavement life as a key design parameter, especially for high traffic volume routes. Include construction specifications for smoothness, design features to maintain smoothness, and	• Reduced environmental impact due to less fuel use, particularly on high traffic volume routes	•

	costing of maintenance to keep surface smooth.		
Use pavement that reduce urban heat island and reduce lighting cost	• Engineer pavement to reduce heat island where is determined to be beneficial.	• Reduce energy use due to less required heating •	• increase impact of pavement layer thickness and material use for thermal characteristics
Use pavement to capture runoff pollutants and reduce hydraulic requirements form storm	• Use fully permeable pavement •	• Reduce pollutants in water and ground water recharge •	May required more materials , thicker layers than conventional shoulders

Pavement management operates on two levels (project-level and network-level management) and involves a coordinated set of activities related to the pavement lifecycle and good pavement engineering practices. Figure 3.2 shows a generic pavement management framework. It includes all the major activity classes in a pavement lifecycle (TAC, 2013). As discussed in Chapter 2 of this thesis, many reports and guides have been published by transportation agencies and associations, transportation associations in Canada and the USA have published some guidelines and protocols for sustainable pavement management. The Transportation Association of Canada Green Guide for Roads identifies twelve objectives to demonstrate environmental stewardship in transportation projects, while the American Association of State Highway and Transportation Officials (AASHTO) Centre for Environmental Excellence identified seven sustainability impact factor areas. The Ontario Road Builders Association published an environmental management practice guidance manual with a focus on several key road building and management activities that interact with the natural environment. The factors highlighted in these reports and other policy documents for considering environmental impacts of pavement design, construction and management are summarized in Table 3.2. They are sorted by Environmental Protection (EP) factors and Resource Management (RM) factors.

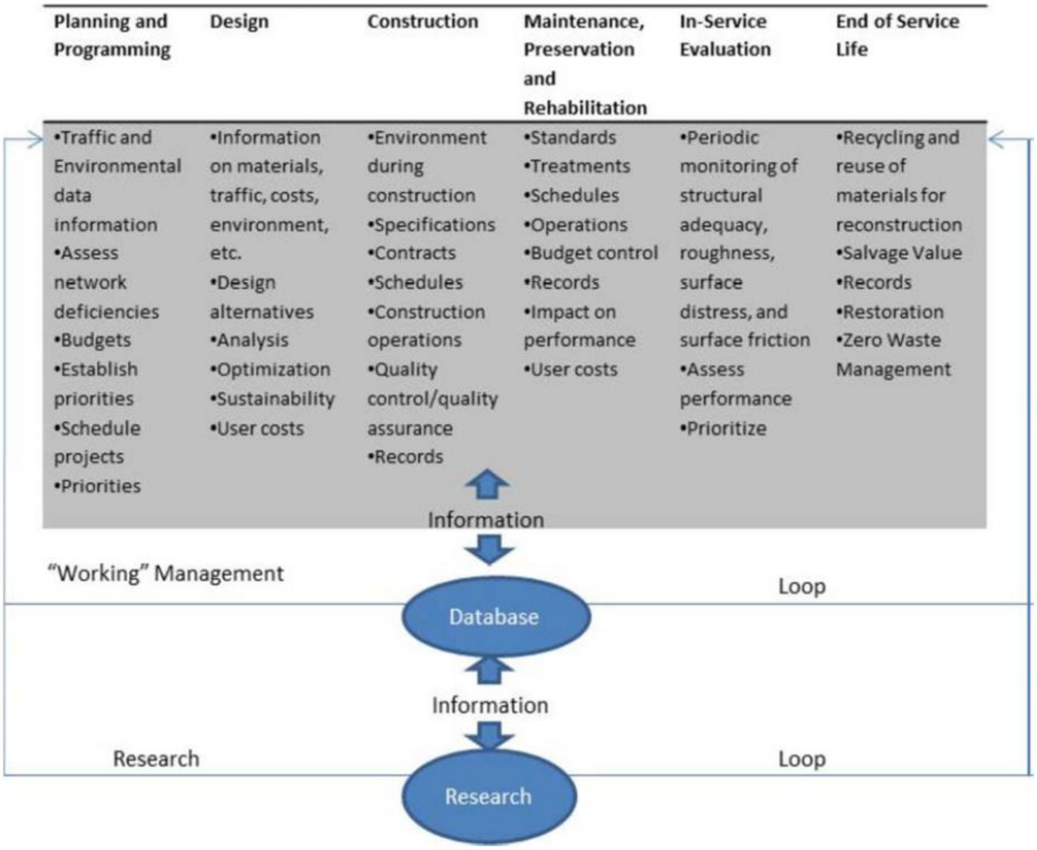

Figure 3.2 Pavement Lifecycle Management Activity Classes adopted from TAC 2013

3.3.2.1 Factors Considered in Evaluation of Pavement Sustainability

In practice, three approaches commonly used to assess the sustainability of pavement are lifecycle cost analysis (LCCA), life-cycle assessment (LCA) and the sustainability rating systems (SRS). The economic viability of pavement design and management alternatives is often assessed based on lifecycle cost analysis (LCCA). The procedure for LCCA is relatively consistent (TAC 2013) and is frequently used in decision making by most agencies (Van Dam et al. 2015).

LCA and SRS are used for environmental impact evaluation. Indicators for operational performance are varied. SRS tools are based on environmental certification models similar to the LEEDS certification, focusing on best practices. SRS indicators are presented as qualitative (text) information, as quantitative data, and as multiple choice options (including yes and no). The SRS appraisal process has several advantages and drawbacks. Compared to LCA, SRS tends to be simpler and easier to implement. However, the selected indicators are usually not based on actual performance. Some best practices can effectuate large changes in sustainability impact factors, while others result in very small changes. Further, their impacts may vary for pavement systems in different environments. The SRS models provide a simpler and thus more intuitive measure of the benefits of sustainable initiatives understandable to more stakeholders (Torres-Machi et al. 2014). Simpler indicators are more likely to be used (Sdoukopoulos et al. 2019). However, that simplicity requires more rigidity and offers less transparency. SRS tools rarely allow customization of the assessment criteria, and can be rigid when it comes to rating parameters. This means that rating frameworks are not generalizable to all projects. Recent efforts to address this challenge in the latest versions of SRS tools (for example, ENVISION) allow customization of rating systems to project types; however, the criteria remain prescriptive. Implications for the collective effects or interactions of multiple actions are also not presented. As an alternative to SRS, the Life Cycle Assessment (LCA) framework provides a guide to assess the environmental performance of the pavement lifecycle considering many environmental impact categories. Specifically, LCA environmental performance indicators identified in literature involve impact criteria building on the ISO 14040:2006 categories of environmental impact: Damage to natural environment; Damage to human health; and Resource Consumption.

In principle, LCA is a comprehensive environmental performance measurement approach. However, not all types of environmental effects and area of protections are equally well covered in practice. Pavement LCA tools to date have utilized limited scope and environmental performance indicators. Previous review studies describe limited comprehensiveness in terms of the life cycle phases and metrics included. In contrast to SRS, the LCA approach process is quite flexible at evaluating performance and provides a tracking structure for performance management. While there is a LCA framework that constitute the principles, guideline and requirements, procedure for conducting pavement LCA, these assessments vary from study to study depending on study goal and methodological choice adopted in each study. Available pavement LCA tools differ in the pavement lifecycle stages and environmental impacts considered, modelling approach and dataset used, depending on tool’s intended use, developer and capabilities. Table 3.2 shows the different impact factors that are assessed by available life cycle impact assessment methods. LCA models can provide more precise evaluations than the SRS models, where reliable data are available (RMRC, 2013). Given the intuitive nature of SRS, Torres-Machi et al. argue that, for a greater dissemination and understanding of the environmental evaluation, the use of SRS model is beneficial but should be supported with objective indicators obtained from LCA models (Toress-Machi et al). Bryce et al argue that a performance measurement approach should be adopted to evaluate the impacts of actions and improve outcomes by using evidence-based indicators to monitor and highlight accountability for sustainability performance.

Common Indicators in LCA:

- Global Warming Potential (GWP): Anthropogenic climate change is caused realising substances into the air that change the Earth's energy balance. The largest contributor to climate change since the Industrial Revolution has been the anthropogenic release of greenhouse gas emissions (IPCC 2021). Greenhouse gas emissions can be summed into a single indicator by weighting the mass of emissions of each substance by its Global Warming Potential. In climate science, the Global Warming Potential refers to how much energy the emissions of 1 ton of a gas will absorb over a given period of time (usually 100 years), relative to the instantaneous emissions of 1 ton of carbon dioxide (CO2). In the LCA literature, GWP refers to this sum, expressed in units of "CO2 equivalent", a unit written as CO2eq or CO2e. Some studies have noted the drawbacks of GWP in representing the timescales of impacts of different technologies on the climate system, recommending time-adjusted indices (Kendall (2012), (Edwards and Trancik 2014)).
- Ozone Depletion Potential: Similar to the GWP, the effect of emissions of ozone-depleting substances (ODS) on the ozone layer can be summed into an equivalent unit of one ODS, CFC-11. Thus, Ozone Depletion Potential is expressed in the mass of CFC-11 equivalent emissions released per functional unit of the product. This is a measurement for the impact caused by thinning ozone layer, which has the function of absorbing harmful ultraviolet radiation before it can reach the surface. Emissions of ODS can result in the catalytic destruction of ozone molecules in the ozone layer. The resulting increase in ultraviolet light at the surface is associated with increased incidence of skin erythema and skin cancer (WMO (World Meteorological Organization) 2018).
- Eutrophication Potential (EP): Eutrophication means the addition of mineral nutrients to the soil or water. In excess amounts, nitrogen or phosphorous results in increased biological oxygen demand (BOD) in water. Eutrophication reduces ecological diversity by creating undesirable shifts in a number of species inside a specific ecosystem. The unit of measurement is grams of nitrogen per functional unit of a product.

- Fossil Fuel Depletion: The impact of non-renewable energy is measured in mega joules (MJ) of fossil-based energy per functional unit of the product. This impact addresses the depletion of fossil fuels but excludes the extraction impacts. This category is helpful in demonstrating positive environmental goals, e.g. reduction in the energy demand in production of a certain product, or producing a product with energy coming from a renewable energy source.
- Acidification Potential (AP): The two main compounds involved in acidification are sulfur and nitrogen compounds. They reach the soil and water mainly by dissolution in water in the atmosphere. The unit of measurement for AP is grams of hydrogen ions per functional unit of product.

A summary is provided in Table 3.3.

Table 3.2 Impact categories and mid-point indicators of LCIA methods

Impact Category	LCIA Methods Midpoint Indicators					Footprint Indicators
	TRACI	CML	Recipe	ILDC	IMPACT +	
Climate Change	✓	✓	✓	✓	✓	✓
Ozone depletion /Ionizing radiation	✓	✓	✓	✓	✓	
Respiratory inorganics		✓	✓		✓	
Respiratory organics						
Human toxicity		✓	✓	✓	✓	
Acidification	✓	✓	✓	✓	✓	
Eutrophication	✓	✓	✓	✓	✓	
Marine Eutrophication			✓		✓	
Freshwater Eutrophication			✓		✓	
Ecological toxicity	✓	✓	✓	✓	✓	
Terrestrial Ecotoxicity					✓	
Marine Ecotoxicity			✓			
Freshwater Ecotoxicity					✓	
Land Use						
Agricultural land occupation						
Urban Land occupation						
Natural Land transformation						

Water Use		✓	✓		✓	✓
Water Depletion						
Resources Use	✓	✓	✓	✓	✓	
Mineral resource depletion		✓			✓	
Fossil resources depletion	✓	✓	✓	✓	✓	
Abiotic resource depletion			✓		✓	✓

LCA has been applied to integrate environmental sustainability assessment into existing asset management practices across multiple studies (Cristina Torres-Machi et al. 2017; Torres-Machí et al. 2015; Santos, Flintsch, and Ferreira 2017; Lidicker et al. 2013; Wang et al. 2012; Pellecuer, Assaf, and St-jacques 2015; Loijos, Santero, and Ochsendorf 2013; Wang, Harvey, and Kendall 2014; Reger, Madanat, and Horvath 2014; 2015; Van Dam et al. 2015). Zhang et al 2013 Santos et al 2015 Gosse et al 2013 Torres-machi et al 2017 Filzar Nasir 2018 Cirilovic et al 2019 Jiang et al 2012 (Louhghalam, Akbarian, and Ulm 2015) (Loijos, Santero, and Ochsendorf 2013; Trupia et al. 2017). Many focus on a few environmental impact factors, defining objectives such as minimizing GHG emission or reducing energy consumption, in order to develop models for optimizing and prioritizing pavement maintenance and rehabilitation policies.

The value of indicator systems, like the LCA framework, should be considered in terms of their intended use. When the intended use is for accounting, reporting, or performance improvement, then a system of quantitative indicators may be both necessary and sufficient. For management, indicators may need to be explicitly pegged to policy objectives, e.g. concentration limits or capacity limits. For decision support, indicators may feed into various decision processes (C. Torres-Machi et al. 2019). One method for doing this is to develop a single index. The challenge is to weight the values of different indicators into a single representative quantity. Guidelines have been developed for the creation of robust indices for sustainable transportation (Zheng et al. 2013; Sdoukopoulos et al. 2019).

One method for weighting indicators derives from economic theory. Preferences across indicators are assessed based on the economic value of associated outcomes. Valuing non-market goods such as well-being or environmental quality is a particular challenge, but multiple methods relying on real or hypothetical markets have been established (U.S. Environmental Protection Agency 2014). Results from such techniques are routinely incorporated in the evaluation of policies affecting the environment, health and safety (Viscusi, Harrington, Jr., and Sappington 2018). When available, estimates of the marginal economic damage, e.g., the economic impact of one additional unit, can be applied to estimate social costs associated with pavement-related activities.

Marginal damage estimates have been applied to internalize the costs of vehicular impacts to air and noise pollution since the 1990s (Demir, Bektaş, and Laporte 2014). Some early examples examined the social cost of noise emitted from motor vehicles (Delucchi, M., & Hsu, S.-L. ,1998), or included noise and emissions along with other social costs of transportation (Levinson and Gillen 1998). Studies of the external cost of transportation are now myriad, codified in handbooks (van Essen 2019) and described in reviews (Merchan et al. 2019; Mostert and Limbourg 2016). Recent studies of sustainable pavement management have applied these approaches to develop indices for comparing pavement management approaches or optimizing pavement systems (Zhang et al. 2010; Chan 2007; Yu, Lu, and Xu 2013; Matthews H. Scott, Hendrickson Chris, and Horvath Arpad 2001; C. Torres-Machi et al. 2019; Achebe et al. 2021)

3.3.2.2 Applications in Canadian Provinces and Territories

In Ontario, the MTO developed its own pavement sustainability rating tool – GreenPave (Kazmierowski and Navarra 2014). Like other available sustainability rating tools, GreenPave is valuable as it encourages incorporation of environmental sustainability principles into infrastructure projects and suggests best practices on sustainability improvements such as use of recycled material.

GreenPave is 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).

Provincial road authorities in Alberta, British Columbia, Manitoba, and Quebec report some experience incorporating environmental impacts into pavement management (Achebe, Saari, and Tighe 2021). British Columbia and Quebec use multiple account or multi-criteria analysis. Manitoba has used some LCA tools, but none were identified as formally adopted. Although a research project sponsored by the Ministry of Transportation Quebec developed a Pavement Environmental Impact Model that account for the environmental cost of pavement use phase, it is not certain if this has been adopted by the agency . Alberta formally includes emissions costs of vehicles in its Benefit Cost Model. The model estimates emission costs for six pollutants based on vehicle-fuel consumption using data from the California Life-Cycle Benefit/Cost Analysis Model (Moges et al. 2017). The emission costs of the six pollutants for a passenger car range from $96.50 to $244,000 per tonne.

3.4 Framework for Pavement Environmental Sustainability Evaluation

3.4.1 Integrating Environmental Sustainability: Evaluation Framework and Key Factors

Sustainability of a pavement system can be understood by how each system component affects sustainability and which outcomes are most desirable given the priorities of the organization (FHWA, 2015). For effective analytical inclusion of environmental sustainability in pavement management decisions, an evaluation framework comprising a set of environmental indicators is proposed. Indicators were sought that met the selection criteria discussed above. Since these criteria emphasize the context, values, purpose, and influence of the intended user, the specific case of pavement managers in Ontario is used to illustrate and operationalize the framework.

To further identify consistent, comprehensive and relevant indicators, selection was based on the effects of the pavement system on sustainability components, and the outcomes that are most desirable give the priorities of road management organizations in Ontario. As shown in Figure 3.3, eleven focus areas were identified as priority of environmental sustainability for pavement designs and management decision in Ontario.

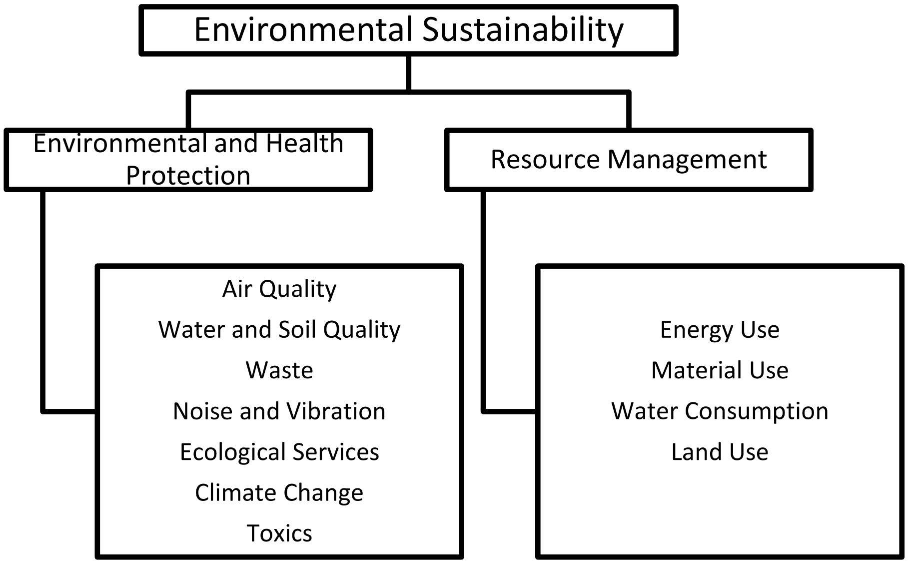

Figure 3.3 Focus Areas for Environmental Sustainability Evaluation

Two main domains of ES are shown in Figure 3.3 are defined based on the concepts and the ES principles of the output rule, the input rule, and the operational principles discussed in section 3.2. Figure 3.3 shows the main environmental focus areas under environmental protection and resource management. From the ecological economics perspective, environmental protection deals with activities that affect ecosystem and the services they produce as well as the protection of the natural sinks and maintaining acceptable conditions. The resource management domain deals with use of renewable and non-renewable resources while ensuring their availability and accessibility for future generations. The ES evaluation framework presented here can help transportation agencies apply sustainability concepts in six core activity classes of pavement management (Figure 2.1) in the life cycle of a pavement asset.

3.4.2 Operationalizing ES: Key Pavement Environmental Performance Evaluation

Apart from relevance, what is decisive for information provision, is methodology. Methodology has general important for empirical work, so disregarding the methodological frame may cause serious errors. Andrew et al 1998 suggest that indicator construction has to cope with conflicting goals of statistical measurability, scientific consistency and policy relevance. For policy relevance we have identified the focus areas that should be guide building of indicator/index for environmental sustainability evaluation of pavement management activities. To address statistical measurability and scientific consistency, each indicator to express each focus areas is selected based on published academic literature and reports. Secondly, the quantification approach and the source is highlighted to bolster the statistical measurability of the indicators.

For several factors, measurability is offered through both output-based and outcome-based indicators. Output-based measures can be applied in a multi-criteria decision-making process if decision-maker preferences are known (Torres-Machi et al., 2019). Since these preferences may not be available, we also provide outcome-based measures based on economic valuation, such as dollars of benefits (or costs), as these offer a fungible unit for directly comparing environmental impacts across indicators. Where possible, (e.g., for climate change damages), we provide long-run marginal costs, as these can account for additional infrastructure. However, there are fewer outcome-based measures available, covering fewer ES components. Further, they represent the context and preferences in which they were derived, which will typically differ from the context and preferences of our case example.

3.4.2.1 Environmental Protection Factors:

There are seven focus areas in this domain. The relevant indicators are discussed below. For each instance possible, measurement approaches for evaluating each factor are provided by pavement lifecycle phase. Where indicators lend themselves to relatively straightforward measures relevant to the case of Ontario, these are provided in supplementary tables. A summary of these are provided in Table 3.3, Table 3.4 and Table 3.5, sorted as input-based, output-based and outcome-based indicators, respectively.

Table 3.3 Input-based Indicators

Issue	**Indicator**	**Measurement Method**	**Reference(s)**
Water Consumption	Mass of Water	Water consumption factors from inputs to pavement	**(Horvath 2007)**

Table 3.4 Output-based Indicators

Issue(s)	Indicator(s)	Measurement Method	Reference(s)
Noise	Noise level	Noise levels associated with activities compared to WHO threshold levels.	(“Pavement Noise” n.d.), (Maryland Department of Transportation: State Highway Administration n.d.), (Toronto Public Health 2017),
Air Pollution, Climate Change, and Toxics	Mass emitted of Air pollutants, GHGs, Dusts, Mercury, and Lead	Emission factors associated with activities from pavement construction and road travel	(Horvath 2007; Nasir 2018; Wang 2018)
Solid waste/ hazardous waste generation	RCRA hazardous waste	Waste generation from pavement construction and De-icing Salt Usage based on pavement length	(US EPA 2019), (MTO 2018)

Table 3.5 Outcome-based Indicators

Issue	Indicator	Measurement Method	Reference
Noise	Social cost of noise	Health Costs associated with activities for road and air	(van Essen 2019)
Air Pollution and Climate Change	Social cost of emissions affecting air quality and climate change	Marginal damages related to increased health risks from exposure to air pollutants, and marginal damages related to climate change	(Fann, Baker, and Fulcher 2012),(Muller, Mendelsohn, and Nordhaus 2011), (Jaramillo and Muller 2016), (Shindell 2015),(Heo, Adams, and Gao 2016a),(Heo, Adams, and Gao 2016b), (Pappin and Hakami 2013), (van Essen 2019),

			(Greenstone, Kopits, and Wolverton 2013)
Habitat Damage	Social Cost Associated with Habitat Damage	Costs for habitat damage, loss and fragmentation: • For every km or km^2 of natural habitat used • For air, and on-road travel activities (passenger and vehicle km travelled)	(van Essen 2019)

1. Air Quality:

Air pollution contributes more to premature death worldwide than any other environmental risk factor (Cohen et al., 2017). A variety of air pollutants are commonly regulated to protect human health and the environment. In Canada, these air pollutants are termed “criteria air contaminants”, and include: sulphur oxides (SOx), volatile organic compounds (VOCs), carbon monoxide (CO), ground level ozone (O3), nitrogen oxides (NOx), particulate matter (PM), and ammonia (NH3). The presence and interaction of these substances give rise to air quality issues such as smog and acid rain (MTO, 2020).

The output-level indicator for air pollutants is based on the mass of atmospheric emissions. Pavement leads to the emissions of air pollutants throughout its lifecycle. Project-level analysis of can take advantage of existing tools for estimating emissions (e.g., PaLATE 2.0 (Horvath 2007), Athena Pavement LCA (Athena Sustainable Materials Institute 2018)), including examples adapted for Ontario (Nasir 2018; Min 2020; C. Torres-Machi et al. 2019; Achebe et al. 2021). For a more high-level analysis, we include emissions factors associated with raw material use relevant in pavements, noting that most life-cycle studies of pavements (excluding the use phase) find that materials contribute the most emissions (see Supplemental Tables in Appendix A).

The use phase of the pavement lifecycle can produce the most emissions, but it is also the phase over which pavement managers have the least influence. For this phase, there are several detailed emissions simulators can be used to estimate pollutant emissions from on-road vehicles, with a helpful review provide in (Demir, Bektaş, and Laporte 2014). Emission rates vary depending on the vehicle technology, fuel type and properties, weather, road type and condition, and speed, among other factors (Demir, Bektaş, and Laporte 2014). For simplicity, we provide emission factors specific to on-road vehicles in Ontario for broad source types using the main fuel types at average conditions for multiple speeds (see, with details in (W. Wang et al. 2020; U. Mukherjee et al. 2020)).

Air pollutant emissions are associated with various outcomes affecting the health and wellbeing of humans, wildlife and ecosystems. Once emissions have been estimated, outcome-based indicators can be derived using impact-pathway or reduced-form approaches (Gilmore et al. 2019). Outcome-based indicators based on economic damages of emissions are provided in Supplemental Table in Appendix A. These economic damage estimates are based on a review of the recent literature and apply four reduced-complexity models to the case of pavements in Ontario.

2. Water and Soil Quality:

The pavement lifecycle can affect water quality, including, for example, the quality and quantity of runoff from the pavement surface affects the fate of nearby aquifer. The toxic pollutants may change the quality of the water body and damage the ecosystem of the fauna dependant on that water body. Moreover, the runoff from pavement surface is usually warmer than the exposed water bodies, e.g. a nearby river, so the warmer water may make the river too warm for the survival of fishes in the river.

Output-based measures of water quality are myriad, but largely revolve around physical, chemical, and biological properties of water. They can include effluent concentrations of relevant characteristics, such as dissolved oxygen, pH, electric conductivity, total suspended solids, turbidity, and other relevant chemical and biological indicators (Sañudo-Fontaneda et al. 2014). Acidity, as measured by pH, is relevant for acidification, which can make water unsuitable for fish and other biota. Other indicators, such as concentrations of nitrogen and phosphorus, are relevant to eutrophication.

Freshwater and marine eutrophication depend on amounts released into a relevant waterbody, as well as its chemical background (Payen and Ledgard 2017). Outcome-based indicators therefore rely on understanding the emissions to water, their fate, and ecosystem exposure to nutrient enrichment (Payen and Ledgard 2017). Once the eutrophication impact is known, economic indicators can be developed, for example, based on the cost of chemicals used to restore the ecosystem (Yao et al. 2021).

3. Waste Management:

Pavements can generate solid and liquid wastes that require treatment and disposal. In the pavement lifecycle, the amount and properties of solid and liquid waste can be addressed through reduction, substitution and reuse at the source. These efforts are captured in resource management indicators described separately below.

Treatment and disposal can further be avoided through recycling / composting and energy recovery (https://www.epa.gov/smm/sustainable-materials-management-non-hazardous-materials-and-waste-management-hierarchy). At different scales of governance, solid waste indicators have been applied to transportation sustainability that include, for example, number or mass of vehicular waste, fuel leaks, per capita waste generation and recycling rates (Jeon and Amekudzi 2005).

For sub-national pavement managers, indicators for solid waste management that reflect their influence can include total or relative measures of material recycling / composting, and total waste transported and disposed (including hazardous waste). The supplementary tables include indicators based on the mass of hazardous waste produced by the consumption of raw materials used in pavements. Hazardous materials are as defined in the U.S. Resource Conservation and Recovery Act (RCRA) (https://www.epa.gov/rcra).

4. Noise and Vibration:

The pavement lifecycle has multiple impacts on noise and vibration. The processes of pavement construction, maintenance, use, and disposal all produce increased noise levels. Elevated noise levels can cause hearing loss, stress responses and cardiovascular outcomes in humans and wildlife (Wolfe, Kramer, and Barrett 2017) (WWF Canada 2017).

Measuring the impacts of noise can be achieved through an output-based indicator of noise levels, or an outcome-based indicator using the environmental cost of noise. Output noise levels can be expressed in the A-weighted scale with units of dBA. The unit (dBA) represents the loudness of sounds in air as heard by the human ear. The acoustic literature generally measures sound/noise levels as the total sound energy over a given period of time. As such, there exist several indicators that can be used to represent sound levels, for example:

- LEq, or LAeq,T: The equivalent continuous sound level over specified time period, T.
- Ldn: Average equivalent sound level over a 24 hour period with a noise penalty of 10 dB added for the hours of 22:00 – 7:00, in order to reflect the effect of the noise.

- Lden or CNEL: The day evening night sound level or the community noise equivalent level over a 24 hour period with penalties of 5 dB and 10 dB added for hours between 19:00 – 22:00 and 22:00 – 7:00, respectively.

According to the U.S. Environmental Protection Agency (US EPA), the threshold to protect hearing is 70 dbA. This threshold holds true for an exposure time period of 24 hours a day over 40 years and is termed as the equivalent continuous sound level over a 24 hour period (Leq, 24).

To support measurement of this indicator, the supplementary material includes some data on the noise output levels associated with on-road transportation by different sources and different traffic volumes. Noise thresholds associated with various health effects, along with World Health Organization noise guidelines are provided. Once noise levels have been determined, an outcome-based indicator based on the social cost of noise can be calculated. Estimates of these costs at different noise levels are provided in the supplementary material.

5. Ecosystem Services:

The pavement lifecycle can have numerous impacts on ecosystem services. Pavements cover land, increasing impervious coverage, and introduce pollution. This can degrade the environmental quality of ecosystems, potentially affecting habitats, biodiversity, and the indigenous way of life (e.g. hunting, gathering, traditional land use practices etc.).

Given Canada’s northern climate, one particular concern in affecting ecosystem services is de-icing. Paved roads in the winter require de-icing. Substantial de-icing salt use is needed in Canada, as demonstrated by a case study of a path of highway running between Sudbury and North Bay, Ontario (MTO 2018). De-icing salts for roads contain chloride ions that can be soaked up by the soil and eventually leach into nearby lakes and groundwater (CBC News · Posted: & January 18, 2019); (US EPA, 1999). Accumulated chloride ions impact wildlife behavioral pattern and lead to habitat fragmentation (e.g. fish not breeding in lakes close to roads). Due to the complex nature of the chemical leaching phenomena, it is difficult to present a simple factor that relates chloride content in the soil with the amount of de-icing salt used.

Habitat fragmentation and loss caused by pavements can alter wildlife behavioural patterns and threaten biodiversity. Impacts can last throughout the pavement lifecycle and thereby negatively impact wildlife and endanger them (e.g., via wildlife collision on highways built through sensitive ecosystems) (van Essen 2019).

The factors that influence habitat loss can include the length of roads built and the area dedicated to new infrastructure. The handbook on the external costs of transport developed by the European Union provides costs pertaining to habitat loss and habitat fragmentation for roads. Supplemental Table in Appendix A lists the habitat loss costs in terms of dollar per km or square km of road infrastructure developed in a year. Supplemental Table in Appendix A presents another way of calculating habitat damage costs based on the passenger km travel or vehicle type km travel.

6. Climate Change:

The output-based indicator for climate change is GWP expressed in in units of "CO2 equivalent", a unit written as CO2eq or CO2e. Measurement methods provided for GWP throughout the pavement lifecycle are the same as those developed for air pollutant emissions and included in those supplementary tables. Similarly, the outcome-based indicator is based on the economic damages associated with increasing GWP. Recommended and alternative options for measuring this outcome are included in the supplementary tables and associated discussion.

In addition to the supplementary data provided, numerous tools are available to estimate GWP associated with pavement (e.g., PaLATE 2.0 (Horvath 2007), PaLATE 2.2 (University of Washington 2011, 2), GreenDOT (Gallivan et al., 2010), FWHA's Infrastructure Carbon Estimator (Gallivan et al., 2014), ROADEO (The World Bank 2011), Highways England Carbon Tool (Highways England 2015), GasCAP (Noland and Hanson 2014), PE-2 (A. Mukherjee 2013), and Athena Pavement LCA (Athena Sustainable Materials Institute 2018). Others address pavement use, including FHWA CMAQ Toolkit (Federal Highway Administration (FHWA) Office of Natural Environment 2020), U.S EPA MOVES (US EPA 2014), GREET (Argonne National Laboratory 2019) and GHGenius (Squared Consultants Inc. 2019). In addition to releasing emissions that increase GWP, pavement and related activities can also serve as carbon sinks, including via the planting of trees (USDA Forest Service, Pacific Southwest Research Station, and Urban Ecosystems and Processes Team, n.d.) or shrubbery (Liu et al., 2014), and carbonation of concrete pavements (Yu and Lu 2012; Santero and Horvath 2009). Not captured in GWP-based indicators based on CO2e are changes in land surface albedo caused by pavement surfaces. One study relating this to GWP found it decreased CO2e by 9% for Portland cement concrete pavement and increased it by 19% for hot mix asphalt pavement (Yu and Lu 2014).

7. Toxins:

There are a wide variety of substances that are regulated for their toxic effects to humans, wildlife, and ecosystems that pavements can release throughout their lifecycle. An output-based indicator is the mass of toxics released into the environment. Output-based indicators for two pervasive and harmful toxics, lead and mercury, are provided in the supplementary tables based on the same methods described for air pollutants.

Tracing the outcomes associated with toxics is complicated. Simple indicators are not available. The link between toxic releases and their effects are complicated by, for example, complex biogeochemical cycles, multiple exposures routes, considerable time lags, and significant parametric uncertainty (Wolfe et al. 2016; Giang and Selin 2016; Thackray et al. 2015).

3.4.2.2 Resource Management Factors

Research on sustainable natural resource use has broadened from traditional financially valuable natural assets (e.g., minerals, fossil resources, forests, fisheries) to include all nature-based stocks from which people draw goods, services, or well-being (Clark and Harley 2020). Criteria for assessing whether natural resource management is sustainable varies depending on the worldview or practice of the wide variety of research programs that address it (e.g., ecosystem services/natural capital, industrial ecology/social metabolism/circular economy, livelihoods, sustainable consumption-production, socio-ecological systems, and others from (Clark and Harley 2020)). Further, pavement managers will have to consider their requirements and influence for resource management within relevant environmental legislations, policies, objectives and practice guidelines.

Here, we focus on indicators and measures that relate explicitly to natural resource use that appear most relevant to the pavement lifecycle. The environmental impacts of resource use, such as greenhouse gas emissions associated with fossil energy use, were intended to be captured in the environmental protection factors and are not duplicated here.

1. Energy

Energy is a rich and complicated resource with significant implications for sustainability (Chu and Majumdar 2012; Chu, Cui, and Liu 2017). The use of energy appears as a common theme in environmental indicators for sustainable transportation. Total and relative measures of energy consumption (e.g., total energy consumption (Joules), per capita or per GDP; energy intensity of materials or processes (e.g., Joules/kg)) and energy conversation (energy efficiency; fuel loss, leaks or spills) are commonly included indicators (Sdoukopoulos et al. 2019; Jeon and Amekudzi 2005). Relevant data on the energy consumption of materials and processes associated with the pavement lifecycle are available from various sources. One example is provided in the Supplementary Tables.

Energy use, by itself, however, is not unsustainable. The environmental sustainability of energy use from a resource management perspective depends, among other factors, on the energy source. In particular, the depletion of non-renewable resources is typically distinguished from renewable sources using indicators for total or relative fossil energy consumption (by share of energy use, energy content, mass, or volume), and renewable energy consumption (Sdoukopoulos et al. 2019; Jeon and Amekudzi 2005). Other indicators include non-fossil or alternative energy consumption, though some non-fossil energy consumes non-renewable resources and may have its own resource management considerations. For example, the Ontario electricity mix is over 93% non-fossil based, though 57% derives from non-renewable nuclear energy (Ontario Energy Board 2021; Gralla et al. 2016).

2. Materials

The production, processing, and use of raw materials can deplete or inhibit equitable access to renewable and non-renewable stocks. Sustainable use of materials involves many factors that will be outside the influence of pavement materials. Resource management and distribution policy will largely fall outside of their purview. However, the quantity of virgin materials consumed, including renewable (e.g., timber) and non-renewable (e.g., mineral, fossil (as an input, e.g. bitumen as an asphalt binder, not for energy) materials can be both tracked an influenced with less material-intensive designs and the use of recycled materials.

3. Water

Although water is a key issue of sustainable development, water use appears to be rarely reflected in sustainable transportation indicators (Sdoukopoulos et al. 2019). Here, we include it because the pavement life cycle is known to consume water. We provide data associated with water usage in the production of pavement materials in the Supplementary tables. We note that such total measures of water usage would ideally be linked to relevant metrics of water resource availability.

4. Land

As mentioned, pavements cover land and affects its properties. It is challenging to develop indictors reflecting the effect of pavement on land distinct from its role in ecosystem services, though land consumption itself is an identified theme separate from habitat loss. Land consumption (by surface area) is thus one potential metric. Other metrics used in transportation sustainability initiatives should be carefully separated from ecosystem services (e.g., ecological footprint, number of contaminated sites undergoing remediation or risk management, percentage of strictly protected area (m2 or percent of ecozone), reduction in number of bare-soil days on agricultural land, and impervious surfaces).

3.5 Discussion and Conclusion

This work presents an environmental sustainability framework, set of indicators and associated measures for the context of pavement management in the case of Ontario. Measuring environmental sustainability can allow pavement managers to improve accountability in the responsible use of ecosystems and resources and monitor their performance on environmental issues. This framework includes seven factors addressing environmental protection, and four reflecting natural resource management. A variety of input-based, output-based, and outcome-based indicators are provided for each factor. Where relatively simple measures are available, they are included in supplementary tables. Measures are provided for indicators including noise, air quality, waste, noise, habitat loss, toxics, and resource consumption (energy and water). Our list attempts to follow advice on selection of environmental indicators, aiming to be comprehensive, consistent, and measurable. Using the case of Ontario, it aims to be context-specific, and informed by values, influence and purpose of pavement managers. This framework and its implementation can inform the development of broader and purpose-built sustainability assessment methods for pavement management.

This work is situated in a rich body of literature on developing frameworks and indicators for sustainable transportation and sustainable civil infrastructure (Sdoukolpoulos et al., 2019; Zheng, J., Garrick, N.W., Atkinson-Palombo, C., McCahill, C., Marshall, W. 2013; Vassallo, J.M., Bueno, P.C. 2021; Jeon et al., 2005; Amekudzi et al., 2010; Oltean-Bumbrava et al., 2014). It contributes by developing a new top-down framework and indicators specific to environmental sustainability of pavement management in Ontario. Measures associated with air quality, climate change, and toxics, in particular, involve new applications and analysis of emissions and damages models for Ontario pavements.

Previous reviews of sustainable transportation initiatives, of which pavement management is one component, identified 2644 indicators across social, economic, and environmental pillars (Sdoukopoulos et al. 2019; Jeon and Amekudzi 2005). These indicators can be grouped into relevant factors. Our factors appear to encompass those environmental factors identified elsewhere (Sdoukopoulos et al. 2019; Jeon and Amekudzi 2005; Zheng et al. 2013), with indicators and associated measures specific for the pavement lifecycle specific to Ontario pavement managers.

The aim was to select indicators that were consistent, comprehensive, measurable, multiple challenges introduced limitations. Consistent indicators should comprise a unique set without overlap. This can be challenging given the clear interactions between factors of environmental protection and resource management. For example, fossil fuels are a material input to pavements, to energy, contribute to climate change, and can result in spills that degrade environmental quality, release toxins, and harm ecosystems. Another important interaction for pavements under a changing climate involves the relationship between mitigation, adaptation, and resilience, with design of pavements for resilience to climate risk presenting potential feedbacks and trade-offs with increasing climate change (Achebe et al. 2021).

The aim of this work was to be as comprehensive as possible, but some factors were excluded. For example, stratospheric ozone depletion was not included because the effects of pavement on ozone depletion appear small (with CFC-11eq emissions several orders of magnitude smaller than other impacts in pavement LCA studies (Grael et al. 2021; Alam et al. 2020)).

The work has been directed at providing relevant context-specific, measurable indicators, which includes relevant data for only a subset of these, and it does not reflect the considerable uncertainty associated therewith (Gilmore et al. 2019; W. Wang et al. 2020). We used Ontario-specific data or aimed to convert it to reflect Ontario conditions. However, the measurement methods for several indicators come from other contexts, especially Europe or the U.S. Output-based indicators will be affected by differences in activities, environments, and their effects on components of ES. Outcome-based indicators will also be affected by differences in characteristics and values of affected populations or receptors. Nonetheless, it is common practice by the Government of Canada and its ministries to adopt measures from other contexts when local data are lacking (Treasury Board of Canada 2007).

This work was meant to be informed by the values and needs of pavement managers in Ontario. It was based on literature, reports, and informal discussions. However, improvements could be proposed. Firstly, using the ISO 14301 framing, the indicators focus more on operations (inputs and outputs) than management (e.g., policy, planning, training). Including such indicators would help for application to a broader array of stakeholders. Secondly, stakeholders should be consulted directly. Pavement managers represent a non-homogenous group with many objectives, values, and levels of influence. This group could include contractors, consultants, pavement mangers and road owners. Future study can couple this top-down process with bottom-up involvement of stakeholders (Oltean-Dumbrava, Watts, and Miah 2014). This would aid in assessing the generalizability and/or adoptability of indicators by road infrastructure managers across Ontario and/or Canada, implementation readiness of these indicators, and their data needs. Validation could be performed by interviewing the different groups of stakeholders who have the potential to influence the environmental performance of pavement.

The framework draws on literature for sustainability assessment frameworks, particularly those relevant to transportation (Sdoukopoulos et al. 2019; Jeon and Amekudzi 2005; Zheng et al. 2013; Pei et al. 2010; Oltean-Dumbrava, Watts, and Miah 2014), as well as the guidelines and practices of transportation agencies, with a focus on Ontario (Achebe, Saari, and Tighe 2021). However, there is useful guidance in this literature, and in the broader sustainability literature, that our framework does not capture. Our framework consists of a list of environmental indicators and potential measures. Environmental indicators alone do not encompass the more modern, broader vision of sustainability as fairness, enhancing well-being across generations (Clark and Harley 2020). Further, they do not account for interactions and feedbacks that occur within Earth's dynamic human-natural system that will affect pavements and their sustainability. Supporting sustainable pavement management more broadly would involve capturing these relevant factors and relationships. Transportation-focused literature in particular points to properties of both frameworks and indicators that future work could enhance. These include, for example, expanding beyond environmental sustainability, capturing interactions among indicators, including long-term effects, and relating indicating indicators to the goals, influence, and interactions of actors within a pavement management organization and across its stakeholders (Sdoukopoulos et al. 2019; Jeon and Amekudzi 2005; Zheng et al. 2013; Pei et al. 2010; Oltean-Dumbrava, Watts, and Miah 2014). Such additional effort could enhance the value of the factors and data contained herein, which offer one approach based on recent science to evaluate environmental sustainability of pavements across their lifecycle within the Ontario context.

Chapter 4

GHG Mitigation Strategies during Highway Design, Construction and Maintenance (HIIFP, 2018)

This chapter is part of the Ministry of Transportation Ontario (MTO) Highway Infrastructure Innovation Funding Program (HIIFP) 2018 Topic 1 project completed by CPATT under the title: "Greenhouse Gas Mitigation in Highway Design, Construction and Maintenance - Jurisdictional Scan". The final report has been submitted and accepted by MTO. For reference: "Achebe J., Saari R. K. Tighe S. L., (2021). Greenhouse Gas Mitigation in Highway Design, Construction and Maintenance - Jurisdictional Scan. Final Report, HIIFP Project #2018-02"

4.1 Introduction

Climate change impacts are becoming evident in Canada and globally. Impacts such as thawing permafrost, increased heat waves, droughts, flooding, storms, and more intense wildfires pose significant risks to critical infrastructure, food and water security, economic growth and human wellbeing. The science is clear that one of the main drivers of the unprecedented changes in Earth's climate is anthropogenic greenhouse gas (GHG) emissions.

Responding to climate change requires action to mitigate anthropogenic GHG emissions and increase climate-resiliency of assets and operations. GHG mitigation is a human intervention to reduce the sources or enhance the sinks of GHGs [IPCC, 2014]. Carbon dioxide (CO_2) is the most important long-lived GHG. GHG emissions can be reduced, for example, through improved energy efficiency and switching to low-carbon or non-carbon energy sources. GHG mitigation is a top priority nationally in Canada, and the government has committed to reduce GHG emission 30% below 1995 levels by 2030. This commitment is established under the Paris Agreement on climate change and in the Pan-Canadian Framework on Clean Growth and Climate Change (Anon n.d.). In Ontario, the government committed to reducing greenhouse gas emissions to 80% below 1990 levels by 2050, and to build a prosperous low-carbon economy. In 2016, Ontario government released a Five Year Climate Change Action Plan, and in 2018, the Made-in-Ontario environment plan was released. The plan identifies specific areas of focus to reduce greenhouse gas emissions such as: ensuring accountability of emissions; investing in technology-based and other solutions to reduce emissions in Ontario; and adjustments to facilities, operations, and traditional procurement to account for low carbon emission opportunities.

The transportation sector accounts for 35% of GHG emissions in Ontario (MOECC 2015). Ontario spends millions of dollars each year on capital and rehabilitation highway construction and maintenance projects across the province. Incorporating climate change mitigation strategies in highway design, construction and maintenance can further enhance the sustainable development of highway management. The Ministry of Transportation (MTO) can better support and strategize its response to these environmental and regulatory challenges by developing GHG mitigation measures in highway design, construction, rehabilitation, and maintenance activities.

GHG emissions mitigation in the highway transportation sector encompasses a variety of possible activities with different implications for management practices and the environment. It may include the use of novel technologies, renewable energy, retrofitting, increasing energy efficiency, or changing management practices in design, construction, rehabilitation and maintenance activities. In order for the MTO to advance its efforts against climate change, an important step is to comprehensively review, compare and evaluate greenhouse gas mitigation strategies, including best practices from different jurisdictions.

4.1.1 Research Objectives

The main objective of this research project is to inform the adoption of GHG mitigation strategies in highway design, construction and maintenance. The specific sub-objectives are:

1. Identify the suite of GHG mitigation measures adopted, at various levels of implementation, by jurisdictions relevant to Ontario in terms of climate, technology, regulatory and geographic contexts for highway design, construction and maintenance, through a comprehensive literature review
2. Assess feasibility of implementing the GHG mitigation measures, through practitioner survey and interviews
3. Propose a framework for selecting GHG mitigation measures for MTO
4. Develop guidelines and recommendations for implementing GHG mitigation measures and practices for MTO.

The research is intended to advance understanding of GHG mitigation approaches and experiences in contexts relevant to MTO, offering a comprehensive list of GHG mitigation activities other jurisdictions, insight into their experiences, and resulting challenges and opportunities for GHG mitigation during highway design, construction and maintenance.

4.2 Research Methodology

The analysis seeks to identify GHG mitigation options, compare them, evaluate their feasibility for Ontario, develop a framework for evaluating GHG measures, and provide recommendations. This is achieved through a combination of literature review, surveys, interviews and feasibility assessment based on the experience from other jurisdictions and factors that influence implementation. This report is structured by the individual tasks completed and shown in **Figure 4.1**.

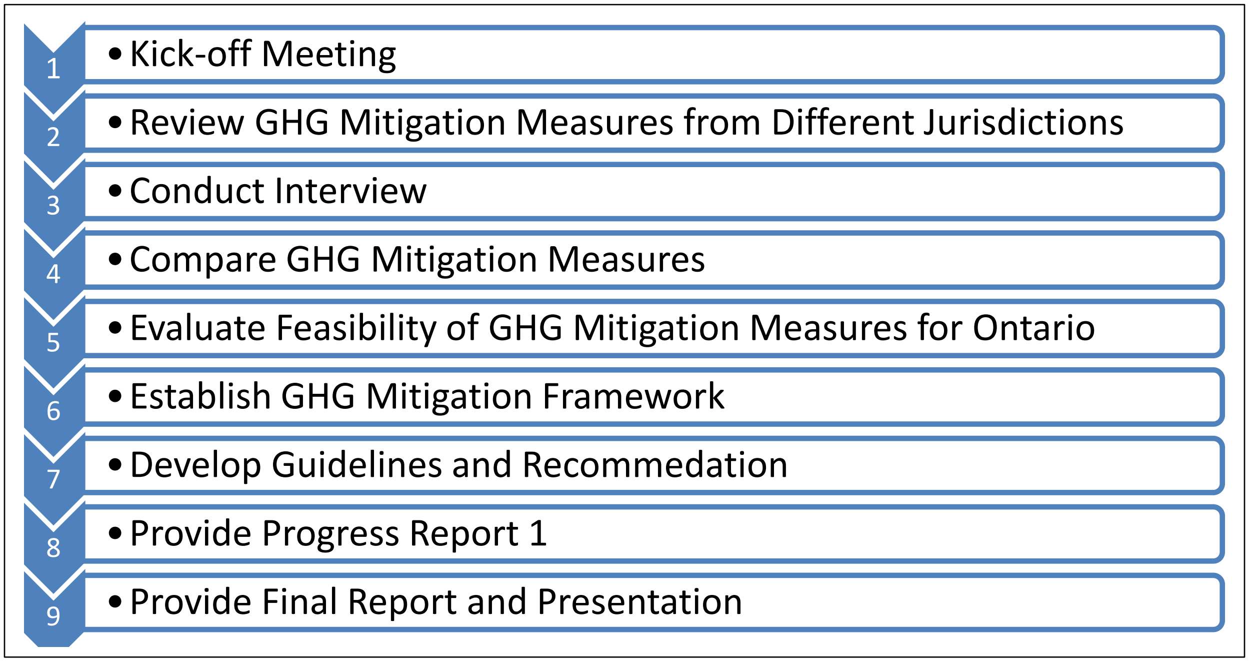

Figure 4.1 Summary of Tasks for This Project

4.2.1 Scoping the Jurisdictional Review

The Kick-off meeting between CPATT research team and the MTO team served to inform the scope of the jurisdictional review, including relevant jurisdictions and mitigation measures. This included a list of possible jurisdictions to review, an initial list of mitigation measures, and supporting references and documentation. Specifically, MTO identified particularly relevant and innovative jurisdictions to review, including the Netherlands, Scandinavian countries, British Columbia in Canada, some US jurisdictions such as California. They further provided a list and other reports on GHG mitigation measure already currently in-use by MTO and others identified but not yet implemented, as provided in Table A.1. in Appendix A.

MTO also provided a context for the development of a GHG mitigation measure selection framework. Specifically, their internal assessments identified four key approaches to manage GHG emission as shown in Figure 4.2.

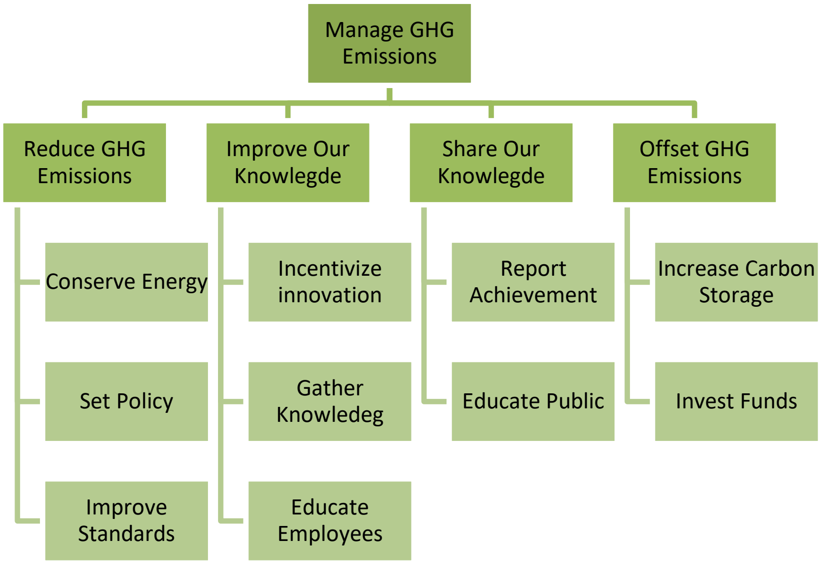

Figure 4.2. How to manage GHG Emissions (adapted from MTO Climate Change Value Engineering Study)

4.2.2 Review of Adoption of GHG Mitigation Measures

The literature review provides the basis for the first sub-objective, to identify GHG mitigation measures in use by other relevant jurisdictions. A list of GHG mitigation strategies already complied by the MTO was first reviewed. This provided a guide to a comprehensive literature review and investigation of select jurisdictions. The data sources are discussed in this section. Per discussion with MTO during the kick-off meeting, the jurisdictions scanned include British Columbia, Alberta, California and select Northern states of United States of America (US), United Kingdom (UK), The Netherlands, Australia, and the Scandinavian countries (Denmark, Norway and Sweden). This review focused on the transportation agencies responsible for design, construction, maintenance and managing the highway or motorways. Innovations from other European countries and rest of the world found in the literature were also recorded. An overview of these agencies is documented in section 3.2.1 of the official report submitted to MTO.

4.2.2.1 Data Collection

Reports, news, peer-reviewed publications, conference proceedings and white papers from multiple sources were reviewed to determine practices, technologies and techniques adopted in other jurisdictions for mitigating GHG emissions during highway design, construction and material considerations, and maintenance. The following sources were searched:

Research and academic databases:

- Google and Google Scholar
- American Society of Civil Engineers (ASCE)
- International Transport Research Documentation (ITRD)
- Scopus
- Science Direct

Transportation agency websites:

- B.C MoTI
- Alberta Transportation
- USDOT Federal Highway Administration (FHWA)
- California Department of transportation (Caltrans) and Other US DOTs
- UK Department of transport and Highways England
- The Royal Norwegian Ministry of Transportation and Communications
- Danish Ministry of Transport
- Queensland Department of Transport and Main Roads
- New Zealand Transport Agency

Other Research Centres' databases:

- Austroads publications website
- USDOT National Transportation Library
- The Center for Environmental Excellence by the American Association of State Highway and Transportation Officials (AASHTO) database
- Sustainable Built Environment National Research Centre (SBEnrc)
- Conference of European Directors of Roads

Others Sources:

- European Union Publications
- Industry websites and reports
- World Bank reports

4.2.2.2 Mitigation Measures from Different Jurisdictions

A broad variety of measures reducing GHG emissions was identified across highway management phases. These phases are planning and design, new construction, rehabilitation / reconstruction, maintenance and policy development. The major work types include Paving – Asphalt & Concrete, Structural, Removals, Grading, Landscaping, Culverts, Drainage, In-water operations, and Electrical.

GHG emissions mitigation measures in the highway management sector encompass a variety of possible activities ranging from administrative programs and policies to engineered techniques, technologies and practices. They included the use of novel materials or technologies and renewable energy, retrofitting old equipment, increasing energy efficiency, or changing management practices in design, construction, rehabilitation and maintenance activities.

The identified set of measures is presented under the four main highway management phases acknowledged by MTO:

- Planning & Design
- New Construction
- Rehabilitation / Reconstruction
- Maintenance

The review identified 80 mitigation measures in some phase of adoption. Adoption was classified into three levels: not in use, occasional or pilot use, and current use. Results are presented for Ontario, along with other national or multinational jurisdictions, including Canada, USA, UK, Netherlands, Scandinavia, Other Europe, Australia and Others. For purposes of space, summary tables are provided in Table A.2 – A.6 in Appendix A.

The results indicate that different regions show different levels of experience across mitigation strategies. For example, Ontario and the UK implemented the broadest suite of pavement preservation techniques to reduce emissions associated with maintenance and rehabilitation. European jurisdictions documented the most experience in congestion-related mitigation strategies.

The variety of measures and level of experience make it difficult to assess feasibility from a literature review alone. For example, while most jurisdictions reported some adoption of alternative fuel and vehicle technology in construction equipment, the type of equipment and its uptake is likely to vary significantly. To better understand jurisdictional experience with mitigation measures, the literature review was used to develop an expert elicitation study.

4.2.3 Practitioner Survey and Interviews

The results from the literature review were supplemented through discussion with practitioners within identified jurisdictions. These additional data and perspectives were secured through a survey and interviews. This required the development of a purpose, identification of participants, a recruitment strategy, development of a survey instrument and interview guide, identification of associated risks and benefits to participants, privacy and security strategy, and consent and withdrawal procedures. This data collection procedure involves human participants, and thus requires approval by the University of Waterloo Research and Ethics Office. This process is a prerequisite for systematic investigation with human participants to ensure research integrity, protection of participant's safety and welfare, and the research complies with the institutional and national guidelines and policies.

4.2.3.1 Survey

The purpose of the survey and interview was to collect more information on mitigation strategies adopted by transportation agencies, especially those most relevant to Ontario. The criteria for selecting jurisdictions to survey were those with some similarity to MTO's climate, resources, and regulatory environment. This led to a focus on jurisdictions in Canada and some American states around Ontario such as Minnesota, Michigan and New York.

Potential participants identified including employees at ten Canadian and six American agencies. The participant pool consisted of the Chief Engineers and other top level decision makers who can attest to the agency's practices of highway design, construction and maintenance. The participants were recruited via email. The contact information of the required respondents were collected from the agency's websites. The recruitment email for the survey is available in Appendix 2 of the project report. The survey was developed using the Qualtrics application accessed through the University of Waterloo Research Ethics Office (REO) website. All surveys are required to complete the ethics process by the REO University of Waterloo, and Ethics approval has been obtained (ORE #40452). All the survey instruments, interview guides, information related to risk and benefit to participants, privacy and security strategy, consent and withdrawal procedure and other research ethics application documents are attached in Appendix 2 of the project report. Email invitation for the survey was sent to participants in 14 transportation agencies in Canada and 5 transportation agencies in the USA. Six responses were received from five Canadian transportation agencies and one American agency.

The first set of questions covered respondents' basic information and were used to assess the expertise and jurisdiction of the participant. Items collected included the jurisdictions, job titles and departments of participants in the online survey.

The next question aimed to assess the factors that respondents' considered when implementing GHG emission mitigation strategies. The aim of this question was to aid in eliminating and sorting measures. Two questions in this block addressed "What is the most important factor(s) for implementation of Greenhouse Gas (GHG) emission mitigation strategies compared to status quo alternatives? Based on your agency's practice". The first question asked the participants to select from a list provided, including an option to add others not in the list. The list of factors includes:

- Cost of implementation (agency cost)
- Internal resource demand (agency labor hours)
- Industry response (industry capacity and experience)
- Public response (public comments)
- Schedule for implementation (length of time)

- Others (option to list other factors)

Once factors were identified, respondents were asked to rank their importance. The next question asked the participants “Please indicate priority (1 to 5) of each factor for ease of implementation of the GHG mitigation strategies compared to status quo, 1 for most important factor and 5 for least important factor.” This ranking of factors can be used in a variety of methods for filtering and ranking strategies. For example, using a single important criterion can be used to eliminate options via feasibility or satisficing, or, potentially, to rank strategies via lexicographic methods.

The remaining blocks of questions provided participants with the list of strategies derived from the literature, including results specific to their jurisdiction with option “other” to add to the list. The participants were asked to quantitatively compare strategies vs. the status quo on four factors – cost, internal resource demand, industry response and public response. These four factors were considered to allow inferences to be made on feasibility of adopting the same strategies in Ontario based on the experience of other jurisdictions.

4.2.3.2 Interviews

The interviews were designed with specific questions for each jurisdiction based on their responses to the online survey questions. Four jurisdictions accepted to participate in a follow-up interview. Three participating agencies were reached and the feedback on their responses to questions on the online survey were clarified. The follow-up interview allowed the project team to obtain more information regarding the agencies’ experience with adoption of the strategies, especially those strategies in the pilot stage. The interviewees responded to how factors such as cost and industry capacity have influenced their decisions regarding full-scale implementation. This feedback was combined with the online survey responses and used for comparison and feasibility evaluations.

4.3 Results and Discussion

4.3.1 Comparison of Mitigation Strategies

One major focus of this project is to identify GHG mitigation strategies appropriate for adoption in Ontario. In service of this aim, this study seeks to systematically compare each strategy against the “business as usual” (BAU) or status quo scenario/practice. The survey results reveal that 54 strategies adopted in other jurisdictions have not been adopted in Ontario (Table A.7 in Appendix A). The list includes strategies that have been implemented as full-scale projects and those still in the pilot stage. This section is structured as follows: identifying strategies adopted in pilot/full, which provides evidence of feasibility; identifying promising strategies versus status quo based on the four influential factors evaluated during the survey and interviews.

Although this comparison is based the four factors, during the course of the interview, it became clear that several other factors could influence a highway manager's decisions to implement a proposed strategy to mitigation. Hardly any two highway projects are alike. A road project's type, size, and location, amongst other performance factors, must be considered in highway design and management decision making. A highway design, construction or maintenance project can manifest as a complex decision making problem. As such, comparing strategies to a BAU alternative was more plausible than ranking the different strategies that are applicable at different stages during highway design, construction and maintenance. This is a common challenge in transportation infrastructure decision making. An interview participant affirmed the challenge saying, "It is kind of hard to rank them in that sense to say that one is the best, since every project is different. So a very complex project could be quite different from the other one. It depends on the type of project it is too." The respondent mentioned the case of rock, balance earth and double handling of material used in grading projects, "Where some are quite large so when you start looking at that then cost might be a driver versus a smaller project where maybe it is a Geo-synthetic that is better to put in versus a significant amount of fill. It becomes a question where other factors lead in decision making."

The response to the question, "What is the most important factor(s) for implementation of a Greenhouse Gas (GHG) emission mitigation strategies compared to status quo alternatives? Based on your agency's practice" show one common consideration is Cost of implementation. However, the importance rank of the factor is subject to other factors such as performance and political influences. The follow-up interview revealed that cost considerations have hindered full-scale implementation of some GHG mitigation strategies. Internal resource demand and industry response were also key factors influencing continued use of some strategies. Public response was rarely noted to be influential.

In one respondent's opinion, cost is one of the important factors since it is usually the driver, and in selecting options sometimes it is just a matter of research and development to try out the different strategies that might be greener to see how they might perform. For some agencies, mitigation measures are secondary to infrastructure resilience measures (new culvert standards, grade raises, etc.). Some jurisdictions consider other factors like performance and climate change impact in a sense of “getting ahead of that curve” with resilient solutions. One respondent noted that an infrastructure manager may have little opportunity to mitigate GHG emissions. Some measures they can put into effect include reducing the idle time of their fleet vehicles and adopting LED lighting. Many opportunities to reduce GHG emissions during highway design, construction and maintenance are highly influenced by road builders/contractors (EPA, 2009).

4.3.1.1 Cost of Adoption

Implementation of any new strategy, program or technique, and changes to business-as-usual practices can have considerable cost implications for any transportation agency making such changes to transportation infrastructure management practice to reduce GHG emissions. Considering the limited available resources and budget constraints at transportation agencies, cost savings or additional costs estimated for changes in current practices or adoption of new strategies will highly influence the decision of the transportation infrastructure manager. For comparison of GHG mitigation strategies, the cost factor is considered as the economic cost to the agency in terms of contract payment or additional cost for internal human resource demand. A major obstacle to procurement of green products is the perception of increased cost compared to those not environmentally friendly (Testa et al. 2012).

The responses from the online survey show that 13 strategies have cost savings compared to BAU alternatives, however only 8 strategies were considered cost-effective by all participants (Table 4.1) Five strategies were considered by some participant as cost-effective while other considered them to increase cost compared to the status quo. The results are based on Table A. 7 in Appendix B**Error! Reference source not found.** considering only strategies that have not been implemented in Ontario including both pilot stage (yellow cell) and full-scale projects (green cell).

Table 4.1 Strategies identified by agencies to have cost savings or no additional cost compared to status quo

Strategies	Cost Saving
Diverging diamond interchange (DDI)	25%
Allow over 40% recycled material in asphalt concrete mixture	0%
Allow over 40% recycled material in hydraulic concrete mixture	0%
Green procurement policy	0%
Life cycle assessment (LCA) tool	5%
Lightweight Concrete	0%
Self-compacting Concrete	0%
Prequalification considerations for Contractor & CA	0%
Requirement for Life cycle assessment (LCA) in EIA for project	7%
Requirement to use locally sourced materials	7%
Reserve strip between carriage way for future development	8%
Storage depots to be used by multiple jobs	10%
On-road vehicle fuel efficiency Programs	0%
Dynamic traffic management systems - variable speed limits	0%
Lighting optimization (dimming, trimming, switch-off)	5%
Renewable energy for lighting	10%

Life cycle assessment (LCA) tools were suggested to offer cost savings compared to the status quo in the pilot stage. However, none of the agencies had a dedicated GHG accounting or an LCA tool internally developed or used. A typical approach is to use consultants to do that estimation when required, for example, for federal cost sharing projects. Some agencies reported trying out some GHG emission calculation tools with a few projects. An interview respondent suggested that the industry would be capable of implementing this strategy of GHG accounting, but the challenge is that they do not know what tool to direct their internal resources or external partners to use.

A similar strategy applicable to design is a cost benefit model that includes GHGs for different alternatives in design. This appears to be a promising strategy from a cost-saving perspective, albeit one without widespread adoption. In pavement designs, life cycle cost (LCC) is used to compare alternatives. Only Alberta Transportation has developed a method and an LCCA tool that includes emission cost. Alberta's Benefit Cost Model User Guide[8] is a tool used to determine which road or bridge project provides the best return on investment when considering different rehabilitation alternatives. The analysis components include initial construction costs (investment), operating and maintenance costs, rehabilitation costs, road user costs (vehicle operating costs, travel time costs, collision costs), and emissions costs. Environmental costs included are those associated with vehicle emissions. Emission costs are estimated based on the fuel consumption as per the number of vehicle kilometers travelled by each vehicle type and running speed on each segment of the defined project. Emissions rate are estimated by the speed of vehicle for each vehicle type and for each defined emission type. On the other hand, a dedicated GHG estimation tool or LCA tool has only been tested by the surveyed Canadian agencies. Based on its pilot study, when the survey respondent from Manitoba Infrastructure assessed the possibility of using available LCA tools in project decision making, they suggested that a 5% cost savings can be achieved when LCA tools are used. Alberta Transportation does not have an LCA tool in place but have appointed a Greenhouse Gas Task Group to look into different options to enable the reduction of GHG emissions, with respect to design and construction, procurement, maintenance of their road network and reducing GHG emissions.

Table 4.2. Strategies with conflicting responses on cost compared to status quo

Strategies	Cost Saving	Cost Increase
Requirement to use only recycled materials for road resurfacing	12%	15%
Restrict project within the existing right of way	2%	25%
Solar/Wind stand-alone hybrids for lighting or signage poles	10%	10%
Solar-powered LED roadway lighting	10%	12%
Thin concrete pavement	10%	25%
Standardized GHG emission calculation methodology	0%	10%
Vehicle purchasing and right sizing policies	7%	18%

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[8] For further details, please refer to the link to the Alberta's Benefit Cost Model User Guide http://www.transportation.alberta.ca/5847.htm

During the follow-up interviews, it was found that, for strategies such as environmental assessment and GHG emission assessment guidelines, the noted cost increase was due to staff internal time, as it is not a normal procedure for their projects. One interviewee noted that, depending on the project context, for example, projects that involve cost sharing between the Federal government and the department or with another government agency, some requirement in the infrastructure funding may depend on addressing GHG emissions in construction and maintenance for federal projects.

From the literature, many of the GHG mitigation measures have shown cost savings. For example, the MRWA “Brown Out” trial project that focused on switching off select streetlights achieved over 30% (AUD$560 000) power cost savings in three years. In one example of using green procurement tools in tender and contract award criteria, the Dutch transportation agency used an environmental costs indicator value (ECI) to assess and monetize the product quality in Design, Build, Maintain and Finance (DBFM) contract. This practice favored suppliers that reduced CO_2 emissions and helped the agency save 21.8 million euros (Jones, Sohn, and Bendsen 2017). Cases involving innovative designs for energy generation from road infrastructure showed savings and additional costs depending on the technology and the level of development. Most of the innovative pavement energy harvesting techniques such as solar pavement technologies have high initial cost, however, feasibility investigations of pilot projects in Europe concluded that the costs can be recovered in the long term through power cost saving from the renewable energy produced. The lifecycle cost including the maintenance cost can provide an overall view of cost implications to inform decision makers; however, many of these technologies are in the pilot stage, which may not reflect the costs of full-scale implementation.

4.3.1.2 Internal Resources

Similar to the cost factor, the responses from the online survey show that 18 strategies have reduced internal resource demand compared to BAU alternatives, however only 12 strategies were considered cost-effective by all participants (Table 4.3). Six strategies were considered by some participant as cost-effective while other considered them to increase internal resource costs compared to the status quo (**Table 4.4**). The results are based on Table A. 7, considering only strategies that have not been implemented in Ontario including both pilot stage (yellow shading) and full-scale projects (green shading).

Table 4.3 Strategies identified by agencies to require the same or fewer internal resources compared to status quo

Strategies	Reduce Internal resource demand
GHG emission consideration in Environmental Assessment (EA)	25%
Allow over 40% recycled material in asphalt concrete mixture	0%
Environmental Protection Requirement for GHG	25%
Green procurement policy	0%
Life cycle assessment (LCA) tool	25%
Standardized GHG emission calculation methodology	25%
Requirement for Life cycle assessment (LCA) in EIA for project	25%
Requirement to use locally sourced materials	0%
Requirement to use only recycled materials for road resurfacing	0%
Renewable energy for lighting	5%
Vehicle purchasing and right sizing policies	0%
Lighting optimization (dimming, trimming, switch-off)	0%
Renewable energy for lighting	5%

Many GHG mitigation measures are new and outside the BAU agency practice. Thus, awareness and knowledge of the impacts of the GHG mitigation measures amongst the internal staff of the organization can influence adoption of the measures. A European study that examined the factors that influence uptake of green procurement practices found that the awareness of GPP initiatives and tools is highly significant in determining the number of tenders that are adopted with the inclusion of environmental criteria (Testa et al. 2012). The study concluded that the more a public administration is informed and acquires competence and know-how in developing GPP practices, the more it is eager to experiment with these new procedures and introduce greener criteria in the tenders. Lack of organizational resources (including people and time), information about the real environmental impacts, operational/information tools, training and awareness of green product suppliers can increase difficulty in promoting policies for considering green products and including environment criteria in call for tenders and purchasing. For comparison of GHG mitigation measures and feasibility evaluation for Ontario, internal sources will be addressed from the demand perspective to an agency human resource from need for new staff, extra time and training.

Table 4.4. Strategies with conflicting responses on internal resource demand compared to status quo

Strategies	Saving	Increase
Reserve strip between carriage way for future development	0%	15%
Solar-powered LED roadway lighting	0%	10%
Vehicle purchasing and right sizing policies	0%	16%
Use Rock within the right of way	3%	25%
Specify Material sources in design	0%	1%
Storage depots to be used by multiple jobs	0%	3%

For some strategies already implemented in Ontario, such as the use of recycled materials, some jurisdictions reported reductions in internal resource demand while others showed the demand for staff time can increase up to 25%. This demand can arise from the need to create new specifications and testing performance of new recycled materials. For example, one respondent said their agency is investigating the use of General Use Limestone cement and the use of recycled concrete aggregate in road pavement. The required testing required staff time to do extra testing or the review of the mix designs. The respondent said the relative staff time demand is usually negligible. Even though the use of recycled material is considered to reduce cost, usually the cost reduction is assimilated by the contractor not by the agency; thus, there is no cost implication for the agency.

HIR has the least demand for internal resources from one agency. The reason provided was that the program has been in place for a number of years and the agency has a target of about a million square meters of HIR on the road network per year. It has the least demand because resources are already allocated to it. However, HIR requires specific weather, so sometimes projects are not finished in a given season and must be carried over.

4.3.1.3 Industry response

Collaboration between road authorities and industry is vital for implementation of strategies to reduce GHG emissions during road design, construction and maintenance. Industry responses to GHG mitigation measures would ideally be assessed through communication with industry. However, given the project scope and focus on transportation agencies, industry response was assessed in terms of capacity, as judged by agency respondents.

For almost all the strategies listed, industry capacity to deliver GHG mitigation strategies in all jurisdictions ranged from very capable to somewhat capable. The only case that stood out was for Alberta Transportation where the Hot-In-Place Recycling (HIR) maintenance strategy was restricted by industry capacity. As an interview participant noted, although HIR is allowed in tenders as an option if applicable (Mill & Inlay), it has not been used for over 7 seven years because the equipment is not in Alberta. The agency still implements other recycled pavement maintenance technologies such as FDR and CIR for specific projects. However, FDR and CIR might have the biggest cost barriers, which are newer tech so can be more expensive than conventional BAU alternatives. The question of industry capacity, which is the measure considered for industry response, will differ for each province and largely depend on the budget for the specific project. The benefits of GHG mitigation can be reduced when there is a need to transport equipment for implementing a particular technique from a different province, since fuel consumption due to transportation increases the GHG emissions from a life cycle perspective.

4.3.1.4 Social Response

Public response was rarely found to be a challenge, only in cases where the changes affect operations of the highway. Other structural changes in terms of material or construction equipment are hardly noticed by the general public. In response to the question, “In terms of public response, has there been any complaints, or perhaps any comments, positive or negative, about any of the strategies?” A participant said, “Not really, because they don’t know a lot of the strategies. They just know that the road is there, but most will not get into the strategies.” They added that the public appeared to be most aware of the roundabout.

Very few participants addressed the factor of public response in the survey. Many responses were "not applicable or unsure". Others were either negative or positive, and no conflicting views were noted (Table 4.5). The results are based on Table A. 7, considering only strategies that have not been implemented in Ontario including both pilot stage (yellow shading) and full-scale projects (green shading).

Two strategies with negative public responses in Table 4.5 stand out, showing that public response can be a challenge to implementation. With respect to the negative public response for implementation of "Reserve strip between carriageway for future development", Manitoba Infrastructure said the negative comments from the public happen when the agency needs to restrict development or hang on to property, and sometimes involve encroachment on privacy. The agency resolves this issue through open house and public consultation. There are also policies that require controlling areas adjacent to infrastructure already in place or planned for the future. The agency provides information and formal responses to the public prior to taking actions.

Public responses may differ for similar strategies across different jurisdictions. The switch-off street light project by MRWA in Australia had no significant crash risks during the three year trial. However, the light dimming test project by Highways England in the UK received considerable backlash from the public, including safety concerns, public annoyance[9] and questioning road of authority's consideration of social impacts of the GHG mitigation decision. The experience with Highways England shows the need for clear communication of the project goal[10]. Informing the public in time to avoid annoyance and assess the safety implications for road users can help to gain positive social responses and help ease the challenges with implementing new strategies.

Table 4.5. Strategies for which a public response was rated (positive, neutral, or negative) compared to status quo

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[9] Environmentalist groups and citizens showing their annoyance of the new policy to switch off street lights and echoing safety concerns of the decision: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/14720/dft-f0009362.pdf

[10] In a response from Highways England, the agency clarified the gaps in communication: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/725949/Highways_England_Response_-_Environmental_Information_Regulations_763574_Redacted.pdf

Strategies	Public Response
Diverging diamond interchange (DDI)	50%
GHG emission consideration in Environmental Assessment (EA)	25%
Allow over 40% recycled material in asphalt concrete mixture	15%
Lightweight Concrete	0%
Self-compacting Concrete	0%
Prequalification considerations for Contractor & CA	10%
Requirement to use locally sourced materials	7%
Reserve strip between carriage way for future development	-24%
On-road vehicle fuel efficiency Programs	-10%
Dynamic traffic management systems - variable speed limits	0%
Lighting optimization (dimming, trimming, switch-off)	0%

4.3.2 Feasibility Evaluation

In this section, we assess the feasibility of those GHG mitigation practices utilized by other jurisdictions for use in Ontario during highway design, construction and maintenance. Results of the literature review, survey and interviews show that MTO is largely in step with other jurisdictions in its adoption of technologies and techniques to reduce GHG emissions. Their experience is used to identify challenges associated with various measures.

The survey and interviews emphasized options with favorable characteristics compared to the status quo, while the feasibility evaluation focuses on potential cost implications. The key factors considered in the survey included cost estimations of adopting mitigation options, industry responses, internal resourcing, and social resistance issues. Of these, cost was established as the most influential factor for the MTO during the progress report update meeting. Transportation agencies have limited budgets, thus infrastructure managers often look to the most cost-effective strategies in decision making. A list of strategies with some added cost is presented alongside the perceived level GHG mitigation reduction possible when compared to the status quo alternative. Table 4.6 provides a list of strategies that are expected to cost more than status quo based on experiences from other jurisdictions and data from review of available literature. Cost differences are grouped into high, medium and low for cost difference more than 25%, less than 25% but more than 10%, and positive but less than 10% respectively. The list includes inputs from the Jurisdiction scan survey and interview (task 3), and from literature review (task 2). From the review of literature on these strategies, GHG saving compared to BAU alternative have been reported as high (>25%), medium (<25% and > 10%), low (<10%). The estimate for some strategies are inconclusive or have not be comprehensively documented (NA), this is the case for the very new technologies still in their pilot stage and the energy harvesting technologies for roads and bridges for example solar roads.

Table 4.6. List of strategies with additional costs compared to status quo alternative measures

Strategies	Cost Increase	GHG savings
CO2 emissions certification scheme for contractors	Medium	Medium
De-icing Technologies (Bridges)	Medium	Low
De-icing Technologies (Pavement)	Medium	Low
Environmental Protection Requirement for GHG	Medium	High
Incentives for reduced deficiencies and/or warranty work	Medium	Medium
Performance Based Specifications & Testing	Low	Medium
Specify Material sources in design	Low	Medium
High Modulus Asphalt	Medium	NA
Aerodynamic improvements Programs	Low	NA
Incentives for Modernize Fleet and Equipment	Medium	NA
Low rolling resistance tires Programs	Low	High
Incentives/Disincentives for haul-to-waste materials for reducing or reusing	Medium	Medium
Storage depots to be used by multiple jobs	High	Medium
Cast-in-place: Alternative Contract Models	Medium	Medium
Precast: Alternative Contract Models	Medium	Medium
Climate Change Experts on CA Team & Contractor Crew	Medium	Medium
24/7 Construction	High	High

Payment adjustments for reducing construction times and congestion queues	Medium	High
Lane Rentals / Flexible Closures	Medium	Medium
Real Time Modelling - Adjusting based on Traffic Conditions	Medium	Medium
Anti-Idling Software & Mechanisms (Idle Limiters)	Medium	Medium
Using Local Electrical Grid to Minimize use of Generators	Medium	Medium
Age Limits & Mechanical Fitness for vehicles and equipment	High	Medium
Removable urban pavement	High	Low
Solar Roads	High	NA
Solar highway barriers	High	NA
Wind turbines along highways	High	NA
Piezo-technology in road construction	High	NA
Energy/Power transfer technology (pavement)- wireless charging	High	NA
Energy/Power transfer technology (pavement)- wired charging	High	NA
Energy/Heat transfer technologies (other structures)	High	NA

Note: NA – Not available/ Unsure

Of those strategies not currently in use by MTO, a list of measures deemed cost-effective in other jurisdictions is given in Table 4.7, along with their approximate GHG savings potential. Such strategies are not eliminated by a feasibility filter focused only on avoiding cost increases. However, in selecting strategies, it is important to consider factors beyond cost. After all, costs associated with internal resource demands have been shown to dissipate with increased awareness and experience, just as costs of novel technologies tend to decrease as knowledge and use of the technology increases. An approach to consider all influencing factors is discussed in the next chapter.

Table 4.7. List of cost-effective feasible GHG mitigation strategies during Highway Design, Construction and Maintenance

Strategies	Approx. GHG savings
Diverging diamond interchange (DDI)	High
Allow use of more recycled material in asphalt concrete mixture	High

Allow use of more recycled material in hydraulic concrete mixture	High
Green procurement policy	High
Life cycle assessment (LCA) tool	Medium
Lightweight Concrete	Low
Self-compacting Concrete	Low
Prequalification considerations for Contractor & CA	Low
Requirement for Life cycle assessment (LCA) in EIA for project	Medium
Requirement to use locally sourced materials	Medium
Reserve strip between carriage way for future development	Low
Storage depots to be used by multiple jobs	Medium
On-road vehicle fuel efficiency Programs	Low
Dynamic traffic management systems - variable speed limits	Low
Lighting optimization (dimming, trimming, switch-off)	High
Renewable energy for lighting	High
Requirement to use only recycled materials for road resurfacing	NA
Restrict project within the existing right of way	NA
Solar/Wind stand-alone hybrids for lighting or signage poles	High
Solar-powered LED roadway lighting	High
Thin concrete pavement	NA
Standardized GHG emission calculation methodology	NA
Vehicle purchasing and right sizing policies	NA

4.3.3 GHG Mitigation Framework

Transportation agencies have complex decisions to make when seeking to adopt GHG mitigation measures and best practices into highway planning programs and policies. A systematic approach can help to informs choices and facilitate a smooth transition to low-carbon innovations in highway design, construction and maintenance. For this purpose, a four-phase framework for selecting and implementing GHG mitigation strategies is depicted in **Figure 4.3** and described below. Given the vast variety of activities undertaken by a transportation ministry like MTO, and the disparate roles and responsibilities of MTO employees that could affect mitigation decisions, this framework is meant to be interpreted broadly. In order to provide a more concrete illustration, steps are described focusing on decisions on a project-level basis.

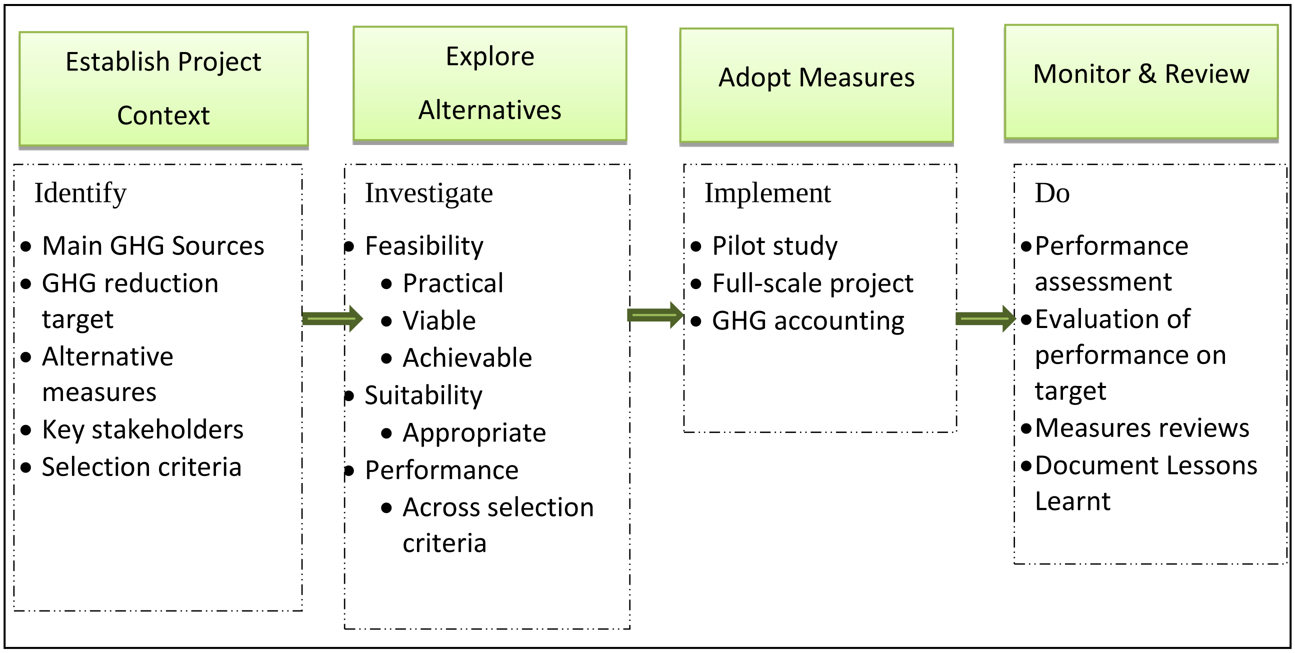


Figure 4.3. Framework for Implementing GHG mitigation Strategies

Phase I: *Establish Project Context*

Highway design, construction and maintenance projects can vary from large and complex to small and straightforward. Thus, context matters. The flowing steps may be taken to establish the project context:

1) Identify the main emission sources of status quo strategy

The life cycle perspective of a highway project should be considered when characterizing project-level GHG emissions and determining emissions. Ideally, an inventory of the significant potential sources of GHG emission and emission estimates should be constructed to identify the main opportunities for abatement. As described earlier, other jurisdictions have addressed this by developing a catalogue of emissions from typical projects, or through contract requirements.

2) GHG reduction target for project

Ascertain a target for GHG reduction for a project in the context of ministry goals and abatement potential identified in step 2.

3) Identify Alternatives

Identify alternative GHG mitigation strategies that can be incorporated into the project. For reference see the list provided in table 2 to 8.

4) Identify Stakeholders

Identify and engage with relevant stakeholders, including decision makers and other affected parties.

5) Ascertain Influential factors

It is important for an infrastructure manager to recognize the influential factors for decision making and identify each factor’s level of importance. In our survey, we included four factors based on dialogue with the MTO that the major challenges associated with implementation of new innovations include potential cost increases of adopting measures, the industry’s capacity to respond to new requirements, availability of internal resources to develop new specifications and contract requirements, and social resistance to change. Relevant factors may vary across projects and over time. Other, might include, for example: scheduling implications, ease of implementation, and other environmental impacts.

Phase II: *Explore Alternatives*

For the identified abatement opportunities, identify suitable possible alternative GHG mitigation measures. Assess the feasibility and suitability of the GHG mitigation measure in the project context.

1) Investigate Feasibility: refers to the viability, practicability and achievability of a strategy. It may be assessed against a given acceptable threshold, if available. The factors below can be assessed (with reference to sections 3.3 and 6) also with other factors identified during the Phase I above

- Technological feasibility and performance implications: Has it been implemented elsewhere? (full or pilot)
- Cost of implementation
- Industry capacity

- Internal resource demand
- Public response: Evidence of past public resistance? (Does it affect the surface or land development?). Might have public response with cost impacts

2) Investigate Suitability: check appropriateness of strategies considered for project context

3) Investigate Performance: evaluate the favorability of alternatives against influential factors identified previously

Phase III: *Implement Measures*

Ultimately, the GHG mitigation measures should be implemented with consideration of factors that can influence implementation. Record any issues arising and the approach to addressing issues. To inform the evaluation process in phase IV, estimate GHG reductions achieved due to implementation of a specific strategy in a specific project context. The main points of actions are:

- Implement the best alternative based on feasibility, suitability, and performance on relevant criteria for the project
- Record changes that arise compare status quo alternatives

Phase IV: *Monitor and Review*

The actions taken here should inform future plans for incorporating GHG mitigation measures in during highway design, construction and maintenance. These include:

- Annual evaluation of GHG reduction performance against relevant goals
- Document Lessons Learnt
- Adjust mitigation strategies as needed

4.4 Recommendations and Conclusion

The CPATT research team has carried out a comprehensive review of GHG mitigation strategies adopted by Canadian, USA and European transportation agencies, providing the basis for several recommendations and conclusions.

The variety of MTO's GHG mitigation activities appears to be in line with those of many jurisdictions in Canada. Some administrative and policy measures are already in place to manage GHG emissions during different phases of highway management. Efforts have been made to use recycling and innovative techniques such as WMA, CIR, FDR, precast concrete pavement, pervious and porous pavement.

Additional actions are available for MTO to consider, beginning with those listed in **Table 4.8**. Activities in other jurisdictions include 51 strategies not currently identified as in use by MTO. Of these strategies, jurisdictions identified several as having no effect or advantageous effects compared to their status quo activities in terms of cost, internal resource demand, and public response. Specifically, 13 were favourable in terms of cost, 18 in internal resource demand, and 9 in terms of public response, respectively. Industry capacity was generally not deemed to be a barrier to adoption across strategies or jurisdictions, except in one case where specialized equipment was unavailable. All strategies not currently adopted by MTO and considered promising are summarized in Table 5.8, grouped based on the activities described in the MTO Climate Change Value Engineering Study .

Such a survey of activities alone is not sufficient for MTO to ensure success or efficiency in reducing GHG emissions. Firstly, simply adopting a strategy does not guarantee results. There are various methods for implementing a given strategy, which will affect various factors including GHG reductions. The aim of GHG mitigation is, at least in part, to actually affect emissions. Thus, regardless of the activities chosen, we recommend taking steps to track mitigation activities and associated reductions. Secondly, MTO should consider their own context and priorities in adopting GHG mitigation strategies. There are limitations to the lessons that can be drawn from other jurisdictions. Their status quo activities may differ, as will conditions that affect relevant factors such as cost, internal resources, industry capacity, and public receptivity. Even within Ontario, the variety of activities and actors at MTO will require further evaluation for specific decisions or projects based on varying needs, priorities, conditions, and resources.

Ultimately, further in-depth evaluation of identified techniques and technologies is necessary to guide selection for best strategies for a given project context. This study acknowledges that different agencies consider different factors when making decisions on implement innovations. The framework presented in Figure 5.3 can guide MTO in selection and evaluation of alternatives for a specific project. If feasible and applicable, the strategy can be implemented in pilot study, monitored, evaluated and documented for consideration in project opportunities to mitigate greenhouse gas emission in road design, construction, rehabilitation and maintenance activities.

Table 4.8. Select GHG mitigation strategies considered most promising

Reduce GHG Emission	Improve and Share Knowledge	Offset GHG emission
Conserve Energy • Use more innovative alternative (see materials Table 4) • Diverging diamond interchange (DDI) • Allow use of more recycled material in asphalt concrete mixture • Allow use of more recycled material in hydraulic concrete mixture	Gather knowledge and report achievements • Inclusion of GHG assessment in annual report and road plans • Life Cycle Assessment (LCA) tool • Standardized GHG accounting method	Invest in carbon storage • Continue highway vegetation including programs for aggressive tree planting

• Reduced deck slab depth for Bridge designs • Oversizing pipes/culverts to allow for future re-linings • Storage depots to be used by multiple jobs • Ultra-High Pressure water cutting • Aggressive Closures • 24/7 Construction • Lane Rentals / Flexible Closures • Dynamic traffic management systems - variable speed limits • Lighting optimization (dimming, trimming, switch-off) • Renewable energy for lighting • Lightweight Concrete • Self-compacting Concrete		

• High Modulus Asphalt • Modular Pavements • Solar/Wind stand-alone hybrids for lighting or signage poles • Solar-powered LED roadway lighting • Solar Roads • Solar highway barriers • Wind turbines along highways • Piezo-technology in road construction • Energy/Heat transfer technologies • Smart Highways		
Set Policy • Environmental Protection Requirement for GHG in Highway Management • Green Procurement Policy	Incentivize Innovation • Scheme to award GHG mitigation innovations • Incentives for reduced deficiencies and/or warranty work • Incentives/Disincentives for haul-to-waste	

- Environmental appraisal of project based on GHG - Requirement for GHG and energy use accounting - Life Cycle Assessment requirement for projects - GHG in prequalification considerations for Contractor & CA - GHG as selection evaluation criteria - RFPs, DBs, CMGCs - Climate change experts on CA Team & Contractor Crew - CO2 emissions certification scheme for contractors - Evaluation of GHGs at contract completion - Payment adjustments for reducing construction times	materials for reducing or reusing - Incentives for Locally Sourced Materials - Aerodynamic improvements Programs - Incentives for Modernize Fleet and Equipment - Low rolling resistance tires Programs	

and congestion queues - Alternative Contract Models (Option A cast-in-place, Option B Precast) - Performance Based Specifications & Testing - Anti-Idling Software & Mechanisms - Using Local Electrical Grid to Minimize use of Generators - Age Limits & Mechanical Fitness for vehicles and equipment - Driver Behavior programs - On-road vehicle fuel efficiency Programs - Vehicle purchasing and right sizing policies		
Improve standards	Educate public and employees	Invest funds

• Review of aggregate by-laws for virgin materials • Specify Material sources in design • Standardization and Stockpile of commonly used precast elements (Culverts)	• Academy program for sharing Knowledge and training	• Invest in research and development, pilot studies of innovative technologies

Chapter 5

GHG Performance of Innovative Technologies

5.1 Introduction

The focus of this chapter is the climate change impact of innovative technologies that have been identified as potential strategies to mitigate GHG emissions during highway design, construction, and maintenance (see chapter 4). Here, three case studies were investigated. Case study 1 provides preliminary analysis that can be done when recycled and supplementary materials are considered in pavement material design mix for structural layers. Case 2 and 3 are based on real projects that have been done at the Centre for Pavement and Transportation Technology (CPATT), University of Waterloo in collaboration with the Ministry of Transportation Ontario (MTO) and other MTO contracts who engaged in the delivery of the different projects. The LCA methodology and tools were used where applicable.

5.2 Research Approach and Data

5.2.1 Methodology

The LCA methodology is adopted in this research to evaluate the environmental performance of the strategies in Case Study 1, 2 and 3. A cradle to gate approach is used to define scope and system boundary.

Goal and Scope

The goal of the LCA is to assess the environmental performance of innovative pavement material mix, design and rehabilitation technologies, and evaluate viability of these technologies to address GHG mitigation goals during highway design, construction and maintenance. The analysis was performed with comparative LCA to identify GHG reductions possible by these technologies compared to the conventional alternatives in pavement design and management. There measures were selected for this investigation and are detailed under case study- 1, 2 and 3 and the product systems selected are discussed in section 5.2.2.

- Case Study 1: Use of recycled, co-product and waste materials in pavement material mix design
- Case Study 2: Use of long-life pavement design strategy

- Case Study 3: Use of expedited rehabilitation techniques

In defining the goal and scope in a comparative LCA study, the functional unit and system boundary is key to provide meaningful results on an equal scale. Different functional units and system boundaries were defined for each case study, such that comparisons can be done within each case study but not across cases. This is because each of these strategies addresses different aspects in pavement design and management and in order to evaluate direct impacts of the strategy, the LCA study will benefit from a streamlined approach rather than a cradle to grave approach where all phases of pavement life cycle is considered. In such cases, an aggregated picture of the impacts can overshadow impacts of a small change in a particular phase of the system since impacts or benefits in other stages of the pavement lifecycle can occur.

Lifecycle Inventory (LCI) and Lifecycle Impact Assessment (LCIA):

The materials quantity required per functional unit of the new pavement mix, structural and rehabilitation designs as identified in each case study, was computed for each design. The electricity and fuel requirements of each process was set using the data in the adapted PALATE tool (Nasir 2018) or obtained from other literature or public datasets. Similarly, the data for the emissions associated with processes were based on the same data sources. Summaries of the life cycle inventories are shown in Appendix C of this thesis. Transportation distances were assumed based on practical estimates from the literature and other public databases. The robustness of the results was tested using sensitivity analysis with respect to transportation distance.

The main impact factor related to the goal of this study is climate change, so the unit of measure is CO_2 emissions in g/function-unit defined in each case study. As carbon emissions can have different effects on the health and the environment, a marginal damage cost presents a way to compare the impact of different strategies on one scale and to inform decisions in a dollar-for-dollar language commonly expressed in decision making. So, the social cost of emissions is adapted for valuation of emissions to assign a dollar value to environmental. The Environmental Cost of Atmospheric Releases estimates for Ontario developed by Nasir (2018) for valuation of the effects of several greenhouse gases pollutants was used as the basis to estimate cost implications of the pollutants. The 2010 marginal damage estimate for carbon is $120 per Mg of carbon emissions. Energy consumption is also reported as the main source of CO_2 emission and precursor to estimating the CO_2 emissions.

Sensitivity Analysis: Sensitivity analysis was conducted to develop a range of the uncertainty in the CO_2 emissions and environmental damage cost estimates; and to assess the sensitivity of the recommended alternative against the input parameters for emissions.

5.2.2 Case Studies

In the design of a new pavement, three strategies that are commonly used to reduce environmental impact are related to material use in the mix design for the structural layer for a pavement.

5.2.2.1 Case Study 1: Innovative Pavement Design Mix

As highlighted in the discussions in chapter 2 and 4, during the design of roadway infrastructure the sustainable strategies considered during pavement design is to reduce material use by utilizing Recycled, Co-product, or Waste Materials (RCWMs) in the pavement material mixtures for the pavement structural layer or in other supporting base and sub-base layers of the pavement structure. The main environmental issues in adopting RCWM in new pavement material mix design are related to the material transportation and processing. Accurate estimates of vehicle emissions is very important in pavement lifecycle environmental performance evaluations because transportation aspects can be seen from the material phase to the use phase and end of life phase of the pavement lifecycle. Studies have shown that even where RCWM have similar performance as conventional alternatives, sustainability benefits could be lost due to the long hauling distance and impacts of preprocessing the materials before use in pavement mixtures. It is thus important to precisely estimate material hauling vehicle energy consumption and related emissions in pavement LCA to determine maximum allowable distance for transportation of RCWM materials to the plants and from the plants to the job site, such that the sustainability benefit of using RCWM is accurately estimated.

Strategies investigated:

- HMA-RCA Mix – investigated environmental impact of recycling of RCA into HMA mix
- Sidewalks Concrete Mix for removable hexagon concrete pavers– investigated environmental impact of using a variety of recycled, by-products and waste material in the concrete mix.

5.2.2.1.1 Use of Recycled Concrete in Asphalt Mixes

In view of the literature related to RCA use in HMA mixtures, it was evident that there is a scarcity of knowledge regarding the environmental and toxic effects of RCA use in HMA for asphalt pavement, and therefore, a considerable research gap presently exists in this area. Furthermore, to the best of the authors' knowledge, there are no investigations that have examined the influence of dataset and modelling approaches of LCA tools on the environmental performance outcomes of HMA mixtures with RCA. To fill this obvious gap, this research particularly focuses on examining the environmental impacts of HMA mix designs with different proportions of CRCA (0%, 15%, 30% and 60%) in the binder and base course of an asphalt pavement. The materials evaluated in this study are based on the constituent materials and HMA-CRCA mixtures developed in Al-Bayati et al study [31]. The base scenario is binder course of HMA with 0% CRCA, and the other five scenarios investigated in this study include a percentage of CRCA as described in **Table 5.1**. The volumetric tests, fatigue and dynamic modulus test for the different materials have been done and documented in a thesis by Al-Bayati (2019).

Table 5.1 Material content in mix design for HMA-CRCA mixes

	Control Mix	**Mix 1**	**Mix 2**	**Mix 3**	**Mix 4**	**Mix 5**
	0% CRCA	**15% CRCA**	**30% CRCA**	**30% Heat treated CRCA**	**30% Acid treated CRCA**	**60% CRCA**
CRCA (%)	0	15	30	30	30	60
Asphalt binder	4.8%	4.9%	5.3%	5.2%	4.9%	5.7%
NA (coarse)	49.5%	41.8%	36.5%	36.5%	36.6%	19.2%
NA (fine)	43.3%	43.2%	40.1%	40.2%	40.3%	42.0%
CRCA	0.0%	7.6%	15.2%	15.2%	15.2%	30.2%
Mineral filler	2.4%	2.5%	2.9%	2.9%	2.9%	2.9%

5.2.2.1.2 Use of Cementitious Supplementary Materials in Portland Cement Concrete Mixes

This study was conducted as part of the feasibility study for “Developing an Urban Interlocking Concrete Pavement”. The focus was on the material component to be included in interlocking concrete pavers (ICPs) selected as a paving method for the street and sidewalk areas of the Quayside neighborhood, located on the northwest corner of the Port Lands, Ontario. This relatively small area will serve as a starting point for innovations which will subsequently be scaled-up across the remaining 325 hectares of the Port Lands. It is part of the Sidewalk, Lab City of Toronto project. ICPs are modular paving elements, which are prefabricated in a production facility and brought to site once they have cured and hardened. They can take various shapes, but hexagonal pavers (Figure 5.1) are the preferred ICP for integration into the Quayside Neighborhood project based on conversations with members of Sidewalk Toronto.

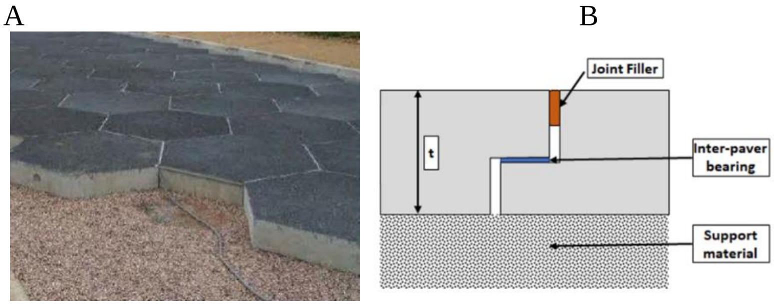


Figure 5.1 Typical hexagonal ICP shapes,

The ICPs are placed on graded base material that provides vertical support. They are often designed to behave independently but are sometimes designed with shear keys that provide load transfer between adjacent ICPs. The ICPs can be placed by hand if they are small enough or by using a vacuum lifting device. ICPs are considered highly adaptable due to their modular design. Any given element can be removed and replaced by another element with the same dimensions, but with desired characteristics. For instance, traditional pavement elements such as those shown in Figure 5.1 can be installed, and later replaced by elements incorporating lights for lane delineation, mounting brackets for bus-shelters, benches or other sidewalk features, or other surface element such as curbs.

Twelve (12) concrete mixes (Mix# 1 to 12) including a control mix, were primarily proposed based on mechanical performance and applicability in a Canadian context, per **Table 5.2**. Mixes consisted of varying percentages of Supplementary Cementations Materials (SCM) and Recycled Concrete Aggregates (RCA) and were noted to outperform control or conventional mix under various tests. Cementitious materials in this study are Glass Pozzolan (GP), Fly Ash (FA), Slag (S), and General Use Limestone (GUL) to replace General Use (GU) cement partially or fully; Recycled Concrete Aggregates (RCA) to partially replace coarse aggregate; and incorporation of Carbon Curing technologies.

Table 5.2 Primary mix design for 1m^3 of concrete mix

Mix #		GU	Coarse	Fine	Water	Steel	GUL	GP 10%	Slag 20%	FA 10%	CRCA 25%
1	**Control Mix, GU 100%)**	417	950	793	188	40	0	0	0	0	0
2	**GUL 100%**	0	950	793	188	40	417	0	0	0	0
3	**90%GU + 10% GP**	375.3	950	793	188	40	0	41.7	0	0	0
4	**80%GU + 20% slag**	333.6	950	793	188	40	0	0	83.4	0	0
5	**70%GU +20% slag+10% GP**	291.9	950	793	188	40	0	41.7	83.4	0	0
6	**80% GU +10%FA+10%GP**	333.6	950	793	188	40	0	41.7	0	41.7	0
7	**100GU + 75%NA + 25% CRCA**	417	712.5	793	188	40	0	0	0	0	237.5
8	**90%GUL + 10% GP**	0	950	793	188	40	375.3	41.7	0	0	0
9	**80%GUL + 20% slag**	0	950	793	188	40	333.6		83.4		
10	**70%GUL +20% slag+10% GP**	0	950	793	188	40	291.9	41.7	83.4	0	0
11	**80% GUL +10%FA+10%GP**	0	950	793	188	40	333.6	41.7	0	41.7	0
12	**100%GUL + 75%NA + 25% CRCA**	0	712.5	793	188	40	417	0	0	0	237.5

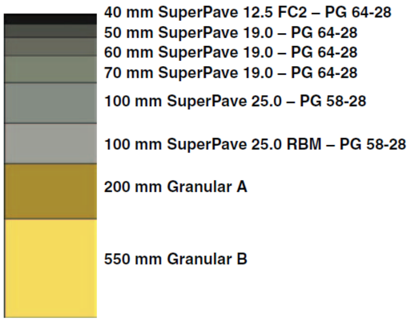
Leveraging the existing research study pioneered by the French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR), material quantities and proportions of mix constituents were obtained from published IFSTTAR documents for mix design. It was found that mix proportioning was similar in practice. Material quantities per metre cube formed the basis for material quantity estimation for each proposed concrete mixture and this was harnessed in the sustainability assessment, laboratory testing plan, and overall mix design development. This thesis provides an environmental assessment of the mixtures in Table 5.2 and the results are discussed in section 5.3.

5.2.2.2 Case Study 2: Functional Pavement Design

The case study for a functional pavement design is a long-life pavement design known as a Perpetual Pavement (PP). This case study builds on the CPATT project documented in a thesis by El-Hakim (2009) on the design and instrumentation of three pavement test sections on Ontario’s Highway 401. The thesis provides details of the PP designs and an equivalent conventional design, which were compared based on structural performance and life cycle cost. The research program documents provide details that will be used to investigate the environmental performance in the life cycle of PP design compared to a convention flexible pavement design.

Construction of three test sections on the Eastbound of Highway 401 approaching Woodstock, Ontario area was completed in the summer of 2009. As shown in Figure 5.2, different pavement cross sections and asphalt mixes are used in two test sections. For that project, one section is built with a conventional flexible pavement design for high traffic roads and the other two consist of perpetual pavement (PP) designs. One of the PP-sections is constructed with a Rich Bottom Mix (RBM) layer which means the binder asphalt content is increased by 0.5% and the other PP section is constructed without having the RBM layer at the bottom asphalt layer. The two perpetual pavement test sections are identical in terms of structural pavement layer characteristics and thicknesses with the exception of the asphalt binder content in the bottom asphalt layer.

Preliminary pavement structural evaluation and analysis was performed for the three pavement designs using the AASHTO-Mechanistic Empirical Pavement Design Guide (MEPDG). The 50-year analysis period simulation models were created using input level three in the software (PMED). The mechanical, physical and chemical properties of the different pavement layers were based on state-of-the-art practice and in line with the design inputs provided in the Ministry of Transportation of Ontario (MTO) pavement design and rehabilitation manual. The results of the roughness performance (IRI in m/km) is shown in Figure 5.3.



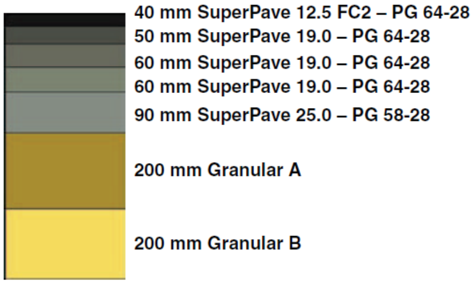


Figure 5.2 Cross section of the pavement designs at the test site, (a) Perpetual pavement design with RBM, (b) conventional flexible pavement design for high traffic, (FC2 = Friction Course 2, PG = performance grade) (Source: El-Hakim and Tighe, 2012)

The RBM layer incorporates a better-than-optimum binder content. El-Hakim and Tighe (2012) reported that RBM layer showed superior performance in terms of resistance to fatigue cracking, reduced moisture susceptibility and in-place air void in field compaction. However, the long term performance predictions of the PP design sections show similar performance over an analysis period of 50 years (El-Hakim, 2009).

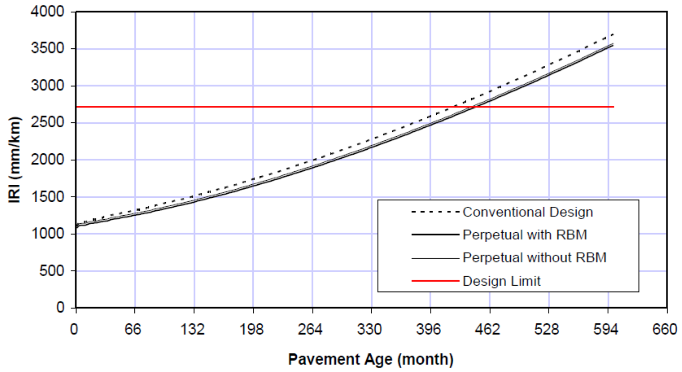


Figure 5.3 IRI performance prediction for the three different sections designed convention method, PP with RM layer and PP without RBM layer.

Based on the performance information, the maintenance plan (see Table 5.3) for 70-years service life was used to evaluate the lifecycle cost of different pavement designs. Since the structural performance of PP with RBM is expected to be same as the performance of PP without RBM, the two sections are expected to have the same maintenance plans.

In this study, the energy use and CO_2 emissions of the construction and maintenance of these alternative pavement design and management program as shown in Table 5.3 were evaluated to determine the environmental sustainability implications of choosing a long-life pavement strategy over a conventional approach for a high-volume roadway in Ontario.

Table 5.3 Maintenance and rehabilitation program for a 70-year design (El-Hakim, 2009)

Perpetual Pavement Design	
Maintenance and Rehabilitation Activity	Year

Conventional Pavement Design	
Maintenance and Rehabilitation Activity	Year

Rout and Crack Sealing (280m/km)	4
Rout and Crack Sealing (280m/km)	9
3% Mill and Patch 40 mm	10
Rout and Crack Sealing (560m/km)	12
15% Mill and patch 40 mm	15
Mill 50mm Asphalt pavement	21
SMA- 50 mm	21
Tack coat	21
Rout and Crack Sealing (280m/km)	24
Rout and Crack Sealing (280m/km)	28
15% Mill and patch 40 mm	32
Rout and Crack Sealing (560m/km)	36
Mill 50mm Asphalt pavement	38
SMA- 50 mm	38
Tack coat	38
Rout and Crack Sealing (280m/km)	42
Rout and Crack Sealing (280m/km)	46
15% Mill and patch 40 mm	50
Rout and Crack Sealing (560m/km)	54
Mill 50mm Asphalt pavement	58
SMA- 50 mm	58
Tack coat	58
Partial Reconstruction of Pavement	62
Rout and Crack Sealing (280m/km)	66
Rout and Crack Sealing (280m/km)	70

Rout and Crack Sealing (352 m/km)	3
Rout and Crack Sealing (352 m/km)	6
Rout and Crack Sealing (352 m/km)	9
5% Mill and patch 50 mm	9
Rout and Crack Sealing (704 m/km)	12
20% Mill and patch 50 mm	15
Rout and Crack Sealing (704 m/km)	18
Tack Coat	19
Mill 50 mm Asphalt Pavement	20
Superpave 12.5 FC2 - 50 mm	20
Rout and Crack Sealing (352 m/km)	21
Rout and Crack Sealing (352 m/km)	24
Rout and Crack Sealing (352 m/km)	28
20% Mill and patch 50 mm	28
Partial Reconstruction of Pavement	30
Rout and Crack Sealing (352 m/km)	33
Rout and Crack Sealing (352 m/km)	36
Rout and Crack Sealing (352 m/km)	39
5% Mill and patch 50 mm	39
Rout and Crack Sealing (704 m/km)	42
20% Mill and patch 50 mm	45
Rout and Crack Sealing (704 m/km)	48
Tack Coat	49
Mill 50 mm Asphalt Pavement	50
Superpave 12.5 FC2 - 50 mm	50
Rout and Crack Sealing (352 m/km)	51
Rout and Crack Sealing (352 m/km)	54
Rout and Crack Sealing (352 m/km)	58
20% Mill and patch 50 mm	58
Partial Reconstruction of Pavement	60
Rout and Crack Sealing (352 m/km)	63
Rout and Crack Sealing (352 m/km)	66
Rout and Crack Sealing (352 m/km)	69
5% Mill and patch 50 mm	69

5.2.2.3 Case Study 3: Rehabilitation Design

The case study for a rehabilitation design is a rapid rehabilitation strategy known as the Precast Concrete Inlay Panels (PCIP). This case study builds on a recent CPATT project documented in a thesis by Pickel (2018) on rehabilitation design and construction of a PCIP trail section on the right-hand northbound lane (Lane #3) of Highway 400, south of Barrie Ontario. The PCIP was developed as option to address the premature rutting failure observed on several high-volume traffic highways in the province of Ontario. The MTO was interested in the development of a new rehabilitation technique using precast concrete panels inlayed into the HMA pavement structure. It was considered an alternative to the full depth rehabilitation (FDR) strategy which can be time-consuming nature so precludes it from use on the 400-series highways due to the MTO's practice of limiting construction windows to the time between 10 pm and 6 am. An FDR approach is a recycling rehabilitation technology considered environmentally friendly due to its reuse of existing roadway (Melese 2019). However, FDR require a minimum of 18 days to complete removal and reconstruction of existing pavement. 18 days is only achieved when FDR is mixed with cement but the general use FDR will require 45 to 50 days of construction time (Reeder et al. 2017). So, the convention practice at MTO to address the issue was application of 40 mm or 80 mm mill and overlay (M&O) procedures, which requires only one night but ends up exhibiting the same failure after another three to seven years (Pickel, 2018). The goal of this is evaluate the environmental performance of adopting an alternative rehabilitation strategy (PCIP) compared to the convention practice (M&O) address premature rutting failure on high-volume traffic roads in Ontario

The design, construction, and performance information for PCIP trial documented in the thesis by Pickel (2018) are collated to guide this study. The PCIP strategy consist of several subprocesses that enables milling an asphalt pavement and placing a precast concrete panel. The PCIP trial section had three sections that each incorporated a different method of providing sub-panel support to the PCIPs, since the support conditions beneath precast concrete pavements can be a significant factor in determining PCIP performance. The Grout-supported (GroS) was found to the preferred in terms of constructability and performance on load transfer efficiency for each joint. Grout Supported Slabs incorporating levelling bolts are placed on the milled asphalt surface with rapid setting bedding grout. So only the GroS-PCIP is included in this investigation. The energy and material use for material production, material transportation, construction equipment and the maintenance schedule for rehabilitation of 1km 1lane pavement section for a 20-year service life is considered in a life cycle assessment of the PCIP strategy and the conventional M&O rehabilitation method. The excess energy due to the work zone and pavement condition during the use phase are also considered in this study.

Precast panel design and materials:

The dimensions of the precast panel are 3.66 m by 4.57m. It contains dowels (38 mm in diameter, 355 mm long) to provide load transfer and are located at the mid height of the panel, and spaced at 300 mm on centre. The panel reinforcement includes two mats of 10M bars. A 205 mm design thickness was considered. Approximately 200 panels are required for 1 km road. PCIP Materials includes the Portland concrete mix (cement, aggregate, water) and steel. Bedding grout material is a mixture of cement, water, and plasticizing admixture. Each panel required approximately 14 bags of bedding grout, An environmental product declaration has been produce for industry-wide structure precast concrete panels (Athena Sustainable Materials Institute 2014), and for cement production in Ontario (Lafarga Canada Inc 2019). These data are used in the LCI, a full documentation of the LCI is available in the Appendix C.

Construction process:

The unit processes for PCIP installation that include equipment processes as provided in the thesis document are:

- Saw cutting Milling
- Asphalt milling and surface cleaning
- PICP Placement
- Placement of transverse joint grout
- Placement of flowable edge grout
- Transverse joint grout saw cutting

The measure IRI post-construction of the PCIP were way above MTO threshold, while the adjacent asphalt surface show very low IRI performance, Pickel (2018) points that diamond grinding will be necessary to meet the road roughness performance requirement. So, Diamond grinding was considered a final step in the construction process.

For comparison, the FDR processes and the conventional M&O is considered, the study by Melese (2019) provides estimates of Co2 emission for the cradle to construction gate of FDR, so the construction process is not included. Thus, construction emissions are estimated separately based on the construction processes detailed in the report by Reeder et al. (2017) and data from Nasir (2018) and Min et al. (2020). M&O cradle to construction CO2 emission have previous been reported by Nasir (2018), her findings are adopted in this study.

Work zone:

One of the main reasons for considering the PCIP is the benefit of accelerated construction and shorter life for work zones. Thus, it is necessary to quantify the effect of work zone using the strategy and compared the effects to those of a conventional rehabilitation strategy. For the work zone impact analysis, construction site and duration information is collated analysed using the Traffic analysis tab in the recently develop Province of Ontario Emission Tracker for Transportation (POETT) by Min et al (2020). The construction work zone was developed based on the layouts described in the Ontario Traffic Manual for Temporary Conditions (Book 7) (Ministry of Transportation of Ontario, 2014). The temporary closure for two lanes of a six-lane road (TL-38) was adopted. For the PCIP strategy, the assumed nightly placement is 40 panels per night, which corresponds to a work zone length of approximately 200 m, and a total length of 1570 m., Thus 4 nights are required for rehabilitation by PCIP strategy. For the alternative method M&O, he length of the construction site is 1370 m plus the length of the construction zone. Since the M/O construction operation can be completed in one night, the full 1 km length of the assumed section is the nightly work zone, which results in a total length of 2370 m. For FDR, similar work zone is considered but for a duration of 18 days. The work zone capacity, traffic speed and throughput calculation are detailed in Appendix C.

5.3 Results and Discussion

5.3.1 Case study 1 - Environmental Performance of innovative Pavement Design Mix

5.3.1.1 Asphalt Mix

HMA-RCA Mix – include the recycling of RCA into HMA mix

Initial environmental assessment was conducted to investigate potential differences in the life-cycle performance outcome of a pavement by applying multiple free-access pavement LCA tools to a case study of HMA-CRCA mix designs. As a result of comparing the potential life-cycle environmental performance outcome of the HMA mix designs and features of different tools, the differences in datasets and life-cycle inventory (LCI) modelling approaches were analyzed as well. The pavement LCA tools adapted were PaLATE, ECORCE M, and Athena pavement LCA. Due to the limitations of PaLATE, another research project at CPATT involved updating the database of the original PaLATE (2004). This version of PaLATE with an update database is also considered here and the results compared with results from the original PaLATE highlight differences in outcomes because of the changes in database. The updates included emission factors and data for CO2 [Mg], SO2 [kg], NOx [kg], PM10 [kg] and CO [kg], and data for energy consumption. The results were presented at the 2018 TAC conference poster presentation. Some of the highlights include:

- For climate change impacts, the Global Warming Potential (GWP) is the performance indicator use, general measure by the Kg CO2 equivalent of GHG emissions. Figure 5.4 shows that the difference in GWP values of mixes containing CRCA compared to the control mix range approximately from -10% to 23%. Similarly, to energy consumption results, Athena tool accounts for benefits of using CRCA. PaLATE results show that energy and climate change impacts increase with increased quantity of NCA substituted with CRCA in HMA mixes.

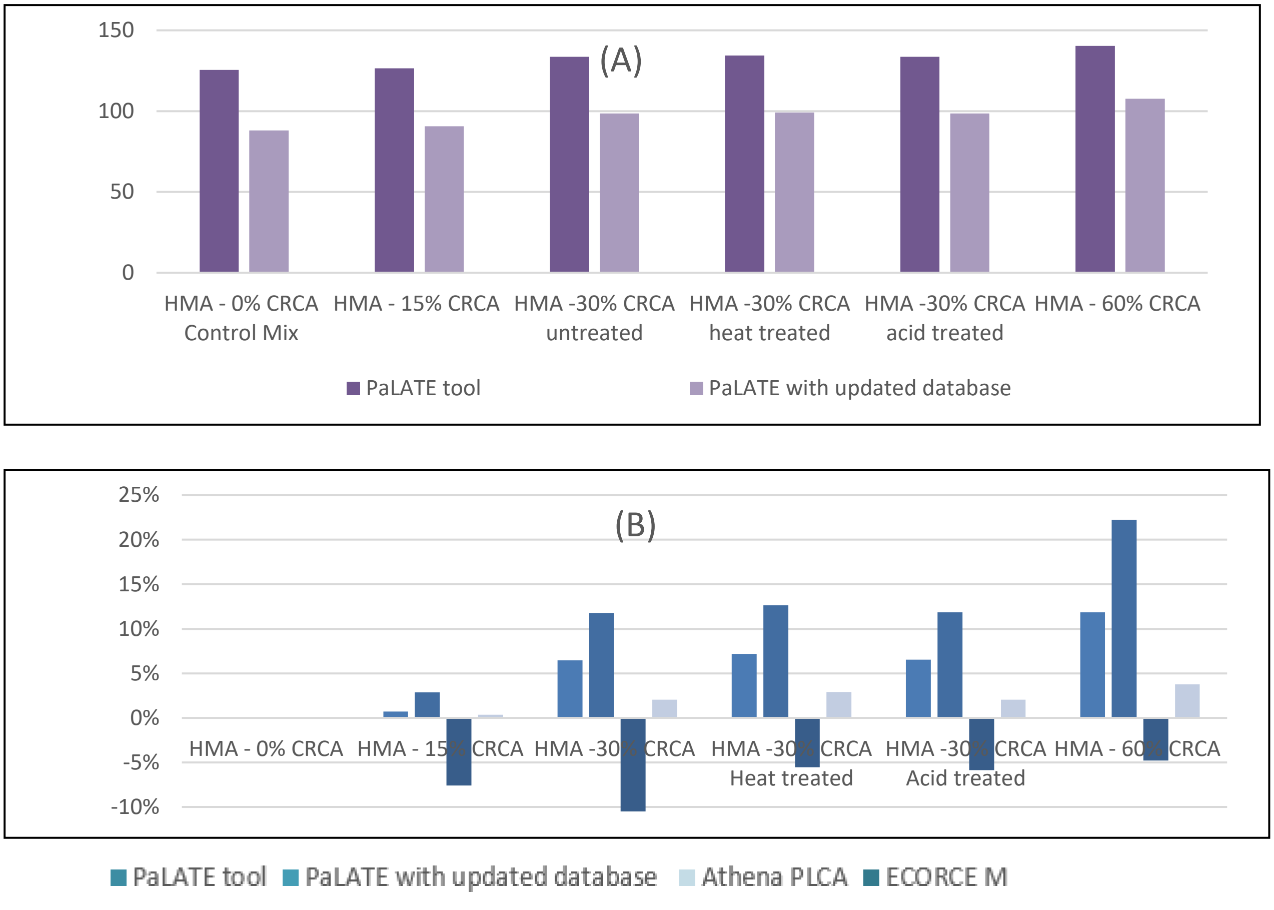


Figure 5.4 (A) GHG effect (Global Warming potential (kg CO2 eq.) estimates of 5 HMA mixes with varying proportions of CRCA compared to control mix with 0% CRCA, (B) GWP (CO2 [Mg]) of pavements with 6 different HMA mix designs for PaLATE with base data and PaLATE with updated data

- Highlight the difference between GWP values reported by the original PaLATE tool and the version with updated data. In general, the scores for all mixes from update PaLATE show a much lower impact than the results from the old PaLATE that present high levels of variability. PaLATE was found to overestimate results the two impact categories climate change and energy consumption, similar findings have been reported in previous study by Santos et al. (2011).
- Some of the main causes of variations in environmental performance of HMA-CRCA mixes reported by the tool were:
    - Discrepancies in data input
    - Modeling and allocation approach characterization of impacts

5.3.1.2 Concrete Mix

Sidewalks Concrete Mix – includes the use of recycle, by-products and waste material into a concrete mix at different proportions (see Table 5.2)

5.3.1.2.1 Environmental impact of materials

Energy Use: Figure 5.5 shows the energy use demand for cradle to gate impact of 1km 2lane pavement section constructed with the mix designs stated in Table 5.4. This shows the sum of energy used for material production, material transportation from plant to construction site, and construction of pavement at the site. Mix 10 seems to provide the best environmental benefit in terms of energy use. All mixes did have less energy demand compared to the control mix (Mix 1) but Mix 7 performed worse. Energy use benefit of Mix 10 is from the use of high percentage of supplementary cementitious material (30%) and the GUL cement which has less energy demand in material production compared to GU cement.

Mix 7 includes recycled materials but the energy required to process the recycled concrete aggregate before using it in the concrete mix make this mix have the worst environmental impact based on energy resource use. For material production, the results mirror the finding for total impact, where mix 10 provide the most benefit and mix 7 has the worst impact (Figure 5.5A). Similarly, performance ranking of mixes is evident in energy demand for material transportation shown in Figure 5.5B.

Table 5.4 Energy use and CO2 Emission contributions from material production and transportation

		Energy Use (MJ)		CO2 Emissions (Kg)	
Mix ID	Description	Material Production	Material Transport	Material Production	Material Transport
Mix#1	Control Mix, GU 100%)	98.0%	2.0%	98.6%	1.4%
Mix#2	GUL 100%	97.8%	2.2%	98.5%	1.5%
Mix#3	90%GU + 10% GP	97.9%	2.1%	98.5%	1.5%
Mix#4	80%GU + 20% slag	97.7%	2.3%	98.3%	1.7%
Mix#5	70%GU +20% slag+10% GP	97.5%	2.5%	98.1%	1.9%
Mix#6	80% GU +10%FA+10%GP	97.7%	2.3%	98.3%	1.7%
Mix#7	100GU + 75%NA + 25% CRCA	98.0%	2.0%	98.6%	1.4%
Mix#8	90%GUL + 10% GP	97.6%	2.4%	98.3%	1.7%
Mix#9	80%GUL + 20% slag	97.5%	2.5%	98.2%	1.8%
Mix#10	70%GUL +20% slag+10% GP	97.3%	2.7%	98.0%	2.0%
Mix#11	80% GUL +10%FA+10%GP	97.5%	2.5%	98.2%	1.8%
Mix#12	100%GUL + 75%NA + 25% CRCA	97.8%	2.2%	98.5%	1.5%

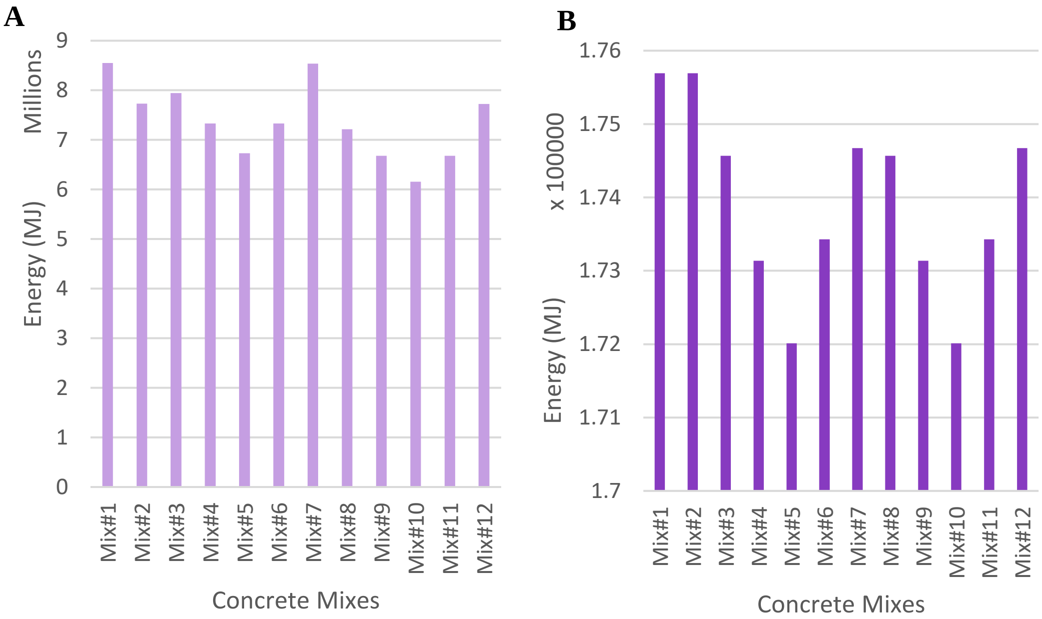


Figure 5.5 Energy use for material production (A) and transportation (B) of mix designs in Table 5.2

Carbon Emission (CO_2)

In terms of Climate change impact (Figure 5.6), all mix designs performance better than the control mix (Mix 1). Mix 10 showed the highest reduction while mix 7 showed the least reduction compared to Mix 1. Figure 5.6A depicts the climate change impact of material production and Figure 5.6B represent the impact of material transportation from material producing plants to construction site.

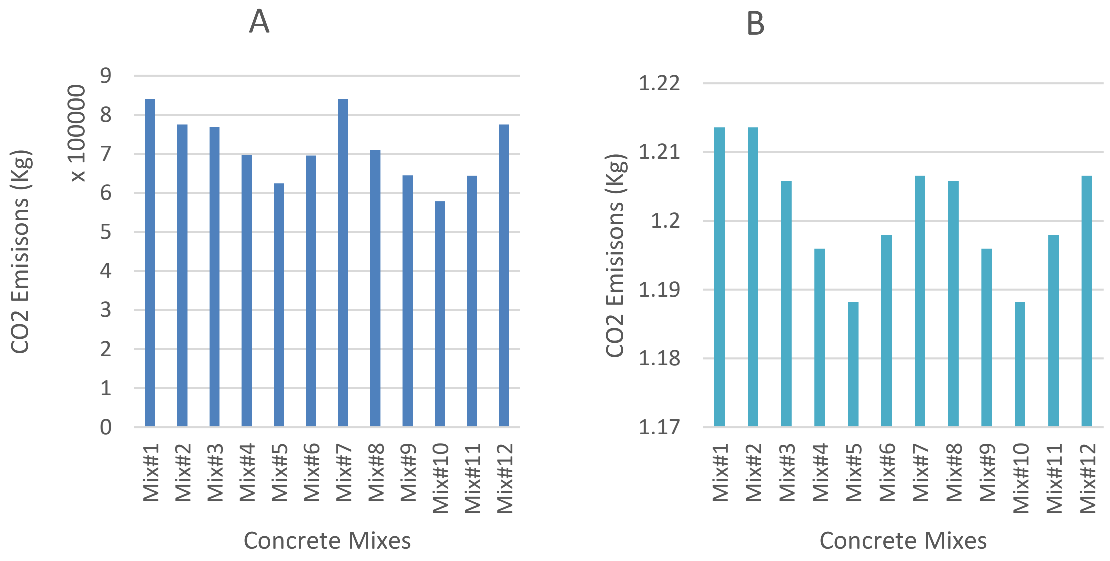


Figure 5.6 Climate change impact of material production and transportation of mix designs in Table 5.2

The effect of material production and transportation benefit can be better visualized when we consider production of $1m^3$ of concrete mix, the result as shown in Figure 5.7 below. Mix 10 has over 30% less energy demand and carbon emissions while Mix 7 has less than 5% energy saving compared to the control mix.

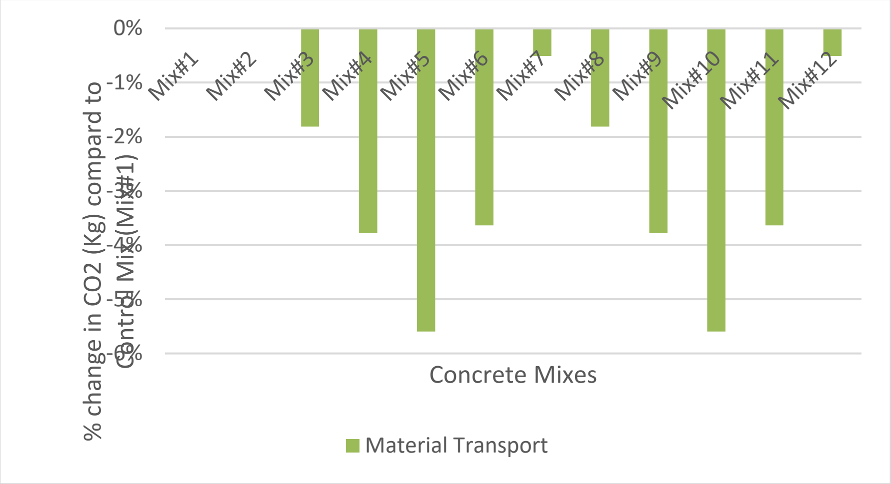


Figure 5.7 Percentage of material production and transportation CO_2 emissions reduction of all mixes in table 1 (Mix 2 – Mix 12) compared to control mix (Mix 1)

Sensitivity analysis

The sensitivity of the results to the transportation distance were analysed. The transportation of RCWM materials were assumed to all be 30km in the base case analysis and distance for Portland cement is 50. The sensitivity analysis investigated the effect of short transportation distance of RCWM in comparison to base case and a 10km increase from base case (Table 5.5). In Table 5.6, the transportation distance of Portland cement was considered. Generally, the result shows that mixes will perform at the same rate when compared across (Mix #2 to Mix#12), but the percentage reduction in carbon emission reduction changes when compared to the conventional Mix #1 as the transportation distance changes.

Table 5.5 Change in CO2 reductions compared to the control and Sensitivity of results to transportation distance of RCWM used in the mixes

CO2

	10km	20km	30km	40km
Mix#1	0%	0%	0%	0%
Mix#2	-8%	-8%	-8%	-8%
Mix#3	-14%	-12%	-11%	-10%
Mix#4	-27%	-23%	-21%	-20%
Mix#5	-41%	-35%	-32%	-30%
Mix#6	-27%	-23%	-21%	-20%
Mix#7	-1%	-1%	-1%	-1%

Mix#8	-21%	-19%	-18%	-17%
Mix#9	-34%	-30%	-28%	-27%
Mix#10	-47%	-41%	-38%	-36%
Mix#11	-34%	-30%	-28%	-27%
Mix#12	-9%	-9%	-10%	-10%

Table 5.6 Sensitivity of results to transportation distance of Portland cement used in the mixes

CO2

	25Km	50Km	75Km	100Km
Mix#1	0%	0%	0%	0%
Mix#2	-8%	-8%	-8%	-8%
Mix#3	-9%	-11%	-12%	-12%
Mix#4	-18%	-21%	-23%	-25%
Mix#5	-28%	-32%	-35%	-37%
Mix#6	-18%	-21%	-23%	-25%
Mix#7	-1%	-1%	-1%	-1%
Mix#8	-17%	-18%	-19%	-20%
Mix#9	-25%	-28%	-30%	-32%
Mix#10	-34%	-38%	-41%	-43%
Mix#11	-25%	-28%	-30%	-32%
Mix#12	-10%	-10%	-9%	-9%

5.3.2 Case Study 2: New Functional Pavement Design

Emissions from material production, material transportation, construction and maintenance of perpetual pavement in comparison to the conventional asphalt pavement are shown in Table 5.7.

Table 5.7 CO2 emission of a perpetual pavement compared to a conventional asphalt pavement

Pavement Type	Life Cycle phases	CO2 Emissions (tonnes)
Perpetual pavement	Material production	1309
	Material transportation	112
	Construction	6
	Maintenance	205

Conventional pavement	Material production	824
	Material transportation	112
	Construction	4
	Maintenance	224

The results reveal that the perpetual pavement will result in more emissions due to the material demand in the initial construction stage. Even though less maintenance requirements re quilted in less CO2 emissions during maintenance phase, the life cycle impact, considering initial construction process and materials production, depicts more emission is produce by adopting perpetual pavement.

In terms of environmental damage cost (Table 5.8), the difference between the two strategies is quite large. The environmental cost of perpetual pavement is about 40% higher than the conventional practice. These results have been estimated based on life cycle phase with the exclusion of the use phase and work zone emissions during maintenance. Those pavement LCA phases were not considered due lack of information regarding performance of PP after construction nor after a maintenance strategy. The work zone information was not available for this project. If those phases were considered, it is possible to see environmental performance in favour of the PP given that less frequent maintenance is expected, and better pavement performance is possible.

Table 5.8 Environmental damages from construction and maintenance of Perpetual pavement compared to conventional pavement.

	Total CO2 Results (kg)	**Environmental Damages of CO2 emissions ($2010 CAD)**
Initial Construction	CO2 (kg)	$2010 CAD
Perpetual Pavement	**1426546**	**$ 167,549.57**
Conventional Asphalt pavement	**939152**	**$ 110,304.56**
Maintenance		
Perpetual Pavement	**1741708**	**$ 204,566**
Conventional Asphalt pavement	**1908523**	**$ 224,158**

5.3.3 Case Study 3: Rehabilitation Design

The lifecycle CO_2 emissions from PCIP rehabilitation technique are shown in Table 5.9. The results reveals that the material production is the major source of emissions. Impacts from the construction site are about 12% and work zone contribution is less than 1%. Given that a nightly construction activity was done, the change to work zone traffic was minimal, thus less queuing and a smaller impact on emissions from vehicles travelling through the work zone.

Table 5.9 Lifecycle CO_2 emissions of the Precast Concrete Inlay Panels (PCIP)

	Amount per 1km-1lane road	Unit Processes	Kg CO_2 per 1km-1lane
PCIP	200 panels	Material production	341814
		Transportation	24012
		Manufacturing	47219
Grout	28000 bags	Material production	218
Milling pavement	$754m^3$	Cut and mill	61187
Work zone	1570m of 2 lanes for 4 days	Work zone traffic	2679.2

In comparison to the conventional M&O, work zone traffic impact per day from the PCIP is less than that from a M&O work zone (see Table 5.10). This this due to the short work zone for PCIP.

Table 5.10 Work zone impact for 9 hours of 2370m (M&O) versus 1570m (PCIP) of lane closure

Work Zone Impact	Capacity = 1800		Wkzone speed = 80km/h	
Summary of the Project Level Result				
Convention M&O	CO_2	CH_4	N_2O	CO_2e
Baseline Total (kg)	24893.06	0.540049	0.221162	24972.07
Work Zone Total (kg)	26036.66	0.586746	0.268077	26130.77
Additional Emissions/day Due to Lane Closure (kg)	1143.598	0.046697	0.046915	1158.699
Total Additional Emissions	1143.598	0.046697	0.046915	1158.699
PCIP Strategy	CO_2	CH_4	N_2O	CO_2e
Baseline Total (kg)	14389.66	0.31218	0.127845	14435.33
Work Zone Total (kg)	15050.73	0.339174	0.154964	15105.13
Additional Emissions/day Due to Lane Closure (kg)	661.0671	0.026994	0.02712	669.7966
Total Additional Emissions	661.0671	0.026994	0.02712	669.7966
Emission Reduction compared to the Alternative Scenario	482.5307	0.019703	0.019795	488.9026

The longer work zone will impact traffic, queuing time and the speed of vehicle passing through. The fuel consumption of vehicles in a work zone are influence by these factors, so are the resulting vehicle emissions for fuel combustion.

The CO2 emission estimates for work zone impact of M&O and FDR were added to the material production and construction estimates collated from literature (Melese 2019; Nasir 2018) to calculate the lifecycle impacts. Table 5.11 provides a summary of the results for conventional M&O used by MTO, and two types of FDR - general use (FDR-GU) and FDR with hydraulic binder to stabilize the structure (FDR-HBR1). As noted earlier, M&O can be done in one night and the road will be open to traffic, but FDR will require about 40 days when FDR-GU is used, and 18 days when FDR-HBR1 is used for road rehabilitation. Although material and construction equipment have less impact on the environment, the long road close on the work zone can have very large environmental and social impacts.

Table 5.11 CO_2 estimate for alternative rehabilitation techniques

Alternative rehabilitation techniques	Materials and Construction Kg CO_2	Work zone Kg CO_2	Total Kg CO_2
Mill and Overlay (M&O)	198743.9	1158.699	199903
FDR – General Use (FDR-GU)	244,270	139043.9	383314
FDR- with Hydraulic binder (FDR-HRB1)	179,331	62569.76	241901

In terms of contribution of each LCA phase, material production and construction are the main source of CO_2 emission when PCIP or M&O is adopted (Figure 5.8). This finding is important to inform engineers and decision makers on designing for sustainability, so that process improvements that aim to reduce environmental impacts can consider changes that can be made in the material production phase to achieve more benefit when adapting PCIP and similar technologies.

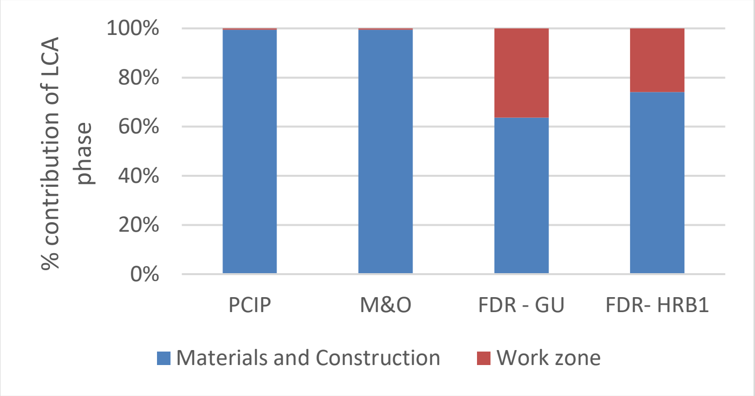


Figure 5.8 Contributions of each LCA phase to the LCA environmental performance.

On a relative scale of contributions by each phase, PCIP seems to perform better than FDR (see Figure 5.9). The difference between M&O and FDR when compared to PCIP reveals that the within phases comparison to the overall environmental performance, PCIP will present better performance than FDR, this is only on a relative scale. FDR was found to produce less CO_2 emissions compared to PCIP based on the results in Table 5.11 and Figure 5.9. While M&O looks better than other technologies, it may not provide a better performance when frequent maintenance is considered, for example compared to no maintenance on a 15-year service life of PCIP.

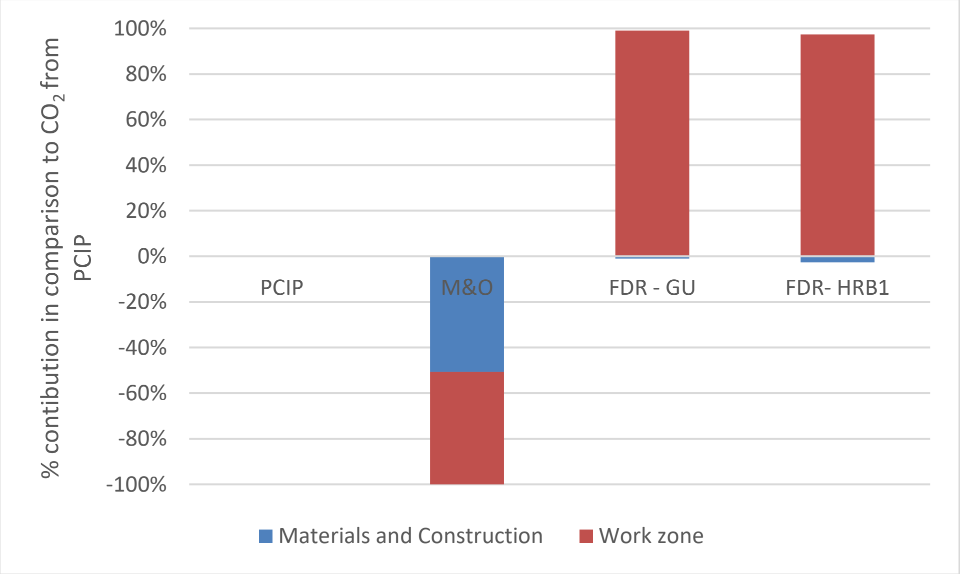


Figure 5.9 CO_2 contributions by each LCA phase of conventional techniques compared to PCIP

Some limitations of this study include a lack of consideration of carbon sequestration from the PCIP and grout installed, and benefits from less frequent maintenance. While research has shown that grout material can be used to reduce CO_2 emissions via mineral carbonation, for example a slurry mix of 100g of dry cement mix in grout can sequestrate up to 17g of CO_2, it was found that it is highly dependent on the water content and initial humidity of the slurries (Uliasz-Bochenczyk and Pomykała 2011). Even though less maintenance is expected, there is no data for long term field observation of the PICP performance and the initial construction is considered the largest contributor to LCC. Pickel (2018) found that the PCIP strategy generally has a higher life cycle cost because of its high initial costs, and the present worth cost difference between the two strategies was sensitive to factors that affected the initial cost, such as the panel unit cost and the installation rate. The analysis was based on several cost and maintenance assumptions that will be further clarified as the service life of the PCIP rehabilitation is better defined. Finally, several design improvements suggestions were made based on the performance and construction of the PCIP trial. These included increased strength specifications, advanced milling control, improved HMA edge protection, joint material design, drainage details, and diamond grinding following the complete installation of the PCIP rehabilitation. These factors can be investigated by future study.

5.4 Recommendations and Conclusion

This chapter investigated the lifecycle carbon footprint of selected measures suggested in the literature to mitigate CO_2 emissions. The first measure focused on the use of recycled, co-product and waste materials (RCWM). The second focused on long-lived pavement design. The last explored the use of expedited technologies for highway rehabilitation. The material production, construction and work zone impacts were considered.

For the use of RCWM, findings show that the CO_2 estimates can be influenced by the LCA tool used for assessment and the transportation distance considered. As discussed in chapter 2, the use of RCWM must ensure that the impacts of material transportation do not negate the benefit of including the material. This will differ by each project and project location. Future studies can investigate the maximum distance for transportation of RCWM for use at a project site in Ontario.

The preliminary assessment performed here for long-life pavements show that perpetual pavement designs will produce more CO_2 emissions compared to a conventional design. The work zone and use phase impacts were not considered; future studies can include these LCA phases in a comprehensive study when the data are available for the field performance of perpetual pavement.

A cradle to grave analysis of the PCIP strategy might be considered in future study when the data required becomes available to support such analysis in a consistent manner for comparative LCA. Pickel (2018) compared the life cycle cost of PCIP strategy to the conventional mill and overlay strategy, but the maintenance schedule was assumed based on the performance of a JPCP pavement, since there was not enough data on PCIP. When long term field performance information from the project sites discussed in this chapter become available, future work can analyse the data and add to this knowledge.

Chapter 6

Sustainability Impact of Pavement under Future Climate Conditions (TRB,2020)

This chapter was presented at a conference in 100th Annual Meeting of the Transportation Research Board, The National Academies of Sciences, Engineering, and Medicine, Washington DC, USA, 2020. It has been published by the Transportation Research Record, reference: “Achebe, J., Oyediji, O., Saari, R. K., Tighe, S., & Nasir, F. (2021). Incorporating Flood Hazards into Pavement Sustainability Assessment. Transportation Research Record. https://doi.org/10.1177/03611981211014525.”

6.1 Introduction

A recent Canada Climate Change Report reveals that the Canadian climate is warming twice as fast as the global average, and that the costs of climate-related externalities have immediate effects (Bush and Lemmen 2019). Physical infrastructures are one the most pressing risk areas in the myriad of threats posed by the widespread impacts of the expected changes in precipitation, temperature, wind and rise in sea level (Council of Canadian Academies 2019). Extreme precipitation – about 126 mm of rainfall in Toronto – created an expensive flood hazard, resulting in approximately $1 billion in socio-economic damages in 2013 (Environment and Climate Change Canada 2013). As the planet warms, extreme climate events (ECE) such as wildfires, flooding, heatwaves, and droughts become more frequent. The historical 100-year return period flood hazard events in south-western Ontario are expected to become 10–60 year return period events by the end of the century (Gaur et al. 2018). Increased rainfall frequency may lead to pavement infrastructure flooding and higher groundwater levels, affecting pavement strength, and lowering pavement’s load bearing capacity (Tighe 2015). The greater frequency of maintenance and rehabilitation required under changing climate may increase the life cycle cost and environmental burden of pavement (Guest et al. 2019; Qiao 2015). Moreover, pavements are under high risk for damage by climate hazards as they were not designed for these extreme conditions (Lu, Tighe, and Xie 2018a; Mallick et al. 2018).

The effect of climate change on paved roads can be positive or negative depending on many factors, including the location, intensity and form of climate impact. Under future climate scenarios with higher average temperatures and precipitation, an approximately 1% reduction in baseline roughness is expected for flexible pavement designed for low volume roads in British Columbia and Quebec.

Equivalent designs constructed in Alberta, Manitoba and Ontario will experience accelerated pavement deterioration estimated at 1.3%, 2%, 1% road roughness increases, respectively, under the same climate scenario (Tighe et al. 2008). Flooded pavement can potentially experience delayed, jump or direct failure effects depending on its level of resilience. That resilience is a function of traffic, pavement age, existing distresses, pavement type, sub-layer support and structural strength. Delayed effect failure occurs when no immediate damage is induced at the time of the flood, but deterioration is accelerated afterward. Jump effect refers to a significant drop in pavement performance after a flood event. The affected pavement may then maintain a constant rate of deterioration after the drop. Direct failure effect characterizes a total loss or a sharp drop in pavement performance after a flood event (Lu et al. 2018a). For flexible pavement, Lu et al (Lu, Tighe, and Xie 2018b) investigated impacts of various precipitation scenarios predicted by 24 global climate models (GCM) and estimated up to a 2.9% damage ratio for typical Ontario collector roads. The resulting risk of asset value loss under minor flood damage is over $100 thousand per kilometer. For rigid pavement, a recent study (R. Oyediji, Lu, and Tighe 2019) found that, in lower cycles of extreme precipitation scenarios, the flood impact on Jointed Plain Concrete Pavement (JPCP) performance results in minor damage (2.22%) based on changes in International Roughness Index (IRI) and loss of structural capacity. By comparing results of other studies on the flood impact of flexible pavement, the authors posit that rigid pavements are less vulnerable to flood damage and recommend adopting rigid pavements as a flood adaptation strategy. However, at higher cycles of extreme precipitation (for example, 3 event cycles under the RCP 4.5 100-year flood scenario) could result in 3.47% additional flood damages, or up to 316 days of pavement life lost for collector roads in Ontario designed with undowelled JPCP (O. Oyediji, Achebe, and Tighe 2019). Thus, more frequent ECE under continued climate change will increase infrastructure damage and associated costs. Transportation agencies, meanwhile, have limited financial resources for road maintenance and face demands for sustainable infrastructure(Li et al. 2012). It is therefore critical to develop integrated frameworks to inform the long-term planning and design of sustainable pavement, and selection of climate change mitigation and adaptation strategies, that account for investment returns and environmental impacts.

Addressing climate change issues in infrastructure management requires both adaptation practices to build resilient structures, and mitigation practice to reduce the environmental burden related to road construction, maintenance and operation. Research studies into pavement resilience under ECE usually adopt a risk-based approach (Meyer, Amekudzi, and O’Har 2010) in measuring related impacts. Several studies have reported changes in infrastructure deterioration trajectories due to changes in prolonged and/or extreme climate loads (Lu et al. 2018a; Mallick et al. 2014; Mills et al. 2007; Tighe 2015). Some studies have further investigated changes in performance and service life by quantifying damage, damage risk, pavement fragility and asset value at risk per probability of flood occurrence, to promote climate change adaptation for pavement resilience in various climate scenarios (Khan et al. 2017; Lu et al. 2018b; Mallick et al. 2018). These studies provided insight into various factors of pavement resilience and sustainability performance under various climate change scenarios. However, the sustainability implications of promoting resilient strategies in pavement design and management under climate change is rarely considered (Enríquez-de-Salamanca 2017). A unified assessment approach that integrates climate hazard impact and risk into sustainability assessment can better inform long-term planning for resilient transportation network (Bocchini et al. 2014) and accelerate sustainable transitions (Shaw et al. 2014).

The current practice of integrating sustainability assessment into pavement-related decision-making typically focuses on a single dimension, usually economic or environmental impacts. This siloed approach is not suitable for long-term planning and sustainable pavement management (Van Dam et al. 2015). A few sustainability performance assessments of pavement integrating climate change impacts have reported the cost burden for road networks (Schweikert et al. 2014), the expected higher life cycle cost (Bles et al. 2016; Qiao 2015) and environmental impact (Guest et al. 2019). Lifecycle cost analysis (LCCA) is often used for economic analysis while lifecycle assessment (LCA) or environmental impact assessment is used to quantify environmental impacts. LCCA is commonly used by transportation agencies across Canada to evaluate the overall long-term cost effectiveness and compare competing pavement designs, but the economic costs of adverse environmental impacts are rarely considered in pavement design and management decisions (M Moges et al. 2017; Transportation Association of Canada (TAC) 2013). Recent studies have estimated social costs of environmental impacts of pavement management activities (including air and water pollution, and noise) to integrate them into existing LCCA (Nasir 2018; Pellecuer 2016; Pellecuer et al. 2015; Yu, Lu, and Xu 2013; Zhang, Keoleian, et al. 2010). A similar approach can be used to assess the sustainability performance of pavement while considering climate change impacts. This study aims to advance the sustainability and resilience assessment of pavement with the consideration of flood hazard impacts. It proposes a framework that enables a reasonable understanding of sustainability impacts associated with future climate conditions and offers a potential integrated approach for climate change adaptation and mitigation.

Typical rigid pavements in Ontario for collector road design (500 ADTT) on a weak subgrade consist of a 190mm Jointed Plain Concrete Pavement (JPCP) slab over a 200mm granular base which provides uniform support for the concrete slabs. In Manitoba, the design for a similar subgrade consists of a JPCP slab ranging between 225mm to 275mm over a 100mm base and 200mm sub-base material (Ahammed, Kass, and Hilderman 2013; Holt, Sullivan, and Hein 2011). The functional performance and structural strength of a concrete pavement is largely within the concrete slab itself due to the fact that the slab's rigidity enables spreading the load over a large area and reduces pressure on the subgrade below. Flooded pavements have experienced reduced pavement strength due to inundation based on previous investigations. Increasing pavement thickness especially in floodplain areas have been recommended as a flood adaptation strategy. Oyediji et al. (O. Oyediji et al. 2019) found that damage magnitude in high volume roads lowered by 2.69% when slab thickness was increased by 50mm, and considered it more beneficial to achieve the necessary structural capacity to promote concrete pavement resilience. Increasing slab thickness may increase economic and environmental costs associated with more material and energy requirements for initial construction, but could be beneficial in terms of service life and adaptive capacity of the roadway over its design life especially for high traffic volume roads with weak subgrade (O. Oyediji et al. 2019). The research focus of this study is to assess life cycle costs and environmental damages of flood impacts on concrete pavement under extreme climate change events that could occur even under the Paris Agreement (Rogelj et al. 2016). This study consists of three key components. First, the AASHTOWare Pavement Mechanistic-Empirical Design Guide software (PMED) by the American Association of State and Transportation Officials (AASHTO) (Applied Research Associates ARA Inc. 2004) is used to simulate the future performance of four case study JPCP designs under the Representative Concentration Pathway (RCP4.5) 100-year flood scenario. This component builds on a recent case study by Oyediji et al (O. Oyediji et al. 2019) for JPCP collector road design and considers different thicknesses of structural layers in the design for Manitoba. Second, it estimates damage as a function of the changes in predicted deterioration of the designs and quantifies improvements related to adaptation measures. Third, it assesses sustainability impacts of collector road design including greenhouse gas (GHG) and air pollutant emissions and lifecycle costs of the road section. The social costs of the impacts are valued based on a Lifecycle Emissions and Social Cost (LESC) framework (Nasir 2018). Lifecycle costs of the road section are estimated using applicable Canadian LCCA techniques (Mizan Moges et al. 2017). The differences in the structural performance and sustainability impacts of the designs with different structural layer thicknesses can be used to rank alternative designs when considering different designs for a roadway.

The ranking provides public agencies with a better understanding of sustainability implications of climate change adaptation and it highlights the need to consider mitigating impacts in pavement climate change adaptation practices.

6.2 Methods and Data

The analysis framework used in our study consist of three phases as shown below:

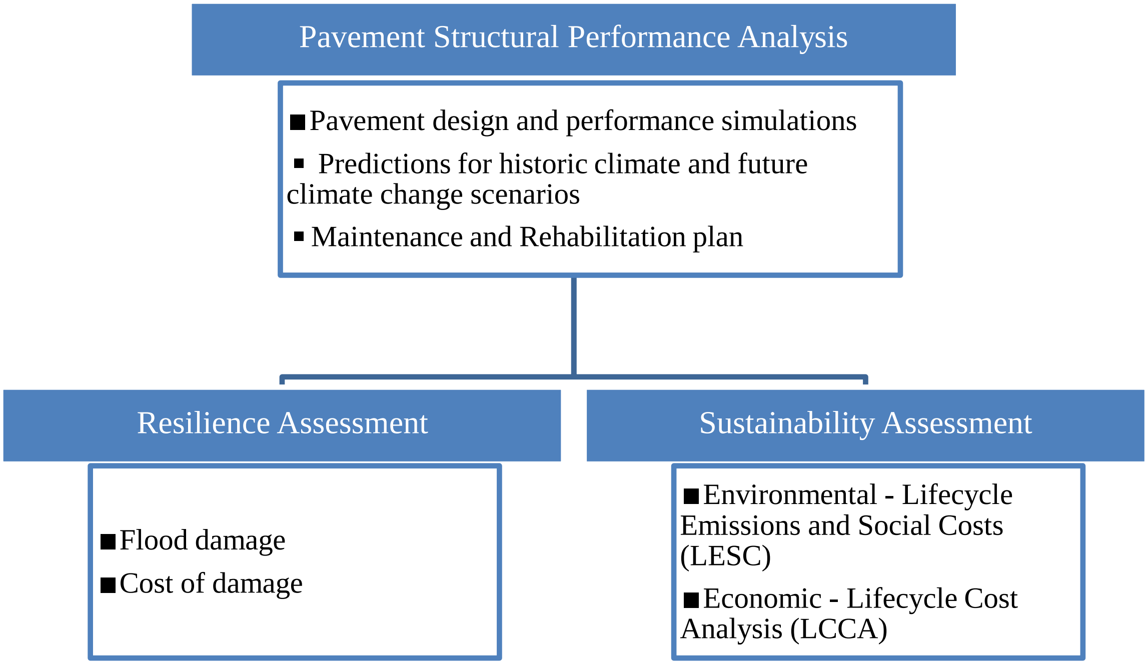


Figure 6.1 Analysis Framework for sustainability and resilience assessment of pavement designs

This streamlined framework provides a unified approach to address both sustainability and resilience issues in pavement design and management. It consists of quantification methods that assess key factors of sustainability and resilience. The first aspect is a technical dimension that feeds into the sustainability and resilience assessments. The environmental and economic aspects are the focus of the sustainability assessment in this study. The economic dimension of the resilience assessment addresses only the direct cost associated with damage from ECE. In this study the ECE of concern is flooding. Other climate change impacts can be considered where the data and models to integrate the stressors are available.

6.2.1 Pavement Design and Deterioration Modelling

Pavement ME Design Features

Input data used for the PMED analysis include general design information, traffic, and pavement structures. Non-stabilized crushed stone is used as the granular base in the design. It should consist of 98% hard durable crushed material. These open graded materials provide greater resistance to the effects of moisture than dense graded materials with high fines contents (Applied Research Associates 2015; Applied Research Associates Inc. 2004).

The JPCP designs investigated are based on typical rigid pavement structures in Ontario (Holt et al. 2011) and Manitoba (Ahammed et al. 2013) for 500 Annual Average Daily Traffic (AADT) and weak subgrade of 30 MPa stiffness. For Ontario JPCP design (ON) identical designs are investigated using historic climate data to estimate baseline performance under a no flooding scenario (ON-HC) and using precipitation data projected for RCP 4.5 under a 100-year flood event to estimate performance under a flooding scenario (ON-CC). For the case of the Manitoba JPCP design (MB), three designs (MB-1, MB-2, MB-3) with slab thicknesses of 225mm (1), 250mm (2), 275mm (3) typical for designs with weak subgrade, are investigated to estimate baseline performances in no flooding scenarios (MB-HC1, MB-HC2, MB-HC3) and in flooding scenarios (MB-CC1, MB-CC2, MB-CC3).

Table 6.1 Input Parameters for PMED Rigid Pavement Design Analysis

Input parameters	**Input Values**	
JPCP designs		
Case Studies	Ontario JPCP (ON)	Manitoba JPCP (MB)
Performance Trigger Values		
International Roughness Index (IRI)	2.70m/km	2.50m/km

Faulting	3.00mm	3.00mm
Transverse Cracking	20%	15%
PCC Layer		
PCC Thickness	190mm	225mm (1), 250mm (2), 275mm (3)
Dowels	Non-dowelled	Non-dowelled
Base Layer		
Soil Material	Granular A (A-1-a)	Crushed Stone (A-1-a)
Soil thickness	200mm	100mm
Sub-base Layer		
Soil Material	No Sub-base Layer	Granular C (A-1-b)
Soil thickness	No thickness	200mm
Subgrade Layer		
Soil Material	High Plasticity clay (A-7-6)	High Plasticity clay (A-7-6)
Traffic		
Two-way AADTT	500	500
Traffic Growth Rate	2%	2%
Truck traffic in design lane	50%	50%
No. of lanes in design direction	1	1
% of trucks in design direction	100%	100%
Design Reliability	75%	90%

Climate Data

Hourly Climate Data (HCD) files of the North American Regional Reanalysis (NARR) data were accessed via the open-source PMED design database (AASHTOWare Pavement ME Design Climatic Data) for two climate stations in Toronto and Winnipeg. NARR's historical data was integrated into the program to establish a baseline or no-flooding scenario (HC). Climate inputs in PMED consist of temperature, relative humidity, precipitation, wind, and sunshine. The precipitation data, modified to account for extreme precipitation scenarios assuming extreme precipitation in the form of flood depth and duration, could indirectly be harnessed to incorporate flood potential in the PMED model. Extreme precipitation data under the RCP 4.5 scenario was obtained using the Intensity Duration Frequency Climate Change Tool (IDF_CC Tool 4.0) (Anon n.d.) to project the required climatic data (2000-2100) for the climate change scenario (CC). The tool engages 24 Global Circulation Models (GCMs) and 9 downscaled GCMs under the Coupled Model Intercomparison Project Phase 5 (CMIP5) using rigorous downscaling methods such as spatial and temporal downscaling, statistical analysis and optimization to update pre-estimated IDF from historical precipitation data to IDF under RCP scenarios (Simonovic et al. 2016).

Considerations were given to flood depth, flood duration and event cycle in the computation of climate data. The 24hrs extreme precipitation data obtained from ensemble of models are 168.84mm and 127.35mm for Toronto, Ontario (43.81174, -79.41639) and Winnipeg, Manitoba (43.86200 -79.37000) stations, respectively, under a RCP 4.5 100-year future return period, with downscaled data gridded at a resolution of 300 arc-seconds (0.0833 degrees, or roughly 10 km) (PCIC 2017). To represent Ontario future IDF projection under RCP 4.5 in Pavement ME climate inputs, available climate data for 2012/2013 was selectively modified and precipitation extremes under RCP 4.5 assumed to start in July, 2013, judging from a historical July 8th, 2013 100-year event (126mm) that caused approximately $1 billion in socio-economic damages in Toronto, Ontario. This event was known as the most expensive natural disaster ever in the Province of Ontario (Environment Canada 2014). PMED's integrated climate file is then modified to include future return floods under RCP 4.5 starting on this date. For Manitoba, precipitation extremes under RCP 4.5 was modelled to begin on May 2011, following the 160mm rainfall event that year. The 2010/2011 climate file was then modified to introduce projected future IDF values. In both the ON and MB cases, a 7-day flood duration was assumed as field studies conducted by (Gaspard et al. 2007) Gaspard et al. (2007) reports no additional damage to pavement after 7 days of inundation. Rainfall magnitude was then translated to flood depth potential. The probability of having a 100-year flood magnitude within a 25-year pavement design period and 50-year pavement analysis period is 25% and 50%, respectively. Hence, there is a 0.5 chance the case study pavement will experience magnitudes of a 100-year recurrent interval and with changing climate conditions, this likelihood will potentially increase. Additional cycles of extreme precipitation were considered in the background paper the authors previously investigated in (Oyediji et al. 2019; Oyediji et al. 2019). Results indicated higher damages from increased event cycles for Ontario roads but no potential damage increase in Manitoba even after two to three cycles.

It is important to state that flood loads can be classified into flood depth, flood duration, flood velocity, flood debris and flood contaminants and all do have damaging impacts on pavement. However, a modelling method for integrating data for all these stressors does not yet exist (R. Oyediji et al. 2019). Thus, this study considered extreme precipitation in the form of flood depth and duration. As a result, PMED Enhanced Integrated Climate Model (EICM) precipitation data were modified to account for and establish extreme precipitation scenarios and applied in the PMED 2.5.3 tool to model impacts on pavement performance in this paper. Although PMED EICM assumes that the pavement system has adequate drainage and currently does not model precipitation infiltration from the surface, it uses a surrogate Thornthwaite water Moisture Index (TMI) to calculate equilibrium suction for the base and subgrade layers. TMI is determined from average monthly precipitation, average monthly temperature, monthly potential evapotranspiration, day length correction factor, number of days for each month, and average water storage capacity of soil (Yue and Bulut 2014; Zareie, Amin, and Amador-Jiménez 2016). Hence, influential climate parameters such as potential evapotranspiration temperature and average water storage capacity of soil, which affect the wetting and drying cycles of underlying pavement layers, were accounted for in TMI monthly estimates. Correlated suction values were used to obtain underlying soil water content and dynamically change resilient modulus as climate conditions changed. As the climate becomes wetter, more positive TMI values are derived and a decrease in matric soil suction occurs. As the climate gets drier, more negative TMI values are estimated and an increase in matric suction occurs (Yue and Bulut 2014).

Pavement Maintenance

Pavement deterioration under traffic loading and environmental effects, over time, leads to unacceptable levels of service. Poor pavement conditions not only reduce driving comfort but can also result in vehicle maintenance costs and excessive fuel consumption. Applying the right maintenance and rehabilitation (M&R) technique at the right time can improve performance and extent the service life of the pavement. Technically, pavement condition measures such as pavement condition/quality index, International roughness index (IRI), cracking, and faulting are commonly used to determine an unacceptable level of pavement condition based on a trigger value, then a maintenance activity is initiated (Fung and Smith 2010). The IRI metric is a widely used parameter for measuring the functional/structural quality of a pavement section. For the sustainability assessment (including environmental and economic measures) in this study to be meaningful and reliable, the trigger values for M&R were decided based on thresholds of pavement performance predicted by the PMED tool. This was done to reflect the most likely activities for each design alternative and scenario being evaluated.

Common M&R practices for concrete roads include corrective and preventive repairs such as crack/joint sealing, diamond grinding, partial depth repair, full depth repair and Hot Mix Asphalt (HMA) overlay. Diamond grinding, partial depth and full depth repairs are considered more resource intensive, but they can improve pavement performance and extend pavement life. Both diamond grinding and partial depth repair can extend the pavement life by 10-12 years. Diamond grinding can reset the IRI back to 1.8 m/km. Full Depth Repairs extend the pavement life by 10 -15 years and reset IRI to 1.1 m/km (MTO 2019; Transportation Association of Canada (TAC) 2013). Similar M&R programs used in Manitoba (Ahammed et al. 2016) and Ontario (Holt et al. 2011) were adopted in this study. The cost and environmental impacts were calculated for all designs with respect to the analysis period of 50 years considering initial construction and expected maintenance activities in subsequent years based on the IRI trigger value. To provide an equivalent analysis, the same group of M&R were considered for the 1st 2nd and 3rd M&R activity as follows:

- 1st M&R – Partial Depth Repair (2% of surface area); expected service life 10 ±2 years and reset IRI to 1.8m/km
- 2nd M&R – Partial Depth (5%), Full Depth Repair (10%) and Diamond Grinding (100%); expected service life 15 ±5 years and reset IRI to 1.1m/km
- 3rd M&R - Partial Depth (5%), Full Depth Repair (15%) and Diamond Grinding (100%); expected service life 15 ±5years and reset IRI to 1.1m/km
- 4th M&R – 1 lift HMA overlay (50mm); expected service life 12 ±2.8years and reset IRI to 1 m/km

6.2.2 Resilience Assessment

The risk analysis approach adopted in this section estimated damages and economic life cycle impacts due to an event based on the weighted possibility of occurrence of that event, as adopted in previous infrastructure resilience studies (Bocchini et al. 2014; Lu et al. 2018b). Flood damage and the expected cost of flood damage were quantified as measures of pavement resilience. The case of 1 cycle of 100 year flood event was considered. Other flood scenarios and climate hazards can be considered as well. The Damage Ratio was calculated as a structural loss measured by the change in IRI as in **Equation 6.1a and Equation 6.1b**. IRI is a regression function of cracking, spalling, faulting, and site factor in addition to an initial IRI. Therefore, IRI gives a holistic assessment of functional performance under inundation. Previous studies (Chen and Zhang 2014; Khan et al. 2017; Lu et al. 2018a; R. Oyediji et al. 2019; Tighe et al. 2008) evaluating concrete and flexible pavement flood impact employed IRI performance in both modelling and field analysis.

$$\delta_{ave}\ (\%) = \frac{\sum_{i=0}^{m}\left(\frac{IRI_{fi} - IRI_{nfi}}{IRI_{nfi}} * 100\%\right)}{m} \qquad (6.1a)$$

$$\delta_{IRI}\ (\%) = \frac{IRI_{f} - IRI_{nf}}{IRI_{nf}} \times 100 \qquad (6.1b)$$

Where:

i = month; δ_{ave} = Mean flood damage (%); δ_{IRI} (%) = IRI or overall damage ratio; m = Pavement design life in months; IRI_{fi} = International Roughness Index of JPCP for Month i under flood conditions (m/km); IRI_{nfi} = International Roughness Index of JPCP for Month i under no-flood conditions (m/km); IRI_{f} = terminal IRI under flood conditions (m/km); IRI_{nf} = terminal IRI under no-flood conditions (m/km)

Based on the damage ratio, risk-based costs have been used in previous studies to estimate the damage cost of extreme events (Bocchini et al. 2014) and value at risk for flooded pavement (Lu et al. 2018b). Both approaches need large amounts of data, yet the second approach needs extensive analysis to estimate pavement asset value as risk. After reviewing different approaches and based on the data available from the pavement network case study, **Equation 6.2**, adopted from Bocchini et al (Bocchini et al. 2014), was considered as the best fit for this study to estimate the cost of flood damage. It was applied in a similar study of an integrated resilience and sustainability assessment of bridge infrastructure at risk of natural hazards. The damage levels were defined in a structural loss approach similar to Lu et al (Lu et al. 2018b), where Minor, Moderate, and Major damage levels refer to damage ratios (δ_{IRI}) exceeding 1%, 1.5%, and 2.5%, respectively. Damage less than 1% was deemed insignificant. Therefore, combining the results of the fragility analysis with the construction costs of each pavement, the direct costs of flood damage were computed as in **Equation 6.2**:

$$C_f = \mathrm{P}_f \,.\, C_c \sum_{d=1}^{4} P_d . D_d \qquad (6.2)$$

Where:

C_f = the expected direct cost associated with the investigated flooding event; P_f = the probability of occurrence of the flooding event over the life of the pavement; C_c = the construction cost of the pavement; P_d = the probability of reaching damage level *d* as computed by the fragility analysis; D_d = the damage ratio associated with damage level *d*.

According to Gaur et al. (Gaur et al. 2018), the 1% probability of exceedance during the 100 years flood based on RCP 4.5 is a projected return period of 10 - 60 years for Southwestern Ontario, and 165-200 years for Manitoba. Taking the mean of 35 years and 182.5 years, this means 0.42% and 0.12% probability of exceedance over the pavement design life (25 years) for Ontario and Manito roads, respectively. The probability of exceedance estimated by a fragility analysis determines the susceptibility of the pavement to a hazard and the uncertainty in the pavement damage. Pavement fragility models and the analysis approach in Lu et al. (Lu, Tighe, and Xie 2017) were adopted. Three damage levels (*d*) were selected for this study and the probability of reaching the damage levels were estimated using the values of the mean flood damage (δ_{ave}) following the procedure adopted in (Lu et al. 2018b). Damage ratios associated with the damage levels are 1%, 1.5% and 2.5%. The resulting probability of the damage levels is shown in **Table 6.2.**

The unit cost for JPCP, base and sub-base layer obtained from Nasir (Nasir 2018) was utilized to calculate the cost of constructing each layer (**Table 6.2).** Using Equation 6.2 for all investigated case study designs and the data shown in **Table 6.2,** the expected direct cost was calculated. This analysis did not include indirect user costs due to structural failure (for example in total closure of the road) or during M&R activities; nor did it include the direct cost of M&R after flood events or during the life of the pavement. This resilience assessment considered only the design life whereas an investigation over the service life should consider the M&R costs as well as indirect user costs.

Table 6.2 Data for Resilience Assessment

Input parameters	**Input Values**			
JPCP Designs	ON	MB-1	MB-2	MB-3
Change in IRI (m/km)				
Average	0.07	0.02	0.04	0.04
Standard deviation	0.019	0.014	0.021	0.025
Cost of Construction ($)				
Surface layer	$1,070,669.00	$1,267,897.50	$1,408,775.00	$1,549,652.50
Base	$227,624.00	$113,812.00	$113,812.00	$113,812.00
Sub-base	- -	$103,600.00	$103,600.00	$103,600.00
Prob. of reaching damage level				
Minor (1%)	4%	42%	23%	18%
Moderate (1.5%)	44%	0%	49%	58%
Major (2.5%)	49%	0%	0%	4%
Insignificant (<1%)	3%	58%	28%	19%

6.2.3 Sustainability Analysis

For the sustainability analysis, the methods of life-cycle cost analysis (Transportation Association of Canada (TAC) 2013), a pavement life-cycle assessment framework (Harvey et al. 2016), and environmental cost calculations (Nasir 2018) are used to assess the impacts along economic and environmental dimensions. These methods allow quantification of sustainability impacts over the pavement life cycle. The assessment is performed for design under historic climate and designs considering the impact of future climate and ECE, i.e. flood impacts in this case. It is assumed that all design alternatives would be part of the same management process.

Environmental Impacts

The pavement service life, predicted performance and expected M&R is integrated with a Lifecycle Emissions and Social Cost (LESC) framework to evaluate the environmental impacts of materials, construction and M&R operations (Nasir 2018). This framework consist of the following steps:

1. Goal and Scope: For this study, two scenarios of four JPCP designs for Ontario and Manitoba are considered. The objective is to quantify the environmental performance change of existing JPCP designs in these regions under a future climate change mitigation scenario. The environmental performance is quantified as the social cost of emissions affecting air quality and climate change using marginal damage estimates of five atmospheric emissions: carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NOx), sulfur dioxide (SO_2) and particulate matter with aerodynamic diameter less than 2.5µm ($PM_{2.5}$). The functional unit of analysis is a two lane 1km collector road section designed for traffic of 500AADTT and a 50-year service life. A lane width of 3.7m was assumed and the dimensions of pavement layers for each are available in Table 1. The scope of the study is limited to three phases of the pavement lifecycle: material production, initial construction and maintenance activities. In the Use phase, factors that contribute to environmental performance include energy consumption due to pavement deterioration, albedo effects, carbonation and roadway lighting, leaching and runoff. Although advances in recent research have suggested models to integrate these uses phase factors, there are still important challenges that may limit their usefulness to the decision making process (Azarijafari et al. 2016). A simplified focus on construction and M&R is adopted here, given that the goal is to demonstrate an approach towards a holistic assessment of pavement design sustainability and resilience. Thus, use phase was excluded here and its analysis is left for future work. The system boundary considers a 50-year service life but not the end of the pavement life, thus end of life environmental impacts were excluded.

2. Emissions Inventory: an inventory of emission for all phases within the scope was created using a version of the Pavement Lifecycle Assessment Tool for Environmental and Economic Effects (PaLATE) tool originally developed by the Consortium on Green Design and Manufacturing at the University of California, Berkeley (Horvath 2007). The version used here was developed by Nasir (Nasir 2018) as part of a research program to quantify the environmental cost of pavement management in Ontario. This version includes updated emissions data, and emissions factors (EMFs) for Ontario or Canada. An EMF refers to the average rate of emissions associated with an activity. The total emissions of a specific pollutant from given a set activities can be calculated using **Equation 3** (Frey n.d.)**:**

$$TE_j = \sum_i (EMF_{i,j} \times A_i) \quad (2)$$

Where: TE_j= Total emission for pollutant j in a given geographical area, and time period, units of mass; $EMF_{i,j}$ = Emission facto for pollutant j from source activity i, units of mass/per unit activity; A_i = Total units of activity. The equation and the EMFs in **Table 3** are used to estimate total emissions for all processes/activities considered within the system boundary of this study.

3. Social Costs of Emissions: Each of the emissions considered have different effects on human health and the environment. Thus, they cannot be directly compared with each other. The environmental impacts of each pollutant were valued by applying their respective marginal damages (MD, in $/ton) to the mass emitted to estimate the full social cost of atmospheric releases. The term "marginal" here refers to damages as compared to baseline damages, where the baseline includes all emissions from all sources in a given baseline year. The "marginal" emissions from the case study here of 1-km pavement designs will have minimal impact on the baseline atmosphere, so MD can be applied. A full simulation of all emission sources in the atmosphere can be computationally prohibitive. As an alternative, multiple different approaches are routinely applied to estimate the MD of emissions the academic literature (see, e.g (Fann, Baker, and Fulcher 2012; Fann, Fulcher, and Hubbell 2009; Gilmore et al. 2019; Heo, Adams, and Gao 2016; Jaramillo and Muller 2016; Mukherjee et al. 2020; Pappin et al. 2015; Shindell 2015; Wang et al. 2020)) and regulatory analysis. MD estimates vary greatly depending on factors such as site and source of emissions, the valuation method used, and the impacts considered (Nasir 2018; Yu 2013). This study uses median values of marginal damage estimates most relevant to pavement-related emission sources in Ontario and converted to year 2010 Canadian dollars, derived from a review of the literature, as detailed in Nasir (Nasir 2018) (**Table 6.3**). The estimates are meant to represent the full social cost of each marginal ton of emission, including effects on the climate, crops, and human health, depending on the relevant emission and underlying MD method. As social costs, they are not directly comparable to the Life Cycle Costs of pavement derived in the next section. However, the MD provide a common unit by which to sum the disparate effects of these emission. The sum of damages can then be used to compare the atmospheric-related impacts of different pavement designs under different scenarios, as presented in subsequent sections.

Table 6.3 Data for Sustainability Assessment

Input parameters	**Input Values**					
Emissions	CO_2	CO	NOx	SO_2	$PM_{2.5}$	References
Material production (EMF)						
Cement (g/Mg)	1100	0.06	3.7	4.1	0.208	(Horvath 2007; Nasir 2018)
Virgin aggregate (g/Mg)	14	--	0.016	--	0.003	
Concrete					0.223	
Transportation and Equipment (EMF)						
Freight trucking (g/tonne-km)	108.21	1.20	1.43	0.01	--	(Frey, Rasdorf, and Lewis 2010; Malzer 2005)
Rail	13.66	0.036	0.224	0.0001	--	
Non-Road Diesel Equipment (g/hp-hr)	375.46	1.51	4.99	0.002	--	
Emission Unit price ($)						
2010 CAD/Mg	$120	$750	$30500	$41160	$272780	(Nasir 2018)

Life Cycle Cost Analysis (LCCA)

The net present worth (NPW) method, which is one of the most commonly used LCCA approaches by Canadian agencies, (M Moges et al. 2017) was adopted. The unit costs for initial construction of each layer and the selected treatments were collected from (Nasir 2018) and listed in **Table 6.3**. The total life cycle cost (LCC_{Total}) was estimated using the net present value approach in **Equation 6.3**.

$$LCC_{Total} = C_{ini} + \left[\sum_{i=1}^{n} Cm,i \times \left(\frac{1}{1+r}\right)^{n}\right] - SV \times \left(\frac{1}{1+r}\right)^{n} \qquad (6.3)$$

Where: C_{ini} = Initial cost of construction ($); C_m = cost of maintenance m in the ith year ($); r = discount rate (4%); i = year of implementation; n = design life; SV= Salvage value ($). Total cost was calculated for the initial construction and maintenance program applied in scenarios with and without climate change. To bring the cost of M&R treatments to present worth, a real discount rate of 4% was used, which reflects common practice in Canada (M Moges et al. 2017; Transportation Association of Canada (TAC) 2013). The salvage value was converted to a present worth considering n = 50th year, as this cost occurs at the end of the period analyzed. Salvage value is calculated using **Equation 6.4**.

$$SV = \frac{L_{rem}}{L_{exp}} \times C_{pvt} \qquad (6.4)$$

Where: L_{rem} = remaining service life of the last M&R treatment; L_{exp} = expected service life of the last M&R treatment; C_{pvt}= cost of the last M&R treatment. The unit price (m^2) used in the analysis of JPCP layer, base, sub-base was assumed $76.15, $15.38 and $7 respectively. While the unit price of M&R follows as $7, $174.34, $264.92 for diamond grinding, partial depth repair and full depth repair, respectively.

6.3 Results and Discussion

6.3.1 JPCP Structural Performance

All three of the performance indicators (IRI, cracking, and faulting) of the PMED simulations at the end of the 25-year design period for the four JPCP case studies designs were examined for the climate change scenario. However, only the IRI threshold was used for M&R scheduling since faulting and cracking are regression variables in the IRI estimation. IRI trigger values for collector road design were 2.7 m/km for the Ontario design case and 2.5 m/km for Manitoba design case. The threshold to trigger M&R was exceeded early in the design life at year 8 and year 7 for ON-HC and ON-CC, respectively. Although Manitoba's faulting, cracking and Ontario's cracking predictions did not cross design trigger values, Ontario's faulting predictions exceeded the limiting threshold before the end of the 25-year design period.

Table 6.4 shows the structural performance results from the PMED modelling. From the deterioration curves, ON designs deteriorated faster than the MB designs. The structural performance of the Ontario design cases ON-HC and ON-CC reached 3.6m/km and 3.69 m/km terminal IRI values, respectively. The terminal IRI values for Manitoba designs were 3.6m/km, 3.65m/km, 3.48m/km, 3.55m/km, 3.4m/km, 3.49m/km for MB-HC1, MB-CC1, MB-HC2, MB-CC2, MB-HC3, MB-CC3, respectively. Increasing slab thickness gave better structural performance. This was true when comparing the MB designs under similar climate conditions (either HC or CC). It was true even when comparing across climate conditions when the slab thickness increase was large enough (in this case, 50 mm). In Manitoba, the flooded IRI of the thickest slab (MB-CC3) was lower than the unflooded IRI of the thinnest slab (MB-HC1).

Table 6.4 Structural Performance Results

Aspect	**Value**							
(per 1km of road)	Ontario design (ON)		Manitoba design 1 (MB-1)		Manitoba design 2 (MB-2)		Manitoba design 3 (MB-3)	
	ON-HC	ON-CC	MB-HC	MB-CC	MB-HC	MB -CC	MB-HC	MB-CC
IRI (m/km)								
Terminal IRI (year 25)	3.6	3.69	3.6	3.65	3.48	3.55	3.4	3.49
Mid-design life (year12.5)	2.93	3.01	2.6	2.63	2.54	2.58	2.5	2.55
At year 10	2.77	2.85	2.4	2.42	2.35	2.38	2.3	2.35
At year 5	2.38	2.45	2	1.98	1.94	1.96	1.9	1.94
Difference in IRI (m/km)								
Average	0.07		0.023		0.037		0.044	
Standard deviation	0.019		0.014		0.021		0.025	

Although structural performance increased with slab thickness, so too did the loss of structural performance under climate change. Table 6.4 shows that the IRI increased under the CC scenarios compared to HC, indicating a loss of structural performance due to flooding. The magnitude of this loss grew for each design case MB1, MB2 and MB3, increasing with increasing slab thickness. Thus, greater slab thickness improved structural performance. Sufficiently high thickness yielded performance under climate change equal to thinner slabs under historical conditions. However, thicker slabs also experienced higher magnitudes of performance loss due to flood.

The IRI predictions informed the maintenance policy for all the design cases (**Figures 6.2 and 6.3**). The difference in IRI predictions between the no flood condition with historic climate (HC) and flood conditions under the climate change scenario (CC) were used to determine damage ratios (**Figure 6.4)** which informed the resilience results in **Table 6.4.**

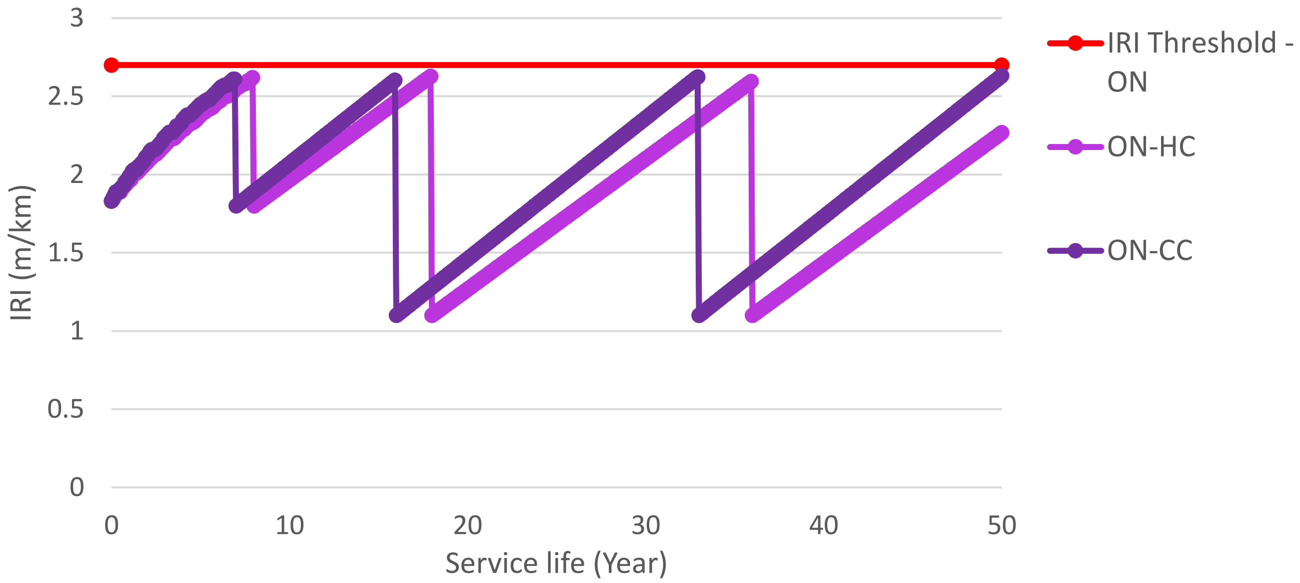


Figure 6.2 Performance of JPCP designs for Ontario collector road (AADTT-500), including maintenance schedules for a 50-year service life

The IRI performance results of PMED simulations and maintenance schedules for the 50-year service life for Ontario JPCP case studies designs under extreme scenarios are presented in **Figure 6.2.** ON-CC have early progression IRI profiles compared to ON-HC, and this means climate change impacts will likely cause a different rate of pavement degradation when compared to the historical climate scenario. Although the case of ON-CC does indicate that an increase in both IRI is likely and can create a significant shift in the maintenance and rehabilitation (M&R) schedule, one preventive maintenance and two corrective repairs were assumed feasible throughout the 50-year service life in both cases. The threshold trigger is based only on IRI as a function of faulting and traverse cracking throughout the design life. The deterioration in performance is more obvious for IRI in the Ontario JPCP design compared to alternative designs for Manitoba (**Figure 6.3**).

Figure 6.3 show Manitoba JPCP collector road IRI dynamics and maintenance interventions for each of the scenarios over a 50-year service life. The performance of MB-HC represents pavement design based on historic climate, while MB-CC considers climate-induced flood impacts on the JPCP design for Manitoba roads. Manitoba JPCP designs exceeded the thresholds at year 11, 10.75, 11.75, 11.25, 12.25 and 11.75 for MB-HC1, MB-CC1, MB-HC2, MB-CC-2, MB-HC3 and MB-CC3 respectively.

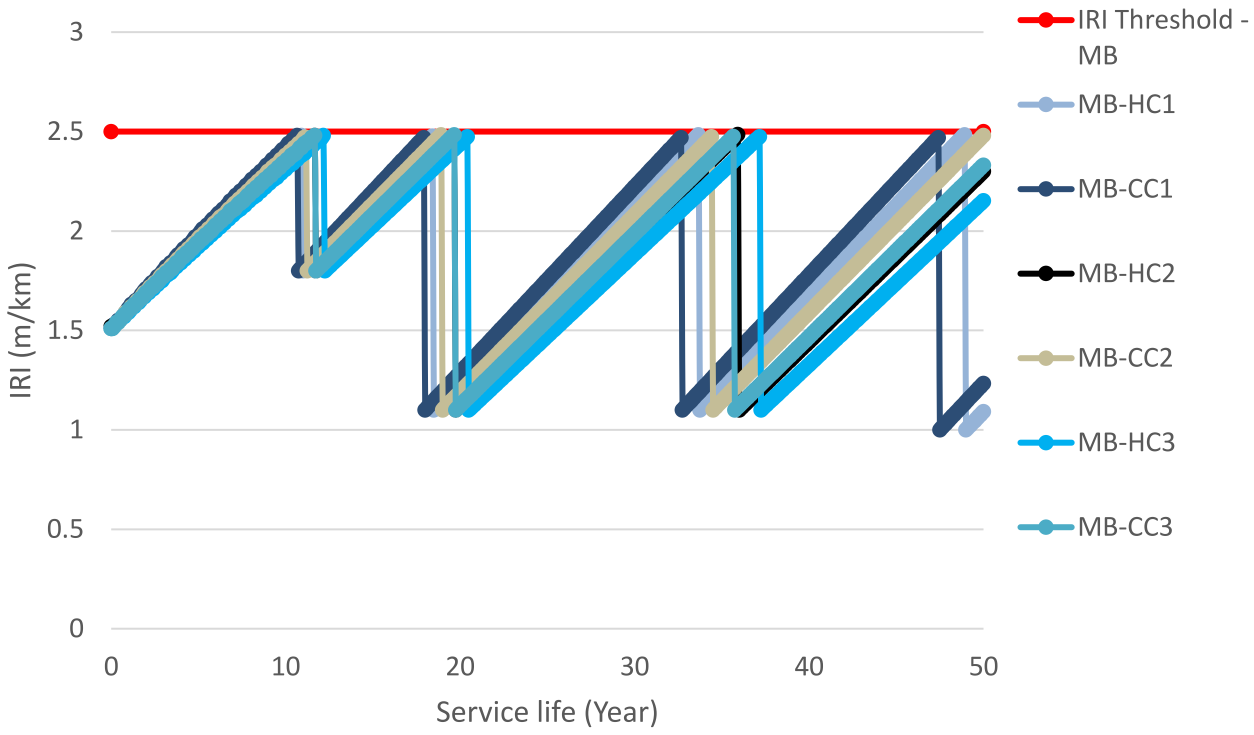


Figure 6.3 Performance of JPCP designs for Manitoba collector road (AADT-500), including maintenance schedules for a 50-year service life

The analysis of Manitoba designs shows that increasing thickness can increase pavement life. However, the use of a lower trigger value can result in additional maintenance as seen for MB-HC1 and MB-CC1 in **Figure 6.3**. Moreover, projected precipitation and flood frequency for Manitoba and Ontario has been low and high, respectively (Gaur et al. 2018), making Ontario road pavements more vulnerable to faster deterioration. Similar findings have been recorded for flexible pavements (Lu et al. 2018a; Tighe et al. 2008) in Ontario.

6.3.2 Resilience of Flooded JPCP

Figure 6.4 depicts the damage ratio over the design life of 25 years for ON-CC and MB-CC considering future climates compared to designs for no-climate change scenarios ON-HC and MB-HC, respectively. The average damage ratio for ON compared to MB is about two times higher. Although estimated service life loss in MB-3 is higher than ON, the service life prior to reaching limiting thresholds is longer in MB than ON. In essence, all MB (MB-1, MB-2 and MB-3) predicted service lives were higher than that of ON. Structural performance is of concern. The service life for ON is only 8 for historic climate and 7 for future climate/flood scenario, which is less than 50% of its expected design life.

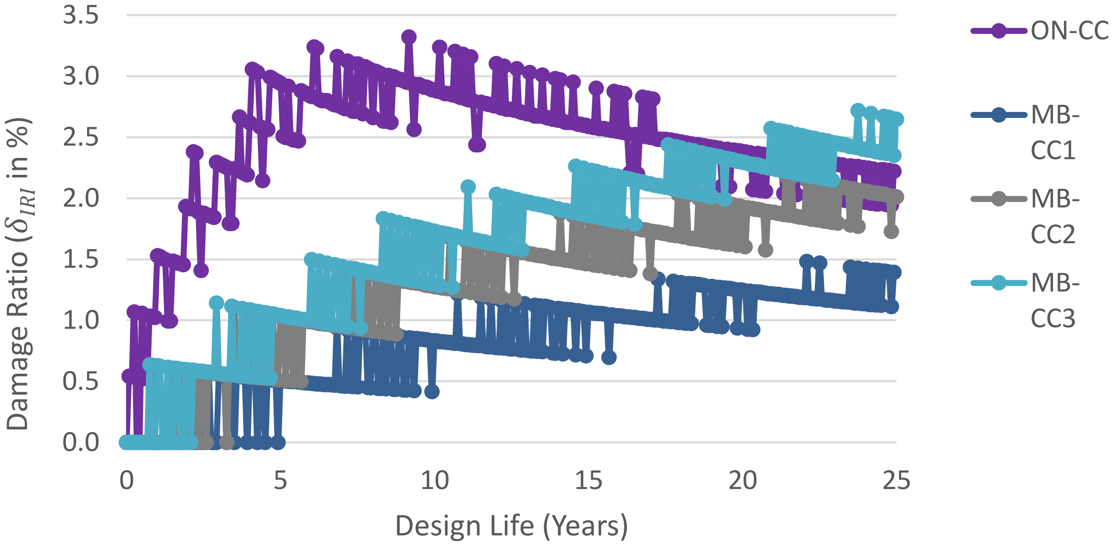


Figure 6.4 Damage ratio of JPCP Collector roads in Manitoba and Ontario (AADTT-500)

Table 6.5 presents the resilience assessment results measured by days of design life loss, average damage ratio over a 25-year design life and expected cost of damage (Equation 6.2). Based on changes in predicted IRI values (Table 6.4), CC scenarios reached higher terminal values compared to HC scenarios which resulted in design life loss, revealing climate change impacts on the design of life of the pavement (Table 6.5). The design with highest construction cost and service life loss was MB-3 for

Manitoba, but the ON design for Ontario experienced the highest average damage and damage cost. The estimated damage cost for ON design was almost 7 times that of the damage cost for other designs for MB. MB designs have larger slab thicknesses (225mm to 275mm) and additional drainage layers (sub-base layer) which may have provided the extra strength for better drainage that resulted in better structural performance and higher resilience. Considering the budget constraints and maintenance backlog at many road agencies in Canada (CIRC 2016), this damage cost could be an important risk for road agencies in Ontario to consider in the near future.

For decision makers in Manitoba, the results on slab thickness present a more complicated story. Thicker slabs performed better, but also incurred higher losses under climate change. In one sense, thicker slabs were more resilient to climate change, since they had lower IRIs after flooding than thinner slabs (as seen by comparing the CC scenarios for MB1,2, and 3 in Table 6.5). However, those thicker, more valuable assets lost more value under climate change. By this measure, they were less resilient. An informed decision should incorporate the life cycle cost, damage cost, absolute structural performance, and other relevant criteria, including environmental costs, which are presented next.

Table 6.5 Resilience Assessment Results

Aspect	**Value**			
	ON	MB-1	MB-2	MB-3
Analysis period-25 years				
Design life loss of CC scenario compared to HC scenario (days)	230	127	184	242
Cost of Construction ($1000)				
Per 1km 2 lane	$1,298.3	$1,485.3	$1,626.2	$1,767.1
Flood Damage				
Damage Ratio (δIRI in %)	2.43 (±0.55)	0.81 (±0.41)	1.32(±0.61)	1.63(±0.72)
Expected Direct Cost ($)	$10,516	$739	$1,895	$2,464

6.3.3 Sustainability Impacts of Flooded JPCP

Emissions and environmental costs were estimated across designs and flooding scenarios. **Figure 6.5** and **Figure 6.6** show the emissions based on pavement lifecycle phases and pavement management schedules.

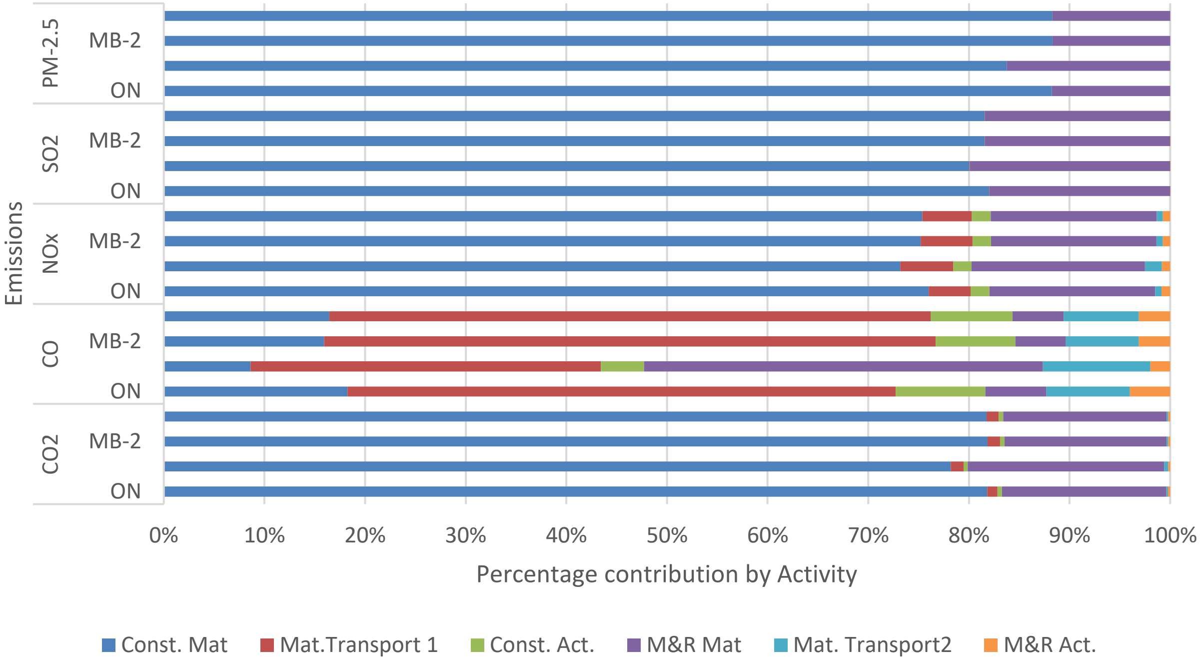


Figure 6.5 Emissions of JPCP Collector roads (AADTT-500) in Ontario (ON) and Manitoba (MB) considering flood impacts and life cycle phases (Const Mat. = Initial construction material production; Mat. Transport1= Initial construction material transportation; Const. Act. = Initial construction processes; M&R Mat. = M&R material production; Mat. Transport2= M&R material transportation; M&R Act. = M&R processes)

As can be observed from **Figure 6.5**, the initial construction material production phase accounts for the majority of the emissions. The emissions increase with increasing slab thickness. Emissions from maintenance activities were similar for all designs, except for MB-HC1 and MB-CC1. This is due to the addition of a 4th M&R to keep the design within the performance threshold at the end of Year 49 and Year 47 of MB-HC1 and MB-CC1, respectively. The increase in NOx is linked to the production of Hot Mix Asphalt for the 4th M&R. Despite this increase, the MB-1 design did not have the highest environmental nor agency cost. **Figure 6.6** shows the environmental costs. Emissions from the initial construction materials and processes were the largest for all designs. This is consistent with previous LCA studies that have showed that the material production process is the most energy and emission intensive phase of the pavement life cycle (Santero et al. 2010). Although not considered in this study, it been found that the use/operation phase impacts are only significant when the road is designed for higher traffic (Wang et al. 2014). The case study designs are for low traffic of 500AADTT.

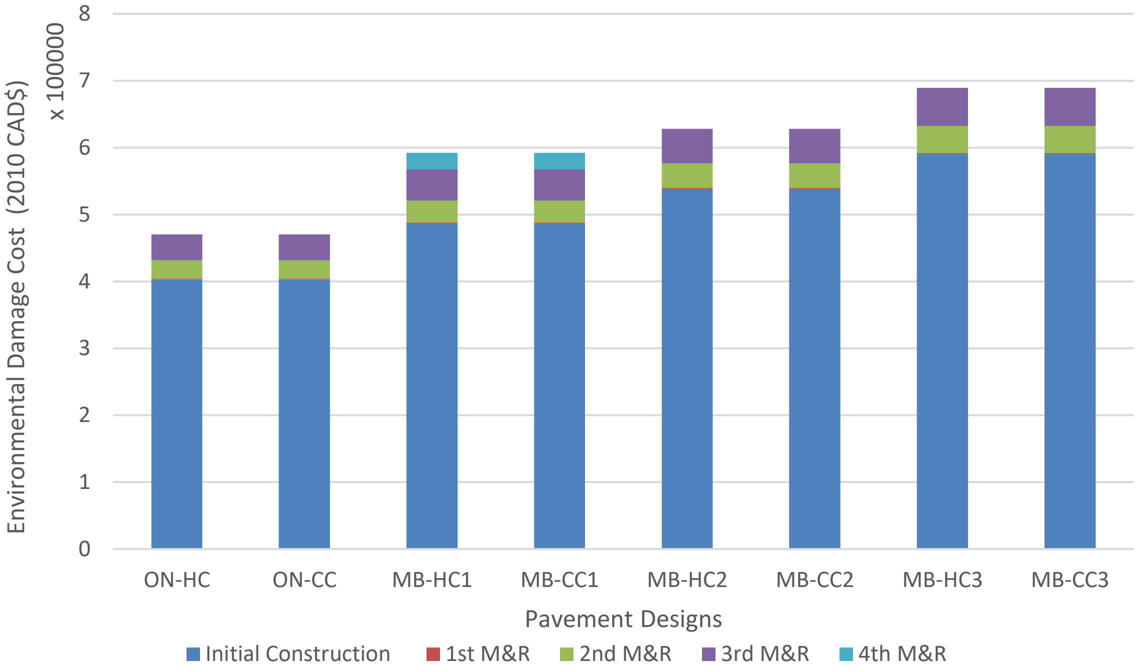


Figure 6.6 Environmental performance of JPCP Collect roads (AADTT-500) in Ontario (ON) and Manitoba (MB) considering no climate change/flooding scenario and climate change/flooding scenario

The economic (or lifecycle) cost of pavement facility construction and maintenance is shown in **Figure 6.7**. It shows that the cost of the pavement facility increases with increasing slab thickness, given that the initial construction cost is the largest for the estimated lifecycle cost. The estimated cost of 1st, 2nd, 3rd and 4th M&R strategies is approximately \$25,000, \$312,000, \$2,000,000, \$108,000 for 1km of the pavement, respectively. These values were discounted to the present value by considering the year M&R treatment was applied. MB3 design has the largest slab thickness, and thus incurred the highest cost for initial construction compared to other designs. MB1 design required a 4th maintenance towards the end of the 50-year analysis period. This improved the pavement and increased the salvage value at year 50 of the pavement life, ultimately resulting in the lowest lifecycle cost among the MB designs.

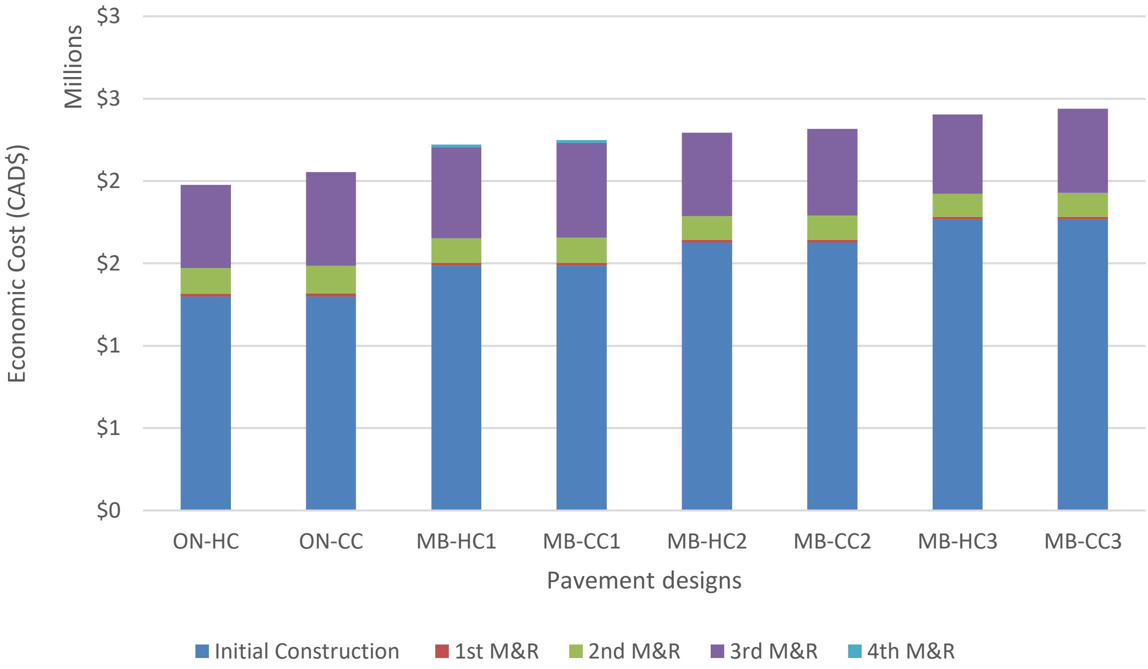


Figure 6.7 Economic performance of JPCP Collect roads (AADTT-500) in Ontario (ON) and Manitoba (MB) considering no climate change/flooding scenario and climate change/flooding scenario

The results of the sustainability analysis as shown in **Table 6.6** illustrate the additional environmental damage cost and the agency life cycle cost due to climate change impacts for the four design cases investigated here. The two values are not directly comparable. The environmental cost represents social costs of environmental damage due to the atmospheric release of emissions. It includes non-market values, such as the willingness-to-pay to reduce the risk of premature mortality associated with exposure to $PM_{2.5}$ and its precursors (Heo et al. 2016) (Heo et al., 2016). The agency lifecycle cost is market-based, derived using actual prices faced by the agency in Ontario (from [16]), including the total cost of building, maintaining and disposing of the pavement facility throughout the asset life.

The highlighted values in **Table 6.6** reflect the highest value for each factor. In terms of both agency and environmental costs, MB-3 had the highest costs due to its larger slab size. MB-CC1 incurred the highest M&R cost due to the additional M&R. Given that the 4th M&R was required later in the analysis period, MB-2 designs had a high salvage value which was considered to reduce the total agency cost within the 50-year period. The 3rd M&R were applied earlier for MB-CC2 and ON-CC at Year-33 and Year-35, respectively. As observed in **Table 6.6**, the IRI values were approaching the trigger value at the end of 50 years, thus there were no salvage value for these two aforementioned designs. All additional agency costs and environmental burden due to flooding impacts on road performance were captured by subtracting cost of CC scenarios from that of HC. MB-3 designs had the largest slab thickness, thus used more material and resources for construction, and resulting in the highest agency cost. When comparing the climate scenarios for each design, lifecycle economic costs and environmental impacts were increased by flooding.

In both environmental and agency costs, the ON design performed poorly compared to MB designs. The Ontario design had the highest percentage change in agency cost due to flood (17%) and environmental cost due to flood (0.3%). Thus, Ontario collector road design proved to be, relatively speaking, the least sustainable in the face of climate-induced flooding under the analysis herein. Thicker slabs in the MB designs had higher overall environmental and agency costs. Flooding added extra costs to each design, but the effect of flooding did not show the same increasing trajectory with thickness. MB1, the design with the smallest slab thickness for Manitoba, yielded the greatest agency cost increase ($56,000) for the province under the ECE. Conversely, from an emissions perspective, the MB3 design caused more environmental damage at 0.22% under flood conditions. The results suggest that slab thickness provides a possible tradeoff between economic and environmental dimensions under climate change. The additional maintenance required in MB-1 before the end of the analysis period increases the percentage change in agency cost due to flood. These findings highlight the challenges of sustainable infrastructure management. Decision making related to climate change adaptation and mitigation is challenging, involves potential trade-offs, and requires a multicriteria decision making approach. The aim to building resilient structures should also consider the associated cost and environmental burden.

Table 6.6 Sustainability Assessment Results

Aspect	**Value**							
(per 1km of road)	Ontario design (ON)		Manitoba design 1 (MB-1)		Manitoba design 2 (MB-2)		Manitoba design 3 (MB-3)	
	ON-HC	ON-CC	MB-HC	MB-CC	MB-HC	MB-CC	MB-HC	MB-CC
Agency Cost ($)								
Initial Cost	1,298,000	1,298,000	1,485,000	1,485,000	1,626,000	1,626,000	1,767,000	1,767,000
M&R Cost	679,000	1,071,000	737,000	763,000	562,000	597,000	537,000	558,000
Salvage value	19,000	0	272,000	244,000	195,000	0	44,000	15,000
Total	1,958,000	2,370,000	1,949,000	2,005,000	2169,000	2,223,000	2,260,000	2,310,000
Extra Agency Cost due to Flood ($)								
CC – HC	412, 000 (17%)		56,000 (2.74%)		54, 000 (2.47%)		50,000 (2.2%)	
IRI at end of analysis period (m/km)								
IRI at Year 50	2.26	2.61	1.09	1.23	2.29	2.48	2.15	2.33

Aspect	**Value**							
Environmental Damage Cost (2015 CAD$)								
Initial Cost	403,000	403,000	486,000	486,000	538,000	538,000	590,000	590,000
Maintenance Cost	23,800	25,300	33,000	34,100	30,600	31,600	32,400	33,800
Salvage value	370	0	3,260	2,910	400	0	1,200	400
Total	426430	428300	515740	517190	568200	569600	621200	623400
Extra Environmental Cost due to Flood ($)								
CC – HC	1,510 (0.3%)		1,040 (0.20%)		1,030 (0.18%)		1,360 (0.22%)	

6.4 Recommendations and Conclusion

Global climate change and its likely consequences such as sea level rise, floods and storms have increasingly threatened pavement infrastructures. The resilience of pavement when facing climate change impacts has drawn considerable attention, yet there remains a need to reduce the environmental burden of pavement infrastructure. This study investigated the impacts of flooding on concrete roads and evaluated the sustainability impacts and resilience of concrete pavement.

An integrated framework was proposed to address sustainability and resilience issues in pavement design. The framework is a streamlined approach to integrate various methods for assessing dimensions sustainability and resilience. The economic and environmental aspects of the assessment build on performance modeling of the pavement under scenarios with and without flooding.

The case studies assumed typical 500AADTT collector road designs for Ontario and Manitoba. Historic climate data were used to assess the baseline scenarios, while the flooding scenarios used future climate precipitation data for 100-year floods under RCP 4.5. Performance outcomes were used to prescribe M&R based on IRI trigger values. The agency and environmental costs associated with the designs were estimated over a service life of 50 years.

This study suggests that Ontario roads will require an early start on adaptation strategies compared to Manitoba. Ontario is expected to have more frequent floods than Manitoba in the near future. In this resilience analysis of a single flood scenario, the Ontario Road had a higher damage risk than the Manitoba road designs, incurring thousands of dollars in damage costs that were nearly 90% higher than for Manitoba roads. The typical Ontario JPCP design for a collector road had a smaller slab thickness (<200mm) than Manitoba. The thicker Manitoba JPCP designs all had lower damage costs and smaller increases in lifecycle agency costs and environmental impacts than Ontario under flooding.

This analysis also found that thicker concrete pavements may be more resilient. However, increasing the slab thickness did not always prove uniformly adaptive, and it introduced potential trade-offs between adaptation and mitigation. Designs with thicker slabs had lower IRIs, including under climate change. They also experienced smaller changes to their lifecycle agency costs. While their change in environmental costs was relatively similar across thicknesses for MB designs, the thickest design had the largest increase in environmental costs due to flooding. However, the thicker designs also had the highest total agency and environmental costs. These more valuable, polluting assets also experienced greater damage ratios and expected costs due to flooding than the thinner MB designs.

This case study suggests that climate change will likely call for adaptive design requirements in the near future for Ontario roads. For designs with low resilience to flood, sustainability impacts and flooding damage costs under future climate may become expensive but increasing thickness to promote resilience may also increase sustainability costs. This work also offers insights to guide future field studies to help calibrate the type of performance criteria models used here. Future work can incorporate such field studies, can include use-phase impacts, and broaden this framework to include more comprehensive decision criteria for pavement management. Overall, it highlights that sustainability costs of adaptive measure should be considered in design and long-term planning for future climates.

Chapter 7

Effects of Pavement Surface Condition on Environmental Performance of Ontario Roads

7.1 Introduction

Transportation energy consumption and the associated emissions from fuel combustion have adverse effects on air quality and healthy living in Canada. Canada's roads in-service are major emitters of air and water pollutants including greenhouse gases (GHG) and criteria air pollutants. With more than thirty-eight thousand kilometres of public roads, and with generation of 155 Mega-tonnes of carbon dioxide equivalent (CO_2eq) emissions, the Canadian roadway network has a significant impact on the environment. In 2019, the Canadian transportation sector accounted for 25% of national GHG emissions, of which on-road vehicles (passenger car, light trucks, and freight trucks) emitted 85% of transportation emissions (Figure 1.1) and experienced the largest growth of emissions in the transportation sector from 1991 to 2019. These road transportation vehicles are the main sources of traffic-related air pollution (TRAP) (Health Canada 2020). When engines burn fuel (gasoline or diesel), air pollutants that can affect your health are emitted. These pollutants include hydrocarbons, greenhouse gases, nitrogen oxides, carbon monoxide, fine particulate matter and volatile organic compounds. Efforts to improve vehicle fuel economy and reduce the consequent pollution have focused on improving engine performance and adopting the latest emission control technologies and cleaner fuels. Although technology improvements have reduced vehicle emissions, there is still cause for concern because older vehicles remain in use and as the population of Canada continues to grow, vehicle numbers increase, even in densely populated urban areas. Moreover, the total kilometres travelled by Canadian vehicles continue to increase. Pavement condition, design and characteristics affect vehicle fuel consumption and the related vehicle emissions; thus, pavement management can provide opportunities to improve fuel economy and reduce the associated air pollution and GHG emissions from road transportation.

Most of the environmental burdens from the transportation system come from the interaction between vehicles and the road. For a vehicle to stay in motion on a roadway, it demands power to overcome many forces such as inertia, gravity, internal friction, aerodynamic drag, and rolling resistance (Figure 7.1). The rolling resistance (RR) of a vehicle is highly dependent on the pavement -vehicle interaction (PVI) which determines the dynamic response and thermal exchange between vehicle tires and the pavement system. The pavement surface condition can affect the fuel consumption of vehicles traveling on the road, as various pavement surface characteristics interacting with tires (Harvey et al., 2016).

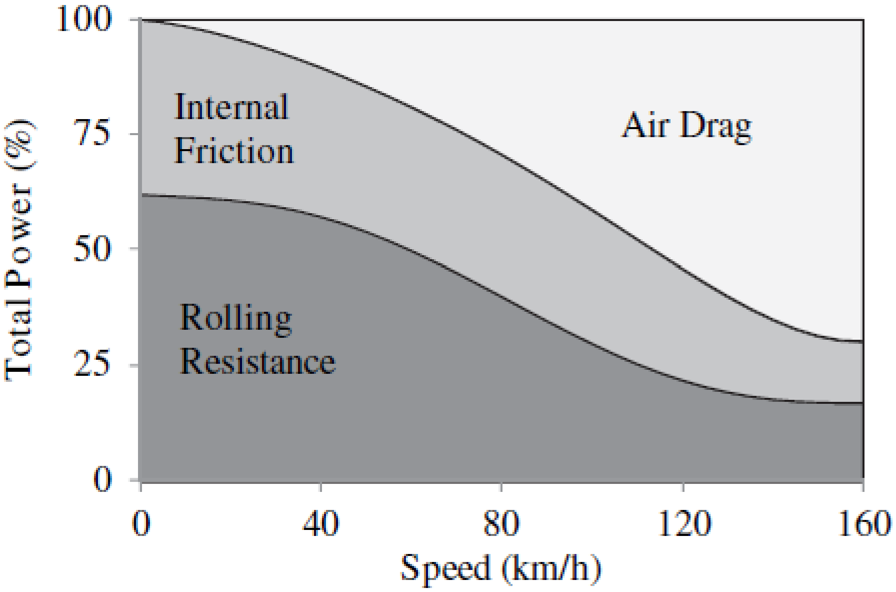


Figure 7.1 Relationship between total power demand, rolling resistance, internal friction, air drag and speed (as referenced in NHRCP report by Chatti and Zaabar 2012)

Pavement-vehicle-interaction (PVI) models can be used to quantitatively assess the excess fuel consumption and emissions due to rolling resistance effects of pavement structural and surface characteristics by considering the impact of different pavement characteristics and designs, and existing climatic and traffic conditions in the roadway network, on the energy dissipation and the ensuing excess fuel consumption. These models are thus important components in evaluating pavement sustainability performance. Programmatic management of pavement-surface conditions can be cost-competitive measures to reduce GHG emissions compared to other abatement measures applied in sustainable transportation asset management. For sustainable pavement management, it provides the shortest path for greenhouse gas emissions savings per maintenance at network scale. A recent study of the Illinois road network found that while vehicle efficiency accounts for about 27% of the potential total energy savings, potential savings from pavement roughness can be up to 7% (Ziyadi et al. 2018). Another study (Louhghalam et al. 2017) suggests that a road network maintenance program that is guided by ranking the pavement section based on excess CO_2 emission due to pavement condition resulted in the shortest path for network level CO_2 emission reduction which optimizes the potential for excess fuel consumption and CO_2 emission reduction for a given maintenance strategy. When applied to an interstate highway system in the State of Virginia, the study found that an informed selection based on ranking PVI-induced emissions, which is an integration of road conditions, traffic loads and climatic conditions, leads to a maximum reduction rate of CO_2 emissions per lane-mile maintained as shown in Figure 7.2.

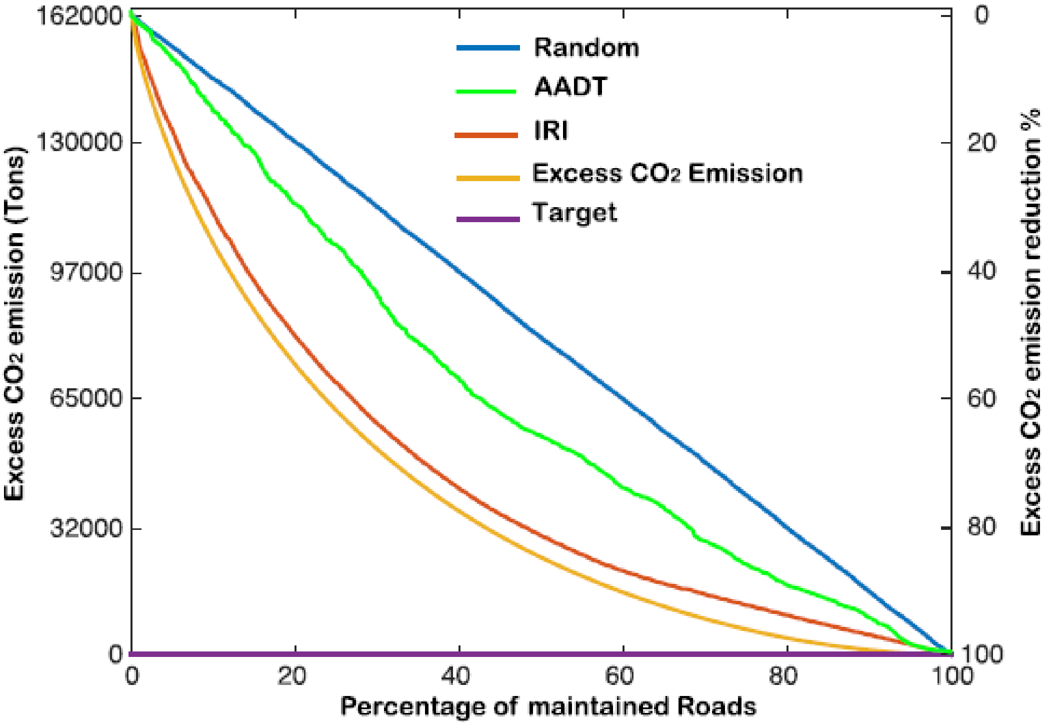


Figure 7.2 Comparison of different road selection strategies for maintenance in terms of emission reduction potential. Selection strategies include random selection, selection based on annual average daily traffic (AADT), international roughness index (IRI) and CO_2 emissions (source: Loughalam et al., 2017)

A pavement system has multiple types of interaction with the environment; the environmental impacts from the material production, construction, maintenance, pavement use and operations, and end of life management can be estimated using the pavement environmental Life Cycle Assessment methodology. While the discussions of pavement LCAs before 2010 have focused on environmental impacts of material production (Huntzinger and Eatmon, 2009) and pavement construction and maintenance phases, the use-phase impact is largely overlooked in most Life Cycle Assessment (LCA) of pavements (Santero et al., 2011). However recent studies have found that the impact of the use phase, especially for high volume traffic roads, is significant and can surpass other embodied emissions for material and construction phases for maintaining the road network (Wang et al., 2012; Araújo et al., 2014). The paucity of knowledge about the use phase impacts and the limited scope in many pavement lifecycle assessment studies (for example (Huntzinger and Eatmon, 2009) (Turk et al., 2016; Huang et al., 2009; Fernandez-Sanchez et al., 2015) has been highlighted as a major limitation of pavement LCA to inform policy and pavement management decisions, motivating the need to close this knowledge gap.

The pavement use phase impact can be attributed to pavement characteristics such as pavement roughness, macrotexture, structural responsiveness of pavement type, permeability, albedo, heat capacity and conductivity (see Figure 2.2). The first three can affect rolling resistance (RR) of a vehicle moving on the pavement, but roughness is generally cited to play a major role (Willis et al., 2015). RR due to pavement surface condition can contribute 15% to 50% to the total vehicle fuel consumption, depending on vehicle speed (Beuving et al., 2004). Even for a pavement section where only environmentally friendly material and construction solutions are used, the aggregated impact of RR can exceed other factors contributing to the lifecycle environmental impact of pavements in a high traffic roadway (Adjois et al. 2014).

Previous models are generally empirical, accounting for only discrete vehicle speeds and limited to only energy consumption. Alternatively, simulation methods like Unites States Environmental Protection Agency (USEPA) motor vehicle emission simulator (MOVES) (USEPA, 2014) can be used to evaluate moving vehicles' environmental impacts. MOVES is an open-source software program used to estimate energy consumption and emissions for moving vehicles as a function of vehicle type, age, technology, fuel type, environment, road grade, etc. Although MOVES can estimate vehicle emissions by considering a wide range of factors, the current version does not consider the roadway surface conditions on vehicles' fuel consumption and emissions. Recent efforts have been made to modify various coefficients in MOVES to reflect road surface characteristics (Wang et al., 2012; Ghosh et al., 2015; Ziyadi et al., 2018). However, the models reflect case specific scenarios for counties and states in the USA. Moreover, the required time-consuming simulations prohibit the use of MOVES directly in pavement management systems (PMS).

This study proposes generalized formulations stemming from vehicle-specific power models to estimate excess fuel consumption and associated emissions resulting from the changes in the pavement surface profile of roadways and vehicle operating conditions. Specific objectives are:

1. Propose models to relate vehicle energy consumption to pavement roughness and pavement texture while considering a wide range of vehicle types, road types and speeds.

2. Extend the proposed model to air pollutants resulting from fuel combustion, such as hydrocarbons, GHG emissions, VOC, PM_{10}, $PM_{2.5}$, SO_2, NOx, NH_3 and CH_4. This set of pollutants is monitored and tracked under the air pollution and air quality indicators of the Canadian Environmental sustainability index.

Finally, these models can be used directly to estimate overall vehicle fuel consumption or in an incremental way to estimate only pavement roughness effect. The proposed model should be an easily implementable method for LCA tool and software development purposes or incorporation into a PMS.

7.2 Literature Review

Three environmental concerns related to pavement vehicle interaction are excess vehicle energy consumption or excess fuel consumption (EFC) and its associated emissions due to the mechanical interaction between the pavement surface and tire surface. The third concern is the traffic noise also resulting from these interactions; however, noise is not considered here.

7.2.1 Pavement-Vehicle Interaction (PVI)

The pavement impact on vehicle fuel economy and emissions is addressed under the pavement-vehicle interaction using in terms of rolling resistance. The movement of on-road vehicles requires the vehicle power unit to overcome the forces resistant to movement. These forces include rolling resistance forces, aerodynamic forces, frictional forces, and the inertial or gravitational forces which are related to acceleration and driving on slopes. The power is converted from the energy contained in the fuel or the battery of the vehicle. Vehicle and tire properties are the main factors that affect vehicle fuel consumption. It has long been recognized that pavement roughness affects the pavement–vehicle interaction (PVI) and contributes to vehicle rolling resistance. RR can be defined as the loss of energy per unit distance travelled which includes the mechanical energy losses due to aerodynamic drag associated with rolling, and friction between the tyres and road, as well as energy losses taking place within the structure of the tire and pavement. It can be difficult to distinguish the effect of the tire from the effect of the pavement, as rolling resistance encompasses various mechanisms of energy losses in the vehicle tire and suspension system, as wells as in the pavement itself (Sandberg, 2011).

In the prominent models adopted in recent LCA studies, pavement surface texture and structural responsiveness to traffic loading have been identified as main pavement characteristics that have effects on RR and the fuel economy of a vehicle traveling on the road pavement. The influence of these pavement characteristics on RR mechanisms are the focus of the growing research on PVI.

Pavement structural responsiveness relates to the pavement deflection, primarily the pavement deformation under wheel loads to the vehicle rolling resistance and fuel consumption. The pavement structural deformation is controlled by the stiffness and thickness of the layers, and the extent of viscoelastic or delayed elasticity behaviour that the layer materials exhibit under different temperatures, moisture conditions, times of wheel loading and vehicle speed. These factors are considered in two mechanisms of excess fuel consumption from pavement structural response: (1) dissipation of energy when surface deflects under traffic loading due to the viscoelastic characteristics of the pavement materials. (2) the energy needed propel a vehicle forward as the geometry between the tire and the pavement surface changes. Models for energy consumed by pavement deflection known as the structural induced excess fuel consumption (EFC) are available and are undergoing evaluation and calibration. Structural induced EFC is dependent on many factors including the pavement stiffness, pavement type and material, pavement structure thickness, the ambient temperature, type of loading, for example passenger car or trucks and speed. These factors are design or project specific and not generalizable. Two studies from Michigan State University investigated the impact of structural response of rigid (Balzarini, Zaabar, and Chatti 2017) and flexible (Balzarini et al. 2019) pavement showed that for a vehicle travelling at 57km/h on flexible pavement, EFC due to structure response can grow from 1% at 27°C to 2% at 40°C and higher, but a 50% increase in pavement structural thickness can decrease the excess energy dissipated by 43.5%. While on rid pavements, the EFC are generally below 0.08%, the increase in speed can increase EFC. A comparison of that structural induced EFC models to two other models (Akbarian et al. 2012; Coleri et al. 2016) which have been adopted in LCA studies (Alam, Hossain, and Bazan 2020; Azarijafari et al. 2016; Louhghalam et al. 2017) and tools

(Anon 2011), has shown that available models produce different results which has not been comprehensively validated mainly due to the differences in the modelling approaches that do not account for the broad range of influence factors (Coleri et al. 2016; J. Harvey et al. 2016). Amongst the three reference, one model ignores the possible effect of pavement distresses such as permanent deformation, and adopts stress, strain, and phase angle integrated over time to calculate dissipated energy in the pavement. While the other two models calculate the dissipated energy based on a wheel moving up slope on the side of the deflection basin but differ in their definition and calculation of deflection basins. All three approaches use the converts the calculated dissipated energy to energy (MJ/km) required to make the vehicle move or overcome the resistance due to surface deflections. The EFC values (mL/km) is estimated by the direct conversion using the calorific value of the fuel (MJ/L) depending on the fuel type for different vehicles. (Coleri et al. 2016). However recent studies adopted the three models refenced above and have found that EFC due to structural response to be generally less important than the effect of surface texture particularly roughness on California road network (J. Harvey et al. 2016). Another study by (Balzarini, Zaabar, and Chatti 2018) also found the effect of Structural Rolling Resistance (SRR) minimal (less than 0.5%) on fuel consumption in the mechanistic analysis for both asphalt and concrete pavements.

7.2.2 Measures of Pavement Surface Condition and PVI

Pavement surface are generally described based on its texture, which can be defined by four components based on the by ranges in wavelength (λ) and amplitude (A), and each have effects on different parts of the tire-pavement interaction as shown in Figure 7.3.

Microtexture is generally associated with the properties of the aggregate used in the pavement construction and it refers to the texture at a scale $\lambda < 0.5$ mm, $1\ \mu m < A < 500\ \mu m$.

Macrotexture is a function of size and distribution of aggregate particles in pavement mix in asphalt pavement, and in concrete pavements the macrotexture is often achieved by tining, burlap dragging, broom finishing, or diamond grinding, macrotexture refers to the scale $0.5\ mm < \lambda < 50\ mm$, $0.1\ mm < A < 20\ mm$.

Megatexture can be on same order of magnitude as the vehicle tire itself and is often manifested as deteriorations in the pavement (potholes, cracking, rutting, etc.). It refers to scale $50\ mm < \lambda < 500\ mm$, $0.1\ mm < A < 50\ mm$

Roughness (also called unevenness) is the maximum dimension of their deviation (wavelength) from a true planar surface and is often a function of several pavement attributes including inherent properties such as surface material type, pavement design and construction technique, and other characteristics that develop and change over time like pavement distresses. Each factor affects the PVI interaction of the vehicles travelling across the pavement at various speed, causing vibrations that have effect on both the vehicle and its passengers. Roughness is commonly measured by the International Roughness Index in unit m/km as developed by the World Bank.

Amongst the numerous factors influence rolling resistance, fuel consumption and emission, roughness has been identified to most influential pavement characteristics. Vehicle rolling resistance can be influence by vehicle engine and tyre characteristics, pavement surface characteristics and climate factors. Impact of roughness (IRI) and macro-texture (MPD) on a vehicles rolling resistance have been extensively studies compared to relationship between rolling resistance and other pavement surface factors.

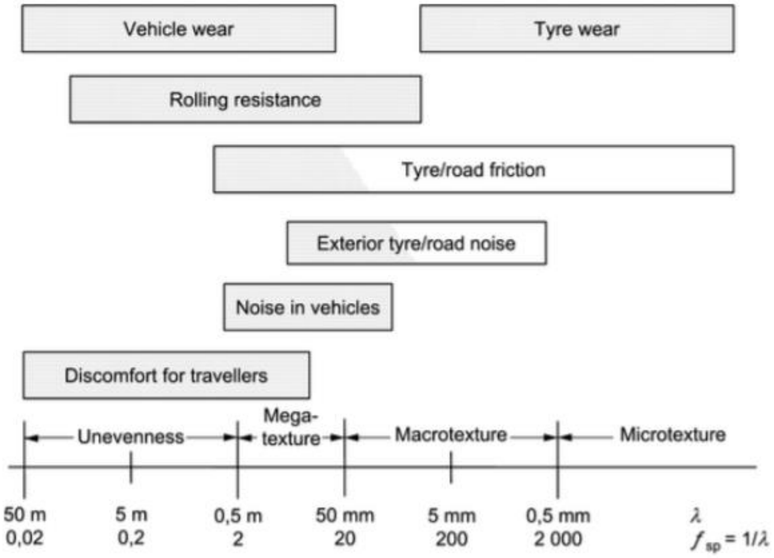


Figure 7.3 Four components of pavement surface texture and their influences on PVI factors

7.2.3 Pavement Surface Condition and Fuel Consumption

Models developed earlier considered rolling resistance to be the result of three energy dissipation mechanisms: smooth-surface rolling losses, roughness induces energy dissipation in the tire, roughness induces losses in the suspension system due to relative motion between sprung and unsprung mass (Lu 1985). Those models were used in a first study Velinsky and White (1979), which investigated the energy dissipation in both tire and suspension as a function of roughness, tire pressure and speed. The study found a 20% increase in rolling loss for driving on rough roads compared to ideal smooth roads, and that the aerodynamic drag coefficient also increased when driving on rough roads. They developed a linear model to predict fuel consumption based on field data of vehicle axle accelerations (Velinsky and White 1979). Other field studies have been conducted considering other factors such as texture (Delanne 1994), speed (Karan and Haas 1976; Yu and Lu 2013), vehicle class (Delanne 1994) and type of pavement (Taylor and Patten 2006). These studies all found a linear relationship between energy consumption and pavement roughness, however, a critical review of the PVI literature by Willis et al (2015) revealed that it is difficult to align results from one study to another given the variety of methods, instruments, and vehicles use in these studies. Moreover, there are difficulties in controlling variables during field measurements (Richard Willis, Robbins, and Thompson 2015).

In recent years two research programs, NCHRP 1-45 study (Chatti & Zaabar 2012) and MIRIAM project (Hammarström et al. 2012), conducted field investigations and considered all the variables in their studies (Sandberg et al. 2011; Zaabar and Chatti 2010a). These studies have led to the two commonly used models relating pavement properties to rolling resistance and fuel consumption. Hammarström et al. (2012) used empirical results from coast-down measurements in Sweden developed models for road condition effects on rolling resistance and fuel consumption. The model was developed for three vehicle types and includes impacts of pavement roughness, macrotexture, temperature, speed, horizontal curvature and the road grade. While Chatti and Zaabar (2010) conducted a field study in Michigan with a wide range of vehicles and used the field data to calibrate the Highway Development and Management Model (HDM4) (Bennett and Greenwood 2001)models for vehicle operating costs. It was considered a calibration suitable for North American roads. The fuel consumption model was calibrated over five different road section using six different vehicles, considering five levels of of speed and a range for roughness (IRI from 0.5m/km to 6m/km) and macrotexture (MTD from 0.2mm to 2.7mm). The study assumed a linear relationship between road roughness and change fuel consumption and suggests that a unit increase in roughness (IRI = 1m/km) will increase fuel consumption by 2.7%. The effects of roughness and texture on fuel consumption were also investigated but focused on the accuracy of the calibrated model to predict the effect of roughness, as the ANCOVA of field date showed that the effect of roughness is statistically significant (p-value is less than 0.05) for all vehicle types analysed and the speed levels considered. A steady-speed was assumed in the linear adapted, where change in fuel consumption, ΔIFC, under various IRIs is defined as:

$$\Delta \mathrm{IFC} = \frac{\delta \mathrm{IFC}_{IRI = k} + \delta \mathrm{IFC}_{IRI = 1}}{\delta IFC^{0}} \times 100$$

Where k = 1,…,5 (m/km) , $\delta \mathrm{IFC}_{IRI = 1}$ = fuel consumption due to roughness at IRI = 1m/km.

$\delta \mathrm{IFC}^{0}$ is the base instant fuel consumption of car, $\delta \mathrm{IFC}^{0} = \xi \times P_i$, i = 1or 2

IFC is an instantaneous fuel consumption (mL/km) estimated based on the HMD4 fueal consumption model express as:

$$\mathrm{IFC} = f(P_{tr}, P_{accs}, P_{eng}) = \frac{1000}{v} \times (max(\alpha, \xi \times P_{tot}) \times (1 + dFuel)))$$

Where v = vehicle speed (m/s), P_{tr}, = power required to overcome traction force (kW0, P_{accs} = power required for engine accessories (kW), P_{eng} = power required to overcome internal engine friction(kW), α = fuela consumption at idling (mL/s), $\xi = energy\ effieciency\ factor\ (mL/kW/s), \alpha, \xi \times P_{tot}$ = total power (kW), and $dFuel$ = excess fuel consumption due to congestion as a percentage.

The instantaneous model estimates the fuel consumption rate as a value per unit time measure at any instant the trip as a function of a tractive power required by the vehicle. The HDM4 model is a steady-speed model but does acknowledge the impact of speed. In the rescaled model by Chatti and Zaabi showed that an increase in IRI of 1m/km will increase fuel consumption of heavy trucks by about 1% at normal highway speed (96 km/h) and about 2% at low speed (56 km/h). Even though many studies have adopted this linear model and estimated CO2 emissions by converting the fuel use estimate to CO2 using the calorific value of the fuel (Azarijafari et al. 2016; Cirilovic, Mladenovic, and Queiroz 2015; J Santos et al. 2017; João Santos, Ferreira, and Flintsch 2017; Yu 2013; Yu and Lu 2012), a network-level pavement LCA study (Cirilovic et al. 2015)showed that when the HDM-4 model is used to estimate CO2 emissions of medium car and heavy truck, the emissions models have a nonlinear behavior for roughness greater than 4 m/km and greater than 5m/km, for medium cars and heavy vehicles, respectively, as shown in Figure 7.4 .

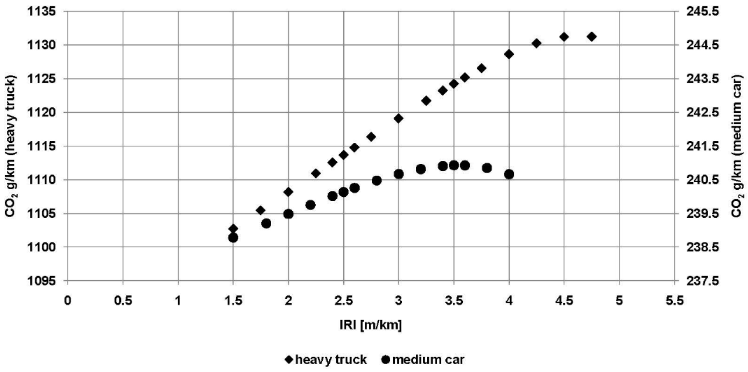


Figure 7.4 Estimated change of CO2 emission with roughness for heavy truck and medium car (Cirilovic et al. 2015)

Other researchers have proposed mechanics-based vehicle models to assess the influence of road roughness on fuel consumption (Kim et al., 2016, 2019; Louhghalam, et al., 2015a, 2015b). Louhghalam, et al., (2015a, 2015b) used a stochastic representation of the road roughness and a quarter-car model and presented a method to calibrate the model to measured data. Roughness parameters were defined by IRI and waviness number. Using Chatti and Zaabar (2012) empirical models, the HDM-4 model was calibrated so that a linear relationship between the total fuel consumption of the vehicle and the IRI is established. Kim et al., (2016) argued that the model become computationally exhaustive as more complicated vehicle types or road profiles are considered. As the typical relative wavelength of roughness can range from 0.5 m to 50mm. Kim et al., (2016, 2019) study made efforts to develop simplified models that considered the combined effect of road roughness and deflection on energy dissipation in vehicle tires and suspension systems. However, the pavement was modelled to have a stiff subgrade, which is not practical for most soils structure in Ontario.

Many of the early studies isolated speed and often considered it as a covariate in investigation of road surface effect vehicle fuel consumption. The roughness speed relationship is also a significant factor when modelling excess fuel consumption. Field studies by (Karan and Haas 1976; Yu and Lu 2013) suggest linear relationships between roughness and speed. Karan et al. (1976) analysed 72 sites in Ontario and found that the vehicle speed drops approximately by 3km/h for every 1m/km to 2m/km increase in IRI. Yu and Lu (2013) Caltrans data analysis suggest that free flow average speed drops by 0.84km/h for every 1 m/km increase of the IRI. The authors proposed fuel consumption factor to describe the effect on fuel consumption when driving on deteriorated pavements. A recent study (Liccardo 2017) applied a new dataset from the Strategic Highway Research Program 2 (SHRP 2) representing roadways in six cities in the United States and found a logistic model was the best fit model to explain the relationship.

7.2.4 Pavement Surface Condition and Vehicle Emissions

A common challenge with the models discussed above is that they considered only discrete speed and the output is mainly fuel consumption which can only be directly translated to CO2 emissions, but the effect of roughness on other vehicle related pollutants cannot be estimated. Alternative approaches have been suggested by Wang et al., 2014 and Ziyadi et al., 2018 to address these challenges by incorporating two models: the calibrated HDM4 model and the United States EPA Motor Vehicle Emission Simulator (MOVES)(USEPA 2014). HDM4 model to quantify rolling resistance. MOVES is an open-source software program used to estimate energy consumption and emissions for moving vehicles as a function of vehicle type, age, technology, fuel type, environment, road grade, etc. In MOVES, total activity is subdivided into categories that differentiate emissions, known as operating mode bins. These operating mode bins vary by pollutants and emission process and are defined by instantaneous vehicle speed and vehicle specific power (VSP). VSP is defined as the instantaneous tractive power per unit vehicle mass, it is an estimate of the power demand on the engine during driving (Koupal et al. 2005; USEPA n.d.). The second-by-second speed values in a driving schedule, along with information about the type of vehicle being operated is required to calculate VSP. The unit of VSP is Kw/Metric Ton, and estimated by:

$$\boldsymbol{VSP = Rolling\ resistance + Air\ resistance + Inertial} \,\&\, \boldsymbol{Gradiant\ resistant + Curvature} \quad \text{Eq. 7.1}$$

The VSP equation implemented by the MOVES program is

$$\text{VSP}= \frac{\boldsymbol{A}}{\boldsymbol{M}} \times \boldsymbol{v} + \frac{\boldsymbol{B}}{\boldsymbol{M}} \times \boldsymbol{v^2} + \frac{\boldsymbol{C}}{\boldsymbol{M}} \times \boldsymbol{v^3} + (\boldsymbol{\alpha}(\mathbf{1} + \boldsymbol{\varepsilon_i}) + \boldsymbol{g} \times \boldsymbol{garde}) \times \boldsymbol{v} \qquad \text{Eq. 7.2}$$

Where;

A = Coefficient of rolling resistance, with units of kW.s/m

B = Coefficient of higher order rolling resistance factors and mechanical

rotating friction losses, with units of kW.s/m, kW.s2/m2,

C = Coefficient of air drag, with units of kW.s3/m3

M = Vehicle mass (kg)

V = vehicle speed (m/s)

α and ε = vehicle acceleration and mass factor terms respectively.

Although MOVES includes rolling resistance coefficients, the current version does not consider the effect of changes in the roadway surface conditions on vehicles' fuel consumption and emissions. Ghosh et al. 2015 and Wang et al. 2012 suggest the HDM4 model can be used to modify various coefficients in MOVES to reflect road surface characteristics. This approach is used to overcome the limitation of the two models. The HDM-4 model considered changes in pavement surface condition a parameter in the model of power demand to overcome traction force (P_{tr}), but the model is steady speed. While MOVES model considered continuous speed and included a rolling resistance factor but the test method for the model was conducted on a plan surface, which is considered to have IRI =0 and MTD =0. To update the rolling resistance model, the transition power (Prr) in HDM4 model is considered equal to the VSP in MOVES model, but the two studies differ in the way the relationship is defined to compute the coefficients of MOVES' VSP model.

Now, from the HDM-4 model, the power to overcome traction force (Prr) is expressed as:

$$\text{Ptrr} = \frac{\boldsymbol{v}}{\boldsymbol{M}} \times (\boldsymbol{F}_{\boldsymbol{rolling}} + \boldsymbol{F}_{\boldsymbol{aerodynamc}} + \boldsymbol{F}_{\boldsymbol{inertial\ and\ gradient}} + \boldsymbol{F}_{\boldsymbol{curvature}} \qquad \text{Eq. 7.3}$$

$$\boldsymbol{F}_{\boldsymbol{rolling}} = \boldsymbol{CR}_{\boldsymbol{2}} \times \boldsymbol{FCLIM}\left(\boldsymbol{b}_{\boldsymbol{11}}\,\boldsymbol{N}_{\boldsymbol{w}} + \boldsymbol{CR}_{\boldsymbol{1}}\left(\boldsymbol{b}_{\boldsymbol{12}}\boldsymbol{M} + \boldsymbol{b}_{\boldsymbol{13}}\,\boldsymbol{v}^{\boldsymbol{2}}\right)\right) \qquad \text{Eq. 7.4}$$

$$\boldsymbol{F}_{\boldsymbol{airdrag}} = \frac{\boldsymbol{1}}{\boldsymbol{2}} \times \boldsymbol{\rho}_{\boldsymbol{a}}\boldsymbol{C}_{\boldsymbol{D}}\boldsymbol{A}_{\boldsymbol{front}}\,\boldsymbol{v}^{\boldsymbol{2}} \qquad \text{Eq. 7.5}$$

Where;

CR2= Surface factor influenced by roughness, surface texture and deflection

CR1= Vehicle tire factor

FCLIM= Climate factor

Nw = Number of wheels

b11, b12, and b13 = Rolling resistance parameters

pa = Air density (1.207 kg/m3 at 20 C)

CD = Aerodynamic drag coefficient

A_{front} = Front area of vehicle (m2)

v = Vehicle speed (m/s)

The relationship between CR2 and IRI is linear:

$\boldsymbol{CR_2 = Kcr2\,.(\,a_0 + a_1 \times Tdsp + a_2 \times IRI + a_3 \times DEF)}$ Eq. 7.6

Where;

a0, a1, a2, and a3 =Model coefficients

Tdsp = Texture depth determined by sand patch method (mm), also known as mean texture depth (MTD)

IRI = International roughness index (m/km)

DEF = Benkelman beam rebound deflection (mm)

Approach 1: According to Wang et al. (2012), Coefficient A in MOVES can be updated by the equation:

$$A_{updated} = A_{default} \times \left(CR_{2pavement} \,/\, CR_{2pavement}\right)$$

Where,

$A_{updated}$ = updated rolling resistance coefficient used in the calculation,

$A_{default}$ = default rolling resistance coefficient in MOVES,

$CR_{2pavement}$ = rolling resistance on real pavement surface,

$CR_{2dynamometer}$ = rolling resistance on a smooth surface (IRI and MPD = 0)

Approach 2: According to Ghosh et al. (2015), the relationship between MOVES and HDM-4 should be established by considering three main resistances forces (rolling, aerodynamic, and inertia and gradient) that VSP must overcome. So, the authors suggest that by equating equations

VSP= $\boldsymbol{\frac{A}{M} \times v + \frac{B}{M} \times v^2 + \frac{C}{M} \times v^3 + (\alpha(1 + \varepsilon_i) + g \times garde) \times v}$ Eq. **7.2**

VSP= $\boldsymbol{\frac{A}{M} \times v + \frac{B}{M} \times v^2 + \frac{C}{M} \times v^3 + (\alpha(1 + \varepsilon_i) + g \times garde) \times v}$ Eq. **7.2**

and

Ptrr = $\boldsymbol{\frac{v}{M} \times (F_{rolling} + F_{aerodynamc} + F_{inertial\ and\ gradient} + F_{curvature}}$ Eq. **7.3**,

with consideration of equations Eq. 4, 5, and 6; a good approximation to VSP can be derived and MOVES model coefficients (A, B, and C) can be related to physical pavement characteristics, such that coefficients A and C to account for pavement roughness can be updated on MOVES.

$$\text{VSP} = \boldsymbol{CR_2} \times \boldsymbol{FCLIM}\left(\boldsymbol{b_{11} N_w} + \boldsymbol{CR_1}\left(\boldsymbol{b_{12} M} + \boldsymbol{b_{13} \nu^2}\right)\right) \times \frac{\boldsymbol{\nu}}{\boldsymbol{M}} + \frac{1}{2} \times \frac{\boldsymbol{\rho_a C_D A_{front} \nu^2}}{\boldsymbol{M}} \times \boldsymbol{\nu} + \boldsymbol{F_{inertial\ and\ gradient}} \times \frac{\boldsymbol{\nu}}{\boldsymbol{M}} \qquad \text{Eq. 7.7}$$

$$\boldsymbol{A = CR_2 \times k_A} \qquad \text{Eq. 7.8}$$

$$\boldsymbol{C = CR_2 \times k_c + b_c} \qquad \text{Eq. 7.9}$$

$$\boldsymbol{k_A = FCLIM\,(b_{11} N_w + CR_1 b_{12} M)} \qquad \text{Eq. 7.10}$$

$$\boldsymbol{k_c = FCLIM\ CR_1 b_{13}} \qquad \text{Eq. 7.11}$$

$$\boldsymbol{b_c = \frac{1}{2} \rho_a C_D A_{front}} \qquad \text{Eq. 7.12}$$

Using equations Eq. 7.1 to Eq. 7.12, the RR term and the air drag term can be calculated for different roughness and texture levels and updated on MOVES for simulating energy use and emission rate of vehicles at different pavement surface conditions.

The two approaches were compared by Al-Saadi (2018) and Approach 2 was found to contain more efficient factors than Approach 1 and provided better outputs to revised MOVES coefficients A and C for MOVES simulation to consider the effect of road roughness on energy consumption. Approach 2 was considered in this study. The main advantages of using VSP as an independent variable for studying the emissions of passenger cars and light-duty trucks are: it can be directly calculated from roadside measurements; it captures most of the dependence of emissions on engine operating parameters; and the driving cycles are defined as a speed versus time trace and can also be specified in terms of VSP. VSP distributions not only represent well the driving characteristics but also are highly correlated with the vehicle emission characteristics. However, running MOVES is computationally intensive and time-consuming simulations prohibit the use of MOVES directly in pavement management systems (PMS). Using MOVES simulation output data, Ziyadi et al. (2018) and Al-Saadi (2018) developed polynomial regressions to estimate energy consumption to IRI values.

Based on the physical interpretation of power and energy, Ziyadi et al. (2018) suggest is the relationship between VSP and energy consumed per distance traveled can be defined by Eq. 8.13, the Energy consumed can be expressed in terms of the roughness-speed impact model in Eq. 814.

$$E \propto \boldsymbol{VSP} \times \boldsymbol{M} \times \frac{\mathbf{1}}{\boldsymbol{v}} \qquad \textbf{Eq. 7.13}$$

$$\text{RSI (Energy)} = \frac{\boldsymbol{P_{idle}}}{\boldsymbol{v}} + (\boldsymbol{k_a} \times \mathbf{IRI} + \boldsymbol{d_a}) + \boldsymbol{b} \times \boldsymbol{v} + (\boldsymbol{k_c} \times \boldsymbol{IRI} + \boldsymbol{d_c})\, \boldsymbol{v}^{\mathbf{2}} \qquad \textbf{Eq. 7.14}$$

$$\boldsymbol{A} = \boldsymbol{k_a} \times \mathbf{IRI} + \boldsymbol{d_a} \qquad \textbf{Eq. 7.15}$$

$$\boldsymbol{C} = \boldsymbol{k_c} \times \boldsymbol{IRI} + \boldsymbol{d_c} \qquad \textbf{Eq. 7.16}$$

Although the RSI model presents a way to predict energy consumption, the energy and VSP in Eq. 7.13 holds true, the coefficients in the model expressed in Eq. 14 do need to be ascertained before the model can be applied. The authors considered only roughness as road surface condition, so expressed the relationship between roughness (IRI) and VSP coefficients (terms for rolling resistance and air drag) as linear.

Ziyadi et al. (2018) also developed linear regression models to predict environmental impacts or roughness-speed based on LCA TRACI criteria and indicators from select environmental protection factors for four vehicle types travelling on a restricted freeway (Ziyadi et al. 2018). While Al-Saadi (2018) developed polynomial regression models to predict on CO2 emissions and total energy consumption of four vehicle types travelling on one road class as a function of coefficient A, Coefficient C and speed. The author did not show how the relations between road surface parameters (roughness and macrotexture) are related to A and C coefficients in the defined models. Both studies suggest that benefit of developing these regression models is that it enables easy implementation of PVI impact assessment in LCA studies and tools that want to estimate the impact of road surface condition on sustainability performance.

MOVES output is specific to the run specification defined which will differ by region, county and project and other criteria. Thus, the outputs from previous studies cannot be directly applied to Ontario, as those studies investigated case specific scenarios for counties and states in the United States. The current study addresses the knowledge gaps and builds on previous studies (Al-Saadi 2018; Ghosh et al. 2015; Zaabar and Chatti 2010a; Ziyadi et al. 2018) to develop regression models more relevant to Canadian road transportation network using local input data.

7.3 Research Methodology

7.3.1 Vehicle Energy Use and Emission Simulation

This research adopts the transportation emission modelling tool MOVES which is widely used in North America and have recently been adopted by Wang (2018) to model transportation emissions and multipollutant impacts of on-road freight movement for Ontario in the year 2012. MOVES was developed by USEPA to estimate emission at national, county and project scale. Wang (2018) showed that available local data can be used to develop input files and create a county database for regionalized emission inventory calculation for Ontario at the census division scale.

To run a simulation in MOVES, a run specification, input data and expected outputs need to be defined in the tool. The MOVES run specification and the considerations made for defining the levels for the road surface condition factors are briefly explained below. The approach 2 discussed in the previous section is adopted as a guiding framework to simulate road surface effects on vehicle fuel consumption and emissions.

7.3.1.1 Set up for MOVES Run Specification, Input and Output Data

To run MOVES, users must provide or create a run specification and input databases (at county or project scales). Here, a county-scale custom domain setup was used following Wang et al. (2020). MOVES creates an output database after executing the analysis with the default data and input data. A simple structure of how to set up MOVES for this study is shown in

Figure 7.5.

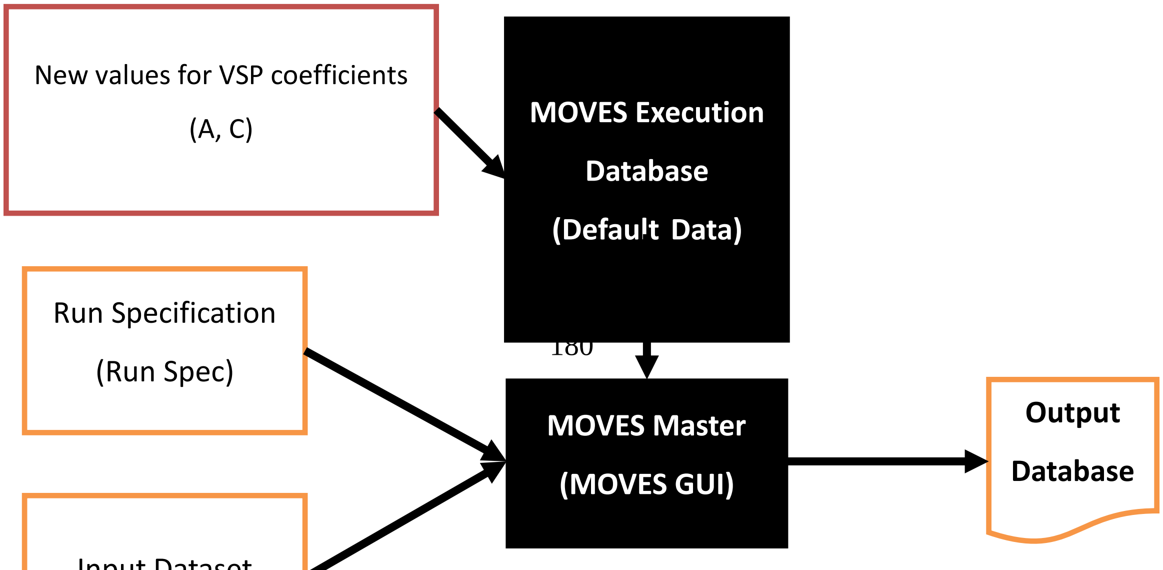


Figure 7.5 The simplified structure of MOVES

VSP Coefficients Inputs:

To change the VSP model parameters A, B, C, the values available in the execution database were updated by estimating A and C using the equation Eq. 7.8 and 7.9 and the subsequent Eq. 7.10 to 12. The default data for A, B and C coefficients in MOVES database are based on a dynamometer test on steel which correspond to driving on a smooth surface where effects of surface texture can be ignored (Wang et al., 2012). The values proposed by Chatti and Zaabar (2012) for the HDM4 model parameters were plugged into the eq.8.8 and eq. 8.9 to establish the equations for A and C at IRI = 0m/km and MTD = 0mm. Next, the established calibrated parameters from the HDM-4 model and the selected roughness (IRI) and macrotexture (MTD) levels (see Table 7.5) were plugged into Equations 8.8 to 8.12 to compute MOVES coefficients A and C at varying IRI and MTD values. The values for the calibrated parameters from Chatti and Zaabar are available in Appendix D.

Run Spec and Input Dataset:

MOVES uses the run specification to guide the analysis done by the tool. The run spec can be defined on the MOVES GUI where selection of spatial and temporal span, road type, vehicle type, pollutants and the units of output data can be defined. In this study, for modelling on road energy use and emission, emission rate per unit activity was the selected calculation type. The county domain which includes all local data was selected to be a custom census-division level domain and database for Ontario developed by Wang (2020). One hour of a weekday in April in 2012 was the selected time span. Four road types (Table 7.1) and seven vehicle types (Table 7.2) were selected.

Table 7.1 MOVES Road Type Distribution Adopted

Road Type ID	Road Type VMTFraction	MOVES Road Type	Ontario Road type
2	0.040327757	Rural Restricted Access	Inter-region Freeway/Expressway (Rural)
3	0.100199877	Rural Unrestricted Access	Local, collector, arterial road (Rural)
4	0.246646102	Urban Restricted Access	Freeway and expressway (Urban)
5	0.612826264	Urban Unrestricted Access	Local, collector, arterial road (Urban)

The road types and vehicle types are detailed under the MOVES input data. Twelve pollutants and total energy consumption were selected along with their emission processes such as running exhaust and crankcase running exhaust. Desired output units selected for the mass, energy consumption and distance travelled were in grams, joules and kilometres respectively.

For vehicle types and classification, MOVES has 13 source types while HDM4 models has 15 vehicle class, so attempts were made to match vehicle types in different contexts. Wang (2018) made attempts to match vehicle types reported in Canada to MOVES source types by using the Canadian vehicle registration data to map Ontario vehicle types to MOVES source types, this effort was considered in matching the MOVES source types to vehicle class used in the HDM4 model. Table 7.2 presents the relationship of the vehicle source types from the Wang's Ontario vehicle classification to the MOVES source types and HDM4 vehicle class used in the study for development of the VSP coefficients A and C.

Table 7.2 Vehicle types considered in the simulation and model development

Ontario vehicle class	MOVES Source Types	HDM4 model vehicle class
Light-duty Vehicles (LDV)	Passenger Car (21)	Small/medium car
	Passenger Trucks (31)	Four-wheel drive
	Light Commercial Truck (32)	Light truck
Medium-duty Vehicles (MDV)	Single Unit Short-haul Truck (52)	Medium Truck
	Single Unit Long-haul Truck (53)	
Heavy-duty Vehicles (HDV)	Combination Short-haul Truck (61)	Heavy Truck
	Combination Long-haul Truck (62)	

As discussed in the literature review, speed is considered to have an effect on how IRI and macrotexture affect vehicle fuel consumption, so this study would also consider the influence of speed on vehicle fuel consumption and emission effect due to road condition. MOVES has 16 speed bins but only 13 bins were considered here with speed range from 4km/h to 100km/h. This is because the maximum speed limit in Ontario is 100km/h. MOVES speed bins are important for calculating VSP for differing operating mode designed in MOVES. The speed bins represent different ranges of speed in miles per hours, so in this study, an average point was selected to represent each speedbin as shown in Table 7.3. Available data on the average speed fraction (see Table 8.3) of each vehicle types in an hour as defined by Wang (2018) was collected for running MOVES and future data post-processing.

Table 7.3 Assigned Average Speed for MOVES Speed Bins

Speed Bin ID	Speed Bin Range (mph)	Assigned Average speed (km/h)	avgSpeedFraction (11, 21, 31, 32)	avgSpeedFraction (52, 53, 61, 62)
1	Speed < 2.5mph	4	0.973298	0.90063
2	2.5mph <= speed < 7.5mph	10	0.001168	0.001382
3	7.5mph <= speed < 12.5mph	15	0.000626	0.00087
4	12.5mph <= speed < 17.5mph	25	0.000389	0.000719
5	17.5mph <= speed < 22.5mph	35	0.000479	0.000905
6	22.5mph <= speed < 27.5mph	40	0.000468	0.000946
7	27.5mph <= speed < 32.5mph	50	0.000448	0.000475
8	32.5mph <= speed < 37.5mph	55	0.001321	0.001322
9	37.5mph <= speed < 42.5mph	65	0.002993	0.004075

10	42.5mph <= speed < 47.5mph	70	0.004694	0.008888
11	47.5mph <= speed < 52.5mph	80	0.009147	0.028788
12	52.5mph <= speed < 57.5mph	90	0.001571	0.013019
13	57.5mph <= speed < 62.5mph	100	0.003398	0.037982

MOVES Output Database:

MOVES output is saved in a database that contain all the different rates measures. The rateperdistance output table was selected, which includes the information for energy and emission rate per distance (1km) traveled by a sources type on a road type. It provides separate data for each for each pollutant for the selected processes. For the pollutants selected in this study, these processes include running exhaust, crack running exhaust and other processes list in Table 1 of Appendix D. The output table is stored in an external database management tool MariaDB, but the data can easily be extracted to other programs such as Microsoft Excel. For the base scenario, over 4732 data points extracted represent fuel consumption and emissions rates of twelve pollutants: Carbon dioxide (CO_2), Nitrous oxide (N_2O), Methane gas (CH_4), Sulphur dioxide (SO_2), Carbon monoxide (CO), Nitrogen dioxide (NO_2), Nitrogen oxides (NOx), Particulate matter 2.5um (PM2.5), Particulate matter 10um (PM10), Ammonia (NH_3), Volatile organic compounds (VOCs) and Hydrocarbons (HC). There were 364 emission rates per vehicle for each pollutant.

7.3.1.2 Define levels for road surface factors:

It is important to note the pavement surface parameters roughness and macro-texture can be attributed to other factors such as overall pavement condition, ride comfort for road users and road safety. These are relevant for decision making based on other pavement management goals and objectives, as such already attracts a stipulated threshold or an expected level of performance for road roughness and macrotexture to meet the target of those objectives. Roughness is a measure ride comfort and can be related to the overall pavement condition measure such as pavement condition index (PCI). Some road authorities in Canada have set performance triggers for maintenance and rehabilitation of the road network based on PCI values. These trigger values are used to prioritize the pavement sections that required treatment during network level pavement maintenance programming and planning. In Ontario, MTO has set the PCI and DMI performance threshold for performance of different roads by function **(Table 7.4)**.

Table 7.4 Performance thresholds per functional class

Functional Class	DMI	PCI	IRI – back calculation
Freeway	7.3	65	1.9
Arterial	7	55	2.9
Collector	6.8	50	3.3
Local	6.8	45	4

Although IRI threshold is not mentioned, it can be back calculated using the equation

$$PCI = Max\,(0, Min\,(100,\; 13.75 + 9 \times DMI - 7.5 \times IRI) \qquad \textbf{Eq. 7.18}$$

Eq. 7.17

Based on this threshold values, four levels of IRI are define in this investigation: 1m/km, 2m/km, 3m/km and 4m/km.

$$PCI = Max\,(0, Min\,(100,\; 13.75 + 9 \times DMI - 7.5 \times IRI) \qquad \textbf{Eq. 7.18}$$

The objectives of addressing road safety factors can be influenced by IRI and macrotexture (Tighe et al. 2000). Friction is of high importance for safe vehicle operation. Positive relationship between pavement friction and various macrotexture indices have been reported in previous case studies for Ontario roads by (Ahammed and Tighe 2010). The research program focus was on quiet pavements and included investigation of both concrete and asphalt pavements. The found that the minimum macrotexture level to achieve adequate friction while reducing noise impacts of both types of pavements is 0.5mm measured by mean textured depth (MTD). They found weak correlation between texture and noise but strong correlation between texture and friction. However, the road friction does not increase when the texture is above 1.8mm MTD, thus there is no significant safety benefit at that point. In fact, field test suggests that for asphalt roads, there is a decline in friction as texture increase beyond 1.8mm. In this study, a range of MTD from 0.5mm to 2mm were initially considered in the simulating vehicle fuel consumption and emissions. On that note, in this study the preliminary analysis design matrix based on four levels of the two factors of road surface as shown in Table was considered for simulation.

For roughness, the four level of IRI with unit m/km are 1, 2, 3, 4. For texture, Mean Texture Depth (MTD) is the measure of macrotexture with unit mm, for four levels: 0.5, 1, 1.5, 2.

Table 7.5 Analysis design matrix for the levels of road surface factors

IRI/MTD	1	2	3	4
0.5	A1	A2	A3	A4
1	A5	A6	A7	A8
1.5	A9	A10	A11	A12
2	A13	A14	A15	A16

7.3.2 Developing Regression Models for Energy Consumption

After investigating individual variable effects and considering the underlying physics, two approaches were considered to develop regression models.

The first approach used the physical interpretation of power and energy along with the linear relationship between VSP and energy consumed per distance traveled already explained by Ziyadi et al. (2018). On that note, the theoretical basis is defined based on Eq. 7.13. However, idling energy is not considered as it is not reflective of relationship in Eq. 7.13 and the relationship between pavement condition parameters are first identified before inclusion in the model. So, equation Eq. 7.18 is a expression of Eq. 7.13.

$$\mathrm{E} \propto \boldsymbol{VSP} \times \boldsymbol{M} \times \frac{\mathbf{1}}{\boldsymbol{v}}$$

$$\mathrm{E} \propto \frac{\boldsymbol{P_{idle}}}{\boldsymbol{v}} + \boldsymbol{A} + \boldsymbol{B} \times \boldsymbol{v} + \boldsymbol{C} \times \boldsymbol{v}^{\mathbf{2}} + \boldsymbol{D} \qquad \textbf{Eq. 7.19}$$

In this form, A, B and C represent the same parameters as in the VSP equation Eq. 7.2. **D** represents the grade and acceleration term and is a constant which can be merged into the definition of A and C since they will include a constant value (Ziyadi, et al 2018). The relationship between pavement surface condition parameters (IRI and MTD) and VSP coefficients (A and C) in Eq. 7.20 and 7.21, were defined based on the estimates for each vehicle type calculated using the 4 levels or IRI and MTD as design in Table 7.5. So, the energy rate model takes the form in Eq. 7.22

$$\boldsymbol{A} = \boldsymbol{a_1} \times \mathbf{IRI} + \boldsymbol{a_2} \times \mathbf{MTD} + \boldsymbol{a_0} \qquad \textbf{Eq. 7.20}$$

$\boldsymbol{C = c_1 \times IRI + c_2 \times MTD + c_0}$ **Eq. 7.21**

E-Rate(ij) = $\frac{\boldsymbol{P_1}}{\boldsymbol{v}} + (\boldsymbol{a_1} \times \mathbf{IRI} + \boldsymbol{a_2} \times \mathbf{MTD} + \boldsymbol{a_0}) + \boldsymbol{b} \times \boldsymbol{v} + (\boldsymbol{c_1} \times \boldsymbol{IRI} + \boldsymbol{c_2} \times \boldsymbol{MTD} + \boldsymbol{c_0})\, \boldsymbol{v^2}$ **Eq. 7.22**

Where;

E-Rate(ij) = estimated energy consumption per vehicle distance (j/km) for a vehicle type (i) driving and a road class (j), i = vehicle classes in Table 7.2, j = road classes in Table 7.1.

IRI = International roughness Index (m/km)

MTD = Mean texture depth (mm)

V = Average speed (km/h)

$\boldsymbol{P_1}, \boldsymbol{a_0}, \boldsymbol{a_1}, \boldsymbol{a_2}, \boldsymbol{c_0}, \boldsymbol{c_1}, \boldsymbol{c_2}, \boldsymbol{and\ b}$ = Model coefficients

With the general form of the regression model in Eq. 7.22, the model coefficients were estimated by performing an ordinary least square fit using the regression model proposed and the data from MOVES simulations for scenario 1 to 16. The regression models were developed for 7 vehicle type (Source ID 21 to 62) per each road type (Road ID 2 to 5). The levels of the pavement condition factors are mapped into 16 scenarios using an orthogonal matrix design of experiment, and each scenario considered the 13 levels of average speed available in MOVES as shown in Table 7.6. The R Studio (RStudio Team 2020) was used for statistical modeling and to check validity of the model.

7.3.3 Developing Regression Models for Environmental Damage Cost of Atmospheric Emissions

The next step in the model development is to formulate a relationship covering roughness impact on the environmental damage cost (EDC) associated with air pollutants Carbon dioxide (CO_2), Carbon monoxide (CO), Nitrogen oxides (NOx), Sulphur dioxide (SO_2) and Particulate matter 2.5um ($PM_{2.5}$) based on the atmospheric damage estimates per Mg of each pollutant developed by Nasir (2018) for Ontario. In the second approach, an attempt was made to develop linear regression models to define a relationship between environmental damage for per vehicle-km travelled in (g/veh-km) as the response variable and three independent variables, IRI and speed, for each MTD level, seven vehicle types and 4 road class.

Such outcome-based models and indicators are vital for integrating environmental sustainability in pavement management decision making as discussed in chapter 3 of this thesis. For easy implementation, simple linear regression models are used to define the EDC-roughness models for each pollutant, given by equation:

$$\mathbf{EDC\text{-}IRI_{(j)} = a + b\ IRI_i} \qquad \textbf{Eq. 7.23}$$

Where:

$EDC\text{-}IRI_{(j)}$ = environmental damage cost from atmospheric release of pollutant j(Mg/km)

j = pollutants: Carbon dioxide (CO_2), Carbon monoxide (CO), Nitrogen oxides (NOx), Sulphur dioxide (SO_2) or Particulate matter 2.5um ($PM_{2.5}$)

IRI_i = road roughness indicated by IRI (m/Km), i = 1 to 4

a, b = model coefficients

Validation:

The results are reported in Section 7.4.1 and the model results are reported in Section 7.4.2. To validate the regression models, first the model predictions and coefficients were checked to ensure agreement with the physical theory, which was typically the guide to developing the model. Then the predicted values were compared with the actual data, and the adjusted R^2 and *P*-values were estimated. Finally, the predicted data were compared to data from previously developed models for fuel consumption. The validation of the models is presented in section 7.4.3.

7.4 Results and Discussion

7.4.1 Preliminary Output Data Analysis

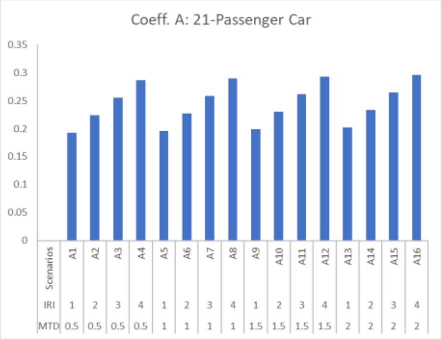
This section shows results of preliminary investigation of variable effects. The preliminary data analysis is an investigation of the individual variable effect, to see if an equation can be set to explain the relationship. Also, the physical theory behind the system is considered. As seen in Table 7.5, there are 16 scenarios/runs that were run to understand the effect of road condition parameters. The VSP rolling resistance coefficient (A) and air drag coefficient (C) were estimated for 7 vehicle types with the various levels of IRI and MTD defined in the 16 scenarios.

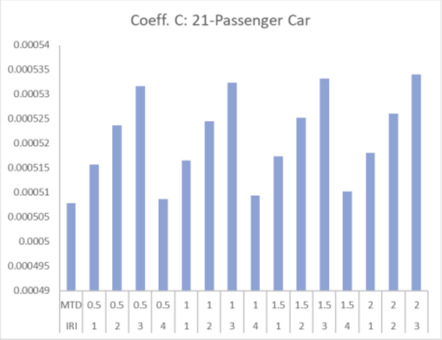
The MOVES output database for each of the runs produces over 430,612 rows x 8 columns for the "Rates-per-distance" table. This table contains 364 rates for energy consumed and for each pollutant emissions. The 364 rate per distance for a pollutant emissions or energy use represents rates per distance travelled at 13 different average speed (Table 7.3) by 7 different vehicle classes (Table 7.2) on 4 road classes (Table 7.1). The preliminary data analysis was done to see the relationship between the individual independent variables (IRI and MTD) on the values of VSP coefficients (A and C), and main dependent variables of concern in this study - rate of fuel consumption and emissions rates of twelve pollutants: Carbon dioxide (CO_2), Nitrous oxide (N_2O), Methane gas (CH_4), Sulphur dioxide (SO_2), Carbon monoxide (CO), Nitrogen dioxide (NO_2), Nitrogen oxides (NOx), Particulate matter 2.5um ($PM_{2.5}$), Particulate matter 10um (PM_{10}), Ammonia (NH_3), Volatile organic compounds (VOCs) and Hydrocarbons (HC).

In the database, the energy consumed is recorded in Joules per 1km traveled for each vehicle (source type) type travelling on 4 different 4 road classes. The pollutants data was stored as rate of emission in gram of Pollutant emitted per vehicle – km travelled for each vehicle type on each road type.

7.4.1.1 Effects on VSP Coefficients

Figure 7.6 show the relationship between the estimated VSP coefficients (A and C) and the pavement surface characteristics (roughness (IRI) and macrotexture (MTD)). The charts are based on the estimates of coefficient A and C calculated by Eq. 7.11 and 7.12 along with the IRI and MTD matric in Table 7.5 and parameters from calibrated HDM4 models. The charts confirm that there is a linear relationship between VSP coefficients and the pavement surface parameters. This was used in applying in the physical theory to regression model development as expressed in equation Eq.7.22.





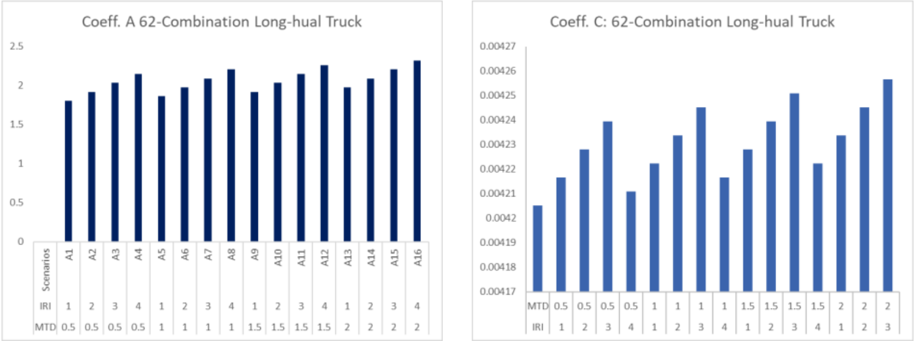


Figure 7.6 Effect of IRI and MTD on VSP rolling resistance (A) and air-drag (C) coefficient for a Passenger Car and a Heavy-Duty Truck

MOVES output contained over 430,000 data points for each scenario (A1 to A16). The data were processed using both the R programming language and Microsoft Excel. Charts are presented in the subsequent sections to show the effects of pavement characteristics on energy consumption and the vehicle emissions. Only the effects on energy and GHG emissions are discussed in this chapter. The effects on other outputs were investigated and the charts to show the relationships have been presented in an Excel document attached to this thesis. All 430613 estimates for energy and 12 pollutants form MOVES are also available in the Excel document.

7.4.1.2 Effects on Vehicle Energy Consumption:

The vehicle energy consumption for a passenger car travelling on a freeway is plotted to give a general picture of the data structure Figure 7.7. As can be seen in Figure 7.7 the distribution of the energy consumption data is right skewed and there seems to be some outliers on the far left. The energy consumption is concentrated at lower levels, with a few cases of high consumption. The effect would be a combination of the different variables considered. Considering individual effects provides a better picture and understanding. In this study, the candidate independent variables are IRI and macrotexture. Speed was considered a confounding variable. For the independent variable, data points were for all speed levels from 4km/h to 100km/h. The speed may be having a great influence on the skewed distribution given that many higher speed levels (8 levels above 40km/h)) are considered compared to lower speed levels (5 levels).

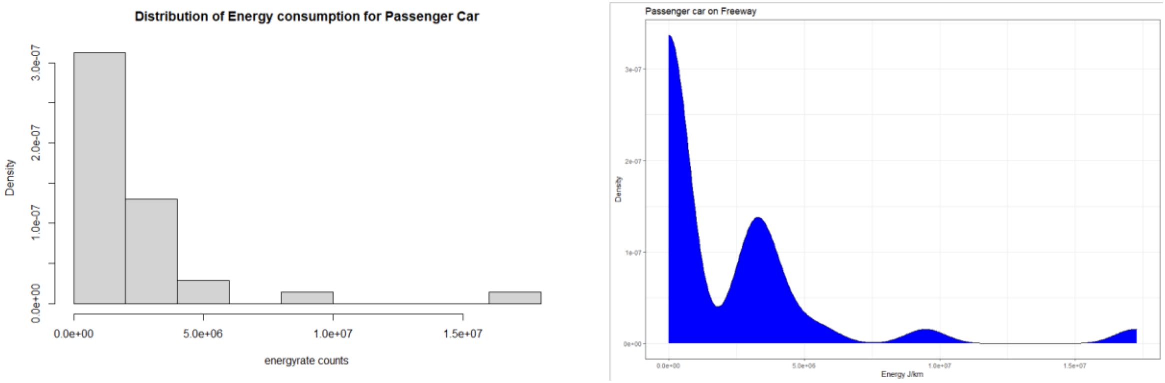
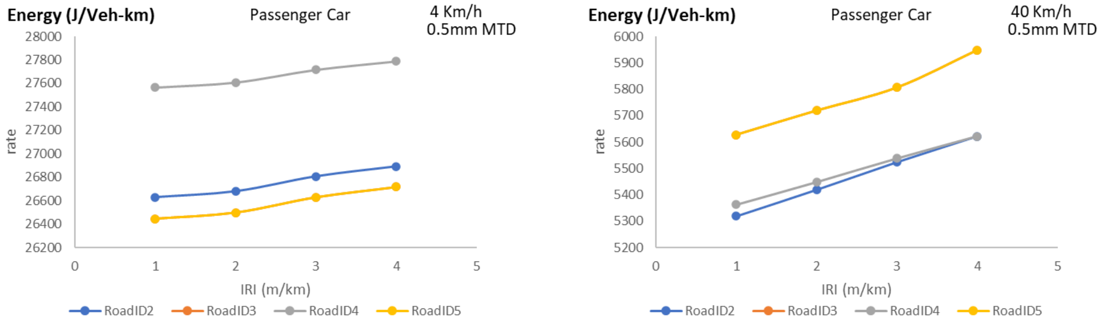


Figure 7.7 Distribution of energy consumption (J/km) by a passenger travel on a freeway with varying road surface conditions, roughness = 1m/km to 4m/km, and macrotexture = 0.5mm to 2mm and at various speed from 4km/h to 100km/h

Effect of Roughness

In Figure 7.8 and Figure 7.9 the energy consumption from a passenger car and combination trucks travelling on the four class is plotted on the range of IRI values (1, 2, 3 and 4 m/km) while other factors (MPD) are kept constant. Four speed levels are considered to show the influence of speed on the date. Both Figure 7.8 and Figure 7.9 show that the energy consumption increases when IRI was increased for passenger cars, and combination long-haul truck respectively. However, the rates differ by road classes and the rate of increase is also a function of speed. The energy consumption rate is higher at lower speed, but the effect of increasing roughness is higher at higher speed. It shows that driving urban freeways (road4), the effect of increase in roughness will be more if the passenger is moving at a higher speed. At lower speed the change in energy consumption rate is about 2% when the IRI changes from 1 m/km to 4m/km. at lower speed it is about 8% higher.



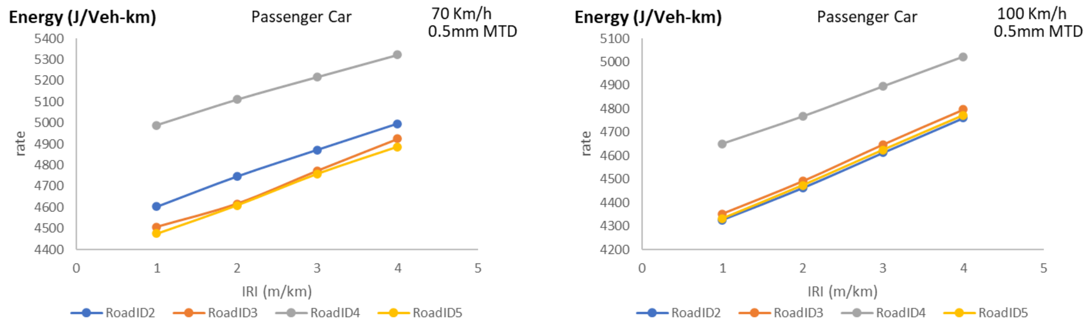


Figure 7.8 Effect of roughness on energy consumption by Passenger car travelling at different speed label on chart) on four road class.

The energy consumption rate will also differ for a truck traveling on same urban freeway, at lower speed the truck will consume more fuels on urban arterial roads compared to freeways. The impact across road shows relatively similar upward trend for increase in roughness, if driving at same speed.

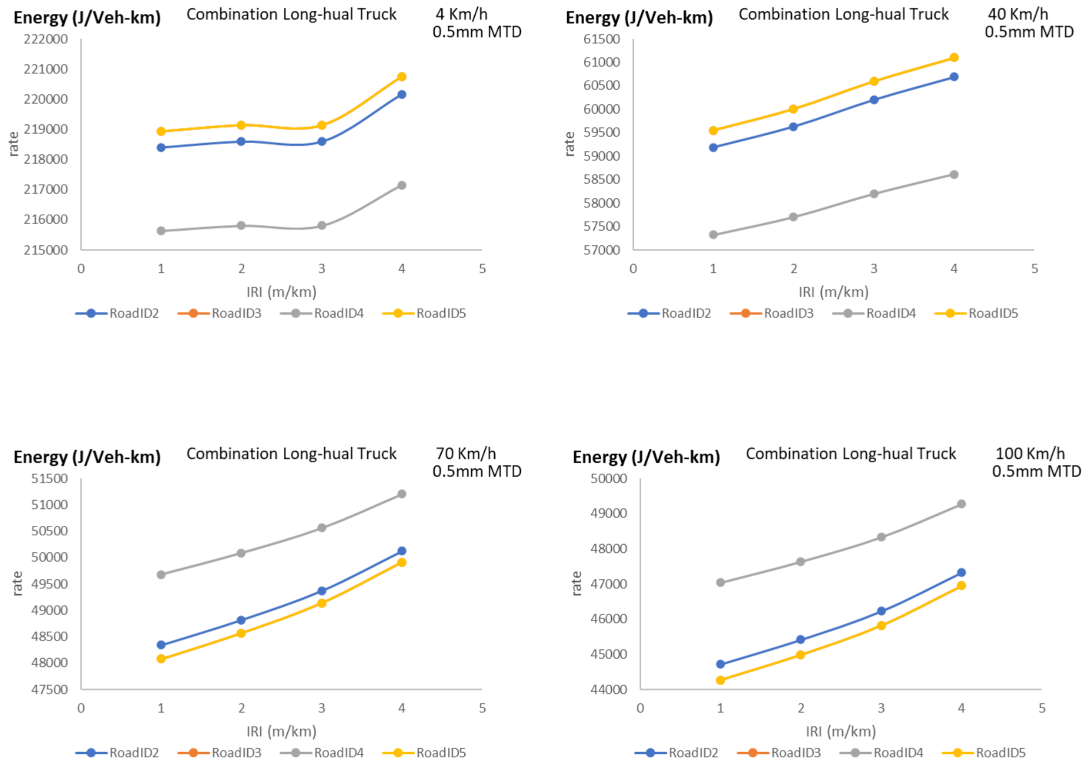


Figure 7.9Effect of IRI on Energy consumption by Heavy Duty Truck, at various speed

Effect of Macrotexture

For macro-texture effects, Figure 7.10 shows no direct correlation can found between fuel consumption and macrotexture increase. There is no visible different between the road types, but the rate of energy consumption is significantly higher when MTD is I.5mm compared to other levels. At contact speed, the rate of energy consumption is the same when MTD is 0.5mm, 1mm and 2 mm for vehicle km-travel.

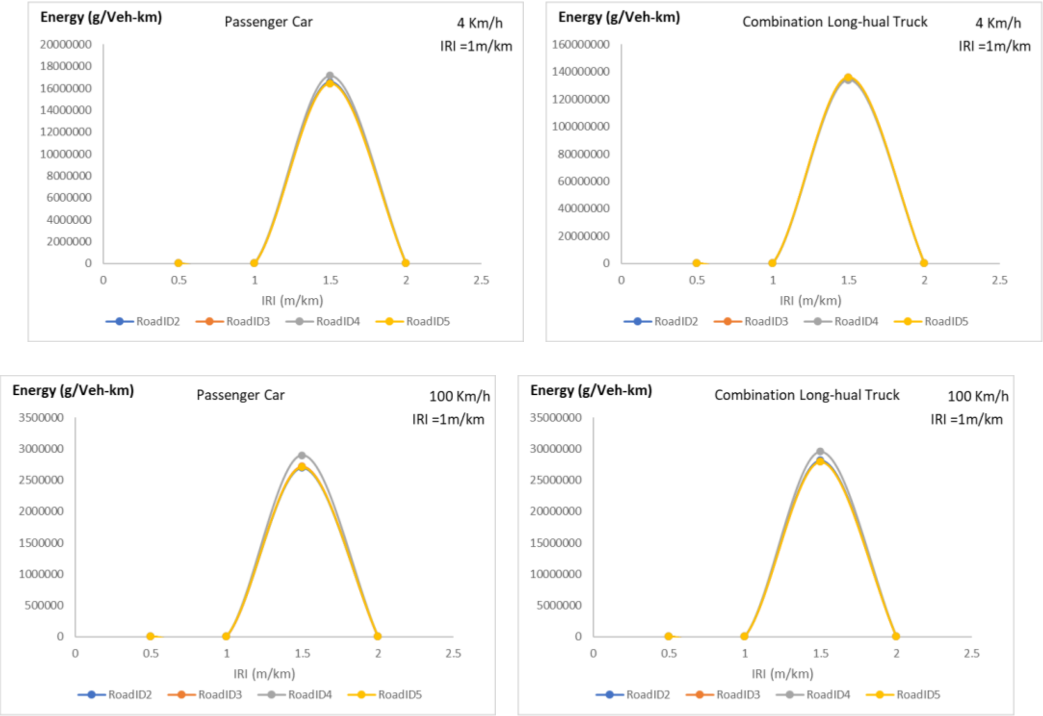


Figure 7.10 Effect of Macrotexture on Energy Consumption per Passenger Car and Heavy Duty Truck travelling at various speed (4km/h, 100km/h)

Effect of Speed

The Figure 7.11 and 7.12 shows the interaction of speed with the pavement parameters. At lower speed, the rate of energy consumption is higher. The energy consumption at lower speed is shown to be higher with increase in MTD and IRI, which reflect the pavement condition can influence driving conditions. Given that on rougher roads, drivers are expected to slow down. Similar relationship between speed and road roughness was found in Yu and Lu (2013) data analysis of California road network, The skewness in the energy rate distribution found in the present study can be related to speed (see Figure 7.7). As shown in Figure 7.11 and 7.12, many data point can be related the higher speed which has lower energy rate and lower energy demand compared to lower speed range.

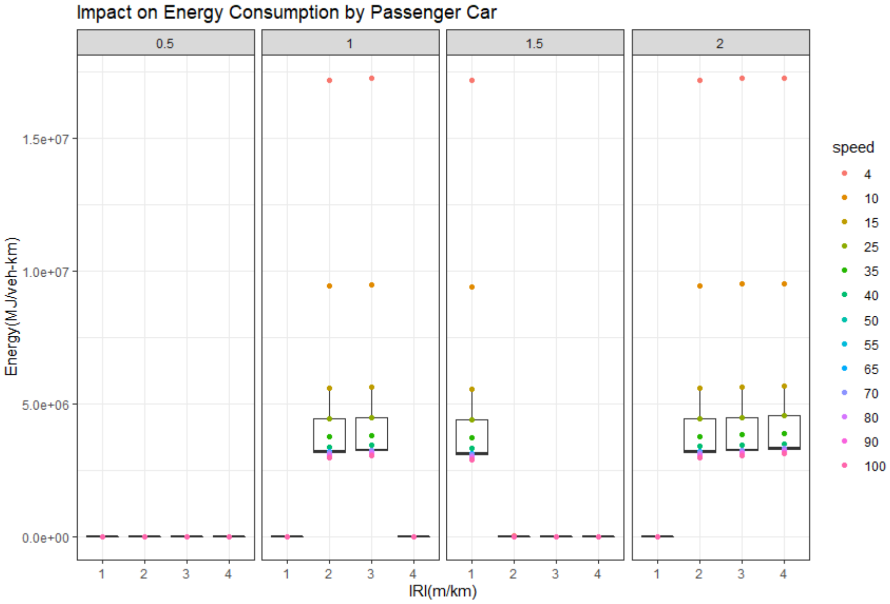


Figure 7.11 Visualization of Urban Freeway for a Passenger car divided into blocks of macrotexture

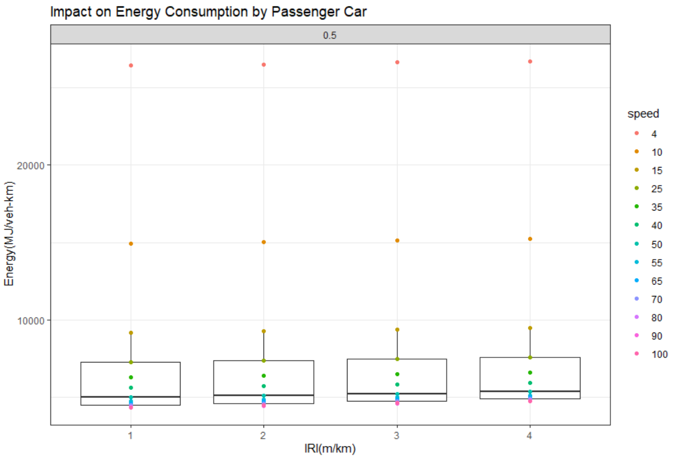


Figure 7.12 Effect of IRI and speed on energy consumption by a passenger on a freeway with macrotexture of 0.5mm

7.4.1.3 Effects on GHG Emission

Carbon Dioxide (CO_2) Emissions

For the ranges of pavement surface condition (roughness = 1m/km to 4m/km, and macrotexture = 0.5mm to 2mm) and at various speed (4km/h to 100km/h) the corresponding CO_2 emission output data distribution is plotted to give a general picture of the data structure, as shown in Figure 7.13. The density plot of the distribution of the CO_2 emission data is slightly right skewed. The CO_2 emission data mainly locate in the lower range reflect lower speed range while what locate within the higher range are relatively higher speed range.

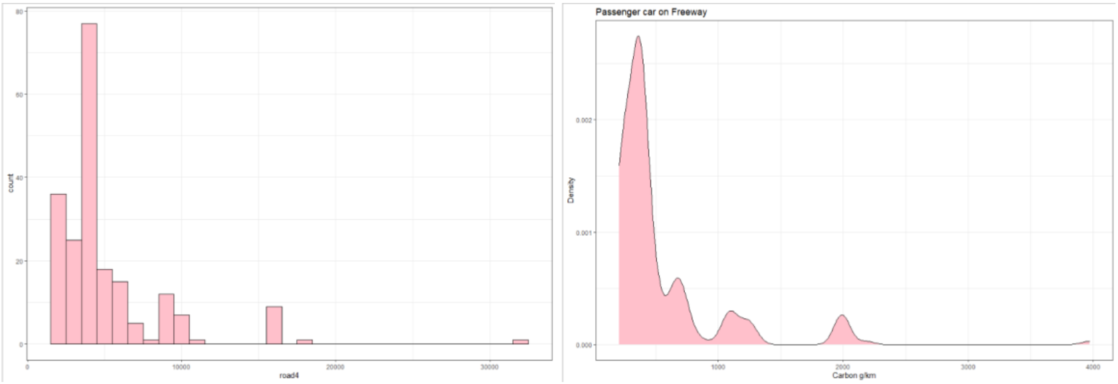
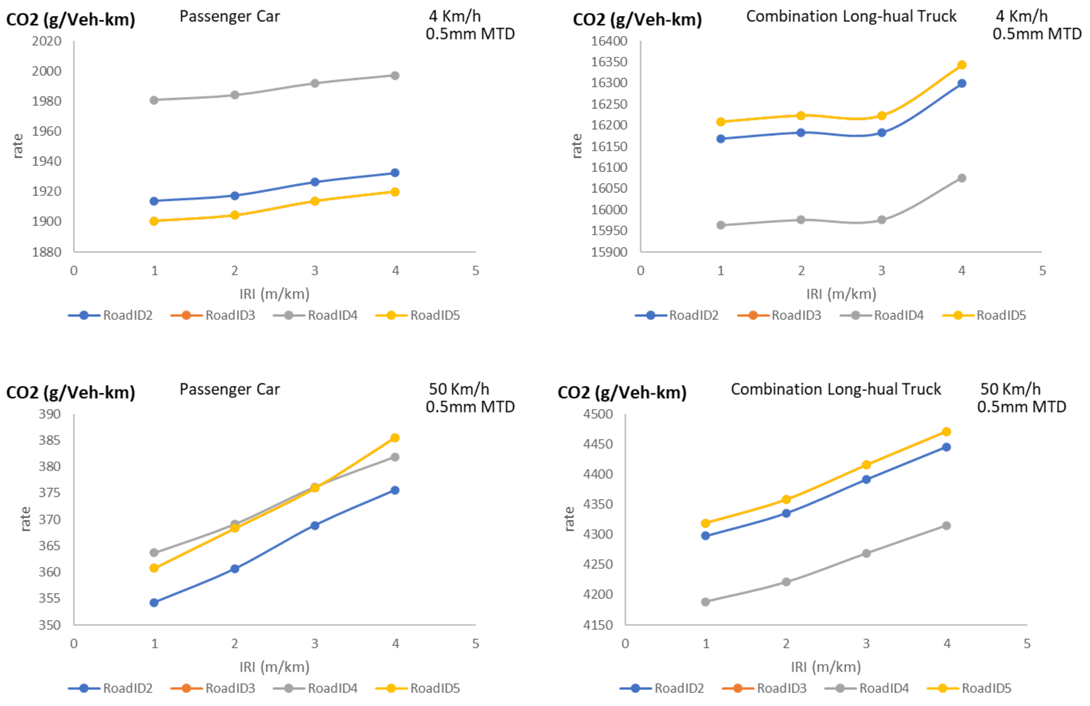


Figure 7.13 Distribution of Carbon dioxide (CO2) emissions (g/ km) from passenger car travel on a freeway with varying road surface conditions, roughness = 1m/km to 4m/km, and macrotexture = 0.5mm to 2mm and at various speed from 4km/h to 100km/h

Effect of Roughness on CO2 emissions

The charts of CO_2 emission rate for different ranges of IRI and MTD are shown in Figure 7.14. Similar to energy consumption, CO_2 emission rate data is higher at lower speed, but the effect of increasing roughness is higher at higher speed. For a passenger car, the results show on average there is 1% increase in CO2 emission unit change in roughness at low speed, but a 2% increase at higher speed. The results show that for a very rough highway (4m/km) the emission rate of a heavy-duty truck driving at 100km/h is 4% higher compared to compared to base case (roughness = 1m/km). The difference for the same vehicle and road condition traveling at 4km/h is only 1%.



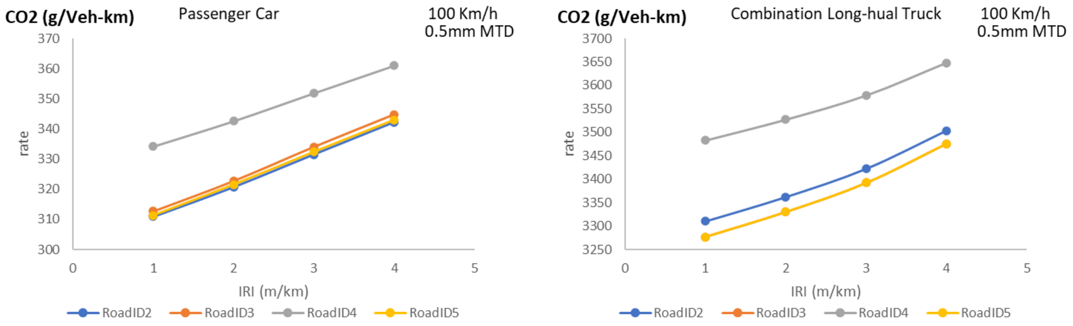


Figure 7.14 Effect of roughness on CO2 emissions from Passenger Car and Heavy Duty Trucks

Effect of Macrotexture on CO2 emissions

Figure 7.15 shows that there is no direct correlation between fuel consumption and macrotexture increase. There is no visible different between the road types and similar to effect of macrotexture on rate of energy consumption, CO2 emission rate is significantly higher when MTD is I.5mm compared to other levels. At contact speed, the emission rate for vehicle km-travel is relatively the same on a road with 1m/km roughness and macrotexture of 0.5mm, 1mm and 2 mm.

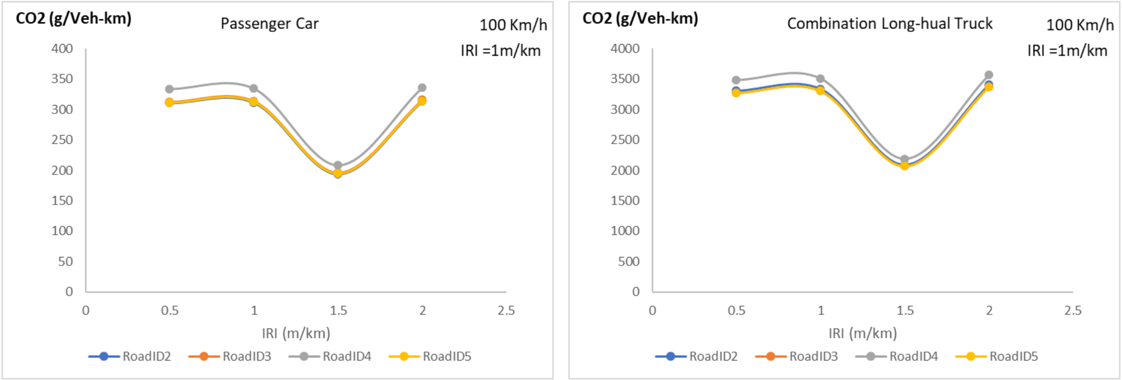


Figure 7.15 Effect of macrotexture on CO2 emissions from Passenger Car and Heavy-duty Trucks at 100km/h

A multi-faceted illustration of the effect of IRI and MTD on CO2 emissions form a passenger car travelling at various speed on 1km of an urban freeway is shown in Figure 7.16. The highest rate of CO2 emissions is found be emitted when the road roughness is 2m/km, MTD is 1.5 mm and speed is 4km/h.

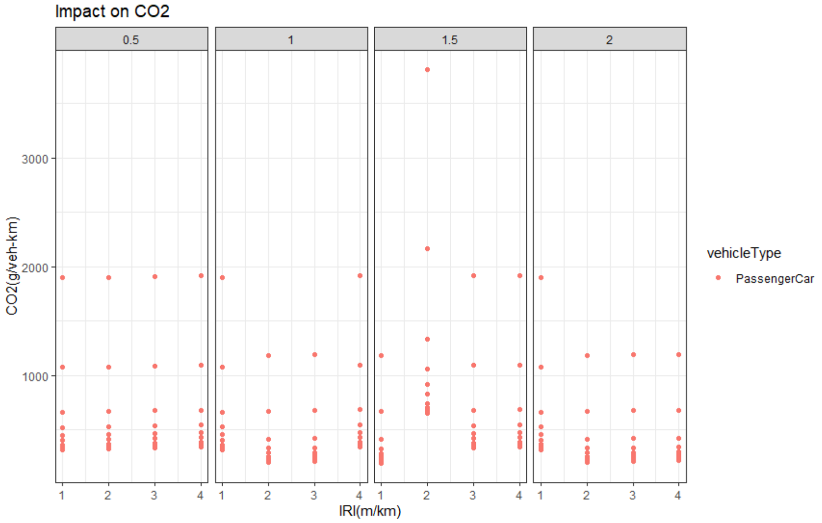


Figure 7.16 Effect of IRI and MTD on CO2 emissions produced by a passenger car.

Methane Gas (CH_4) emission

Figure 7.17 shows CH_4 emission output data distribution is plotted for a passenger car (source type 21) on a freeway (road type 4) to give a general picture of the data structure for the ranges of pavement surface condition (roughness = 1m/km to 4m/km, and macrotexture = 0.5mm to 2mm) and at various speed (4km/h to 100km/h). CH_4 emission output from the MOVES simulations as shown in the density plot reveals a slightly right skewed dataset. The CH_4 emission data ploted on the histogram show that the spikes of the density plot are due to few data point, so unlike the CO2 data and energy data, the difference with the higher speed data point could be large. This would be further reveled in the next few charts.

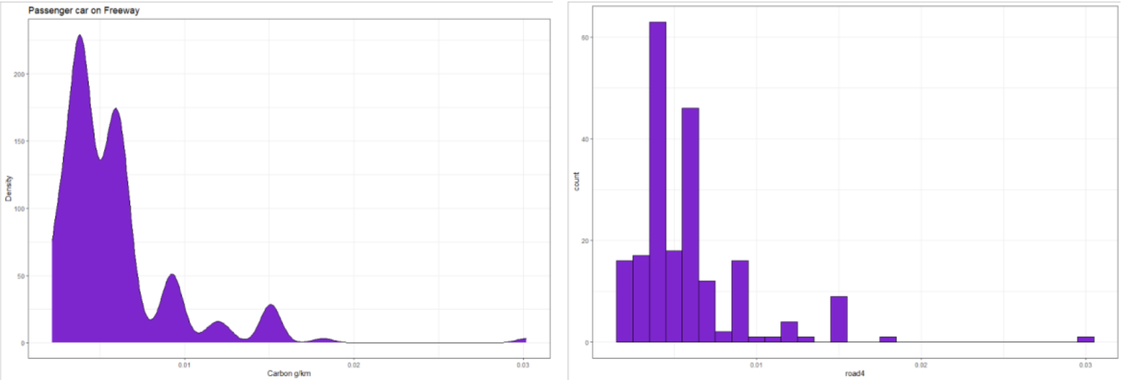
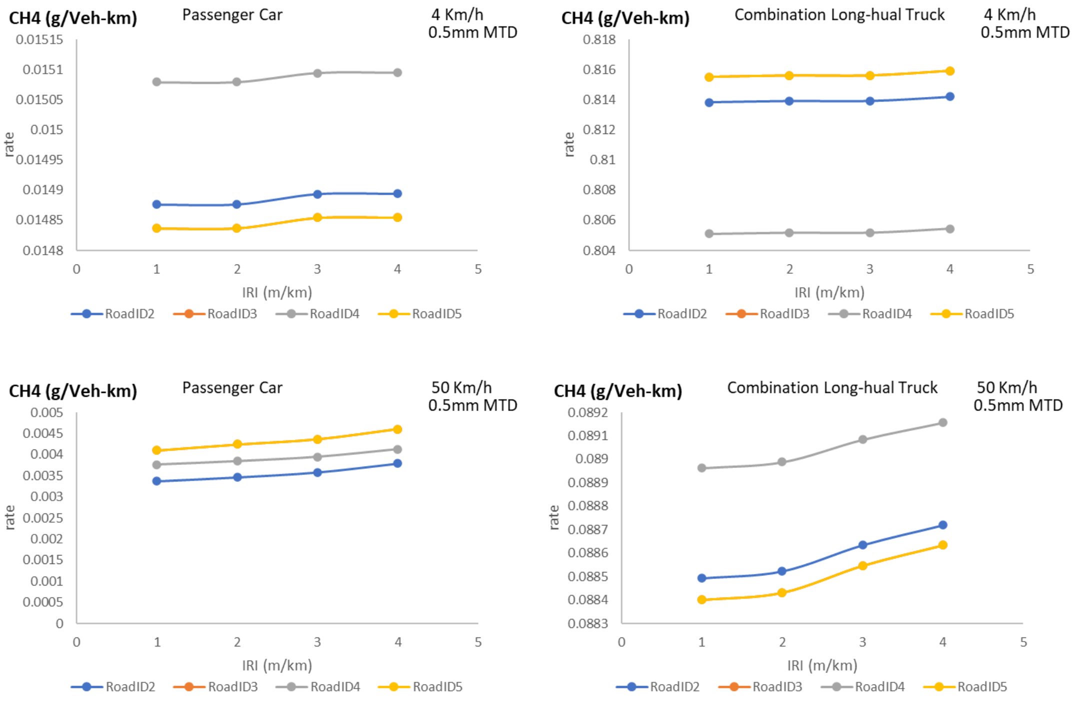


Figure 7.17Distribution of Methane gas (CH4) emissions (g/ km) from passenger car travel on a freeway with varying road surface conditions, roughness = 1m/km to 4m/km, and macrotexture = 0.5mm to 2mm and at various speed from 4km/h to 100km/h

Effect of Roughness on CH4 emissions

The charts of CH_4 emission rate for different ranges of IRI and 0.5mm MTD are shown in Figure 7.18. CH_4 emission rate data is higher at lower speed, but the effect of increasing roughness is higher at higher speed for passenger car. Emission rates estimates for heavy trucks started to show a downward projection, reflecting lower emission rates at speed 55. This could be due to the modeling approach for methane gas embedded in the MOVES tool. For a passenger car, the results show on average there is less than 0.1% increase in CO2 emission unit change in roughness at low speed, while at higher speed it can be up to 0.5% depending on road type. The difference for the same vehicle and road condition traveling at 4km/h is only 1%..



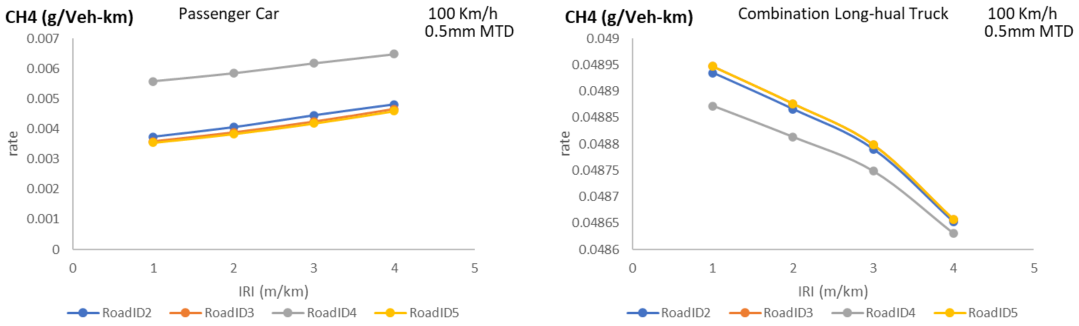


Figure 7.18 Effect of roughness on CH4 emissions from passenger and trucks

Nitrous oxides (N_2O)

For the ranges of pavement surface condition (roughness = 1m/km to 4m/km, and macrotexture = 0.5mm to 2mm) and at various speed (4km/h to 100km/h) the corresponding N_2O emission output data distribution is plotted to give a general picture of the data structure, as shown in Figure 7.19. similar to energy and CO2 data, the density plot of the distribution of the N_2O emission data is slightly right skewed.

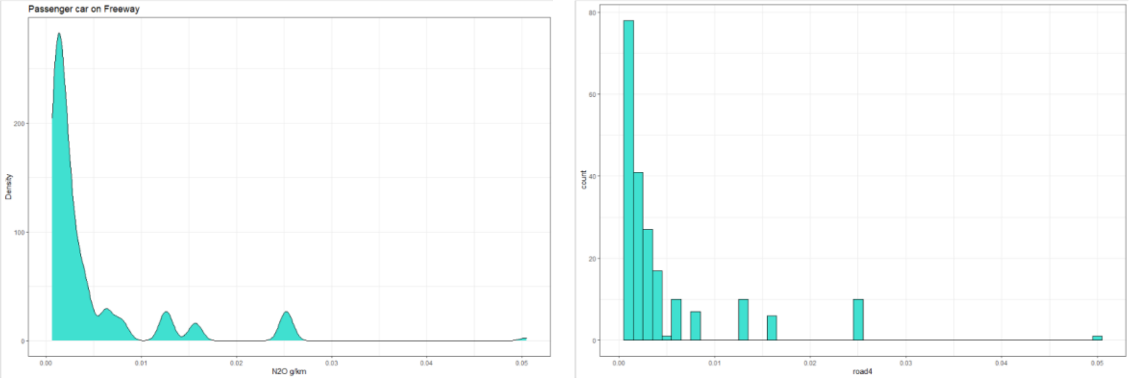


Figure 7.19 Distribution of Nitrous oxide (N2O) emissions (g/ km) from passenger car travel on a freeway with varying road surface conditions, roughness = 1m/km to 4m/km, and macrotexture = 0.5mm to 2mm and at various speed from 4km/h to 100km/h

Effect of Roughness on N2O emissions

The charts of CO_2 emission rate for passenger car and heavy-duty trucks driving at various speed (4km/h, 50km/h, 100km/h) on an urban freeway with different ranges of IRI at 0.5mmMTD are shown in Figure 7.20. NO2 rates per passenger car show varying rates for increase in IRI at different speed range. For low speed range, the effect of 1 unit of roughness from the base case for a passenger car is different from a heavy duty truck, passenger car show increase in emission while the it is the opposite for heavy duty trucks,

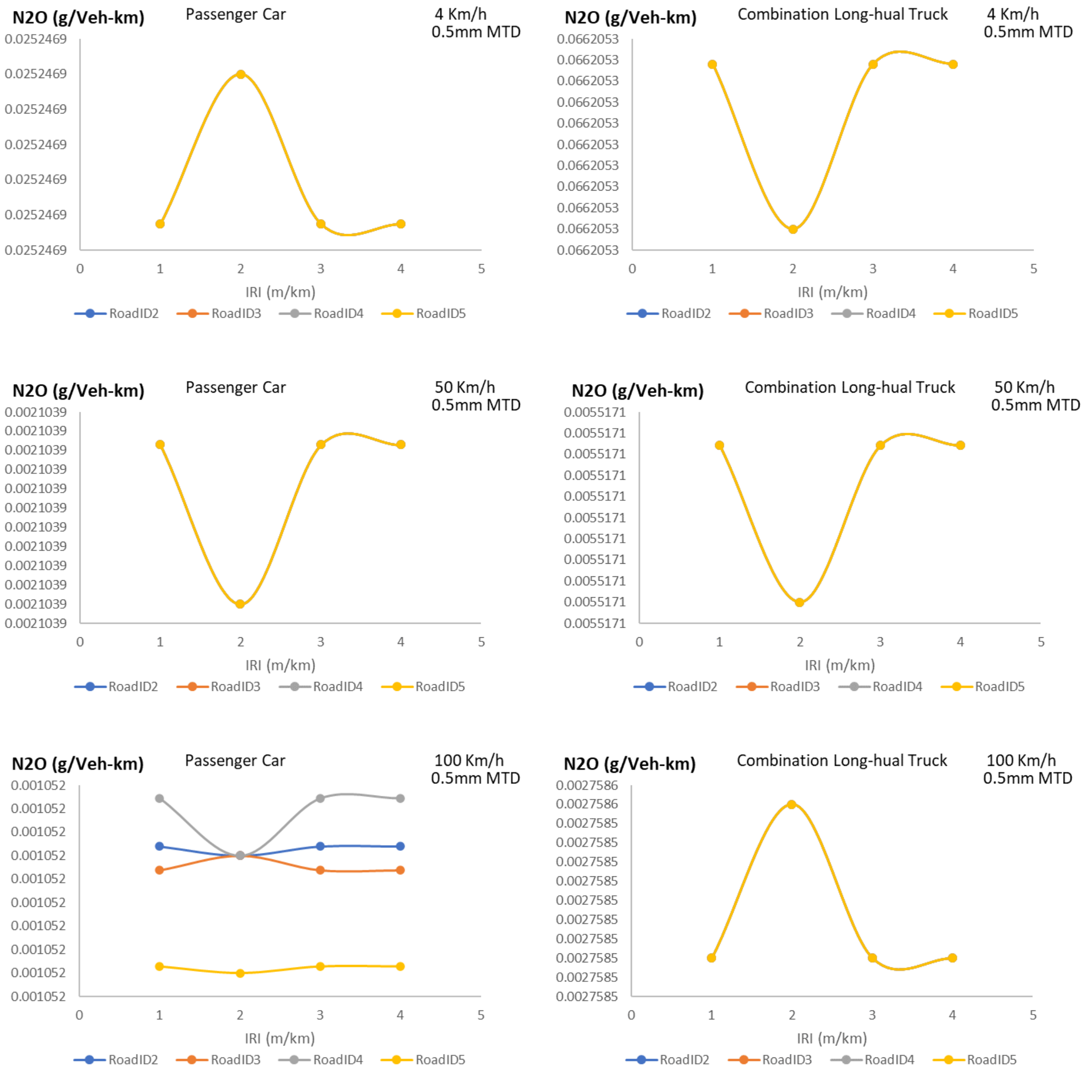
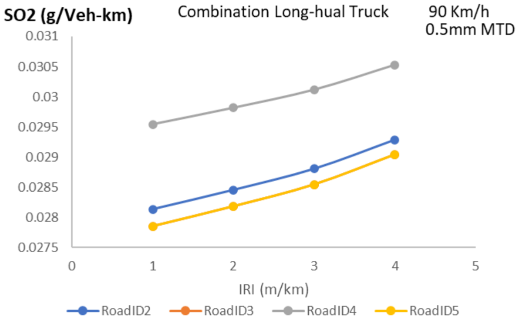
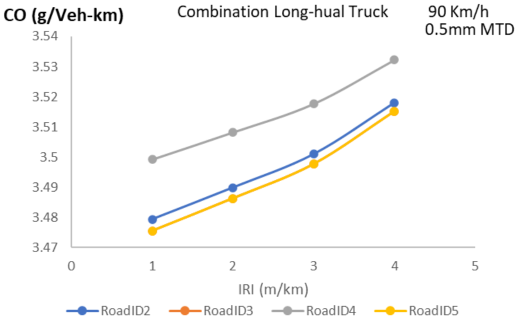


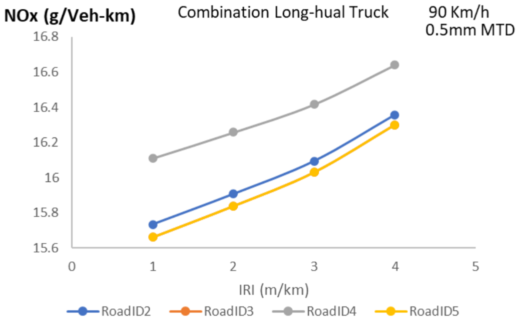
Figure 7.20 Effect of roughness on N2O emissions from passenger and trucks

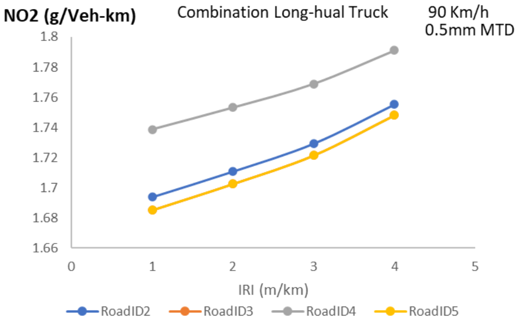
7.4.1.4 Effects on the Criteria Air Contaminants

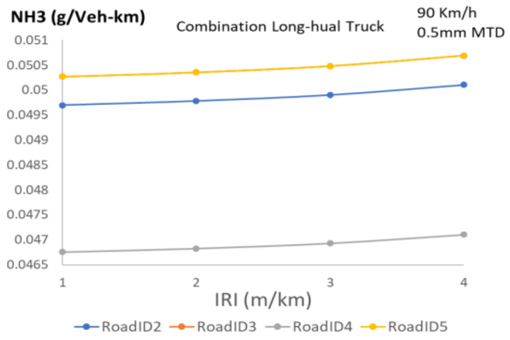
The effects of changes in pavement surface on the criteria air contaminants - Sulphur dioxide (SO2), Carbon monoxide (CO), Nitrogen dioxide (NO2), Nitrogen oxides (NOx), Particulate matter 2.5um (PM2.5), Particulate matter 10um (PM10), Ammonia (NH3) and Volatile organic compounds (VOCs) show similar upward trend for increase in roughness, the rate of increase varies largely and dependent on speed. The effect of macrotexture is show similar trend and the chart to visualize the effects are shown in the appendix D.

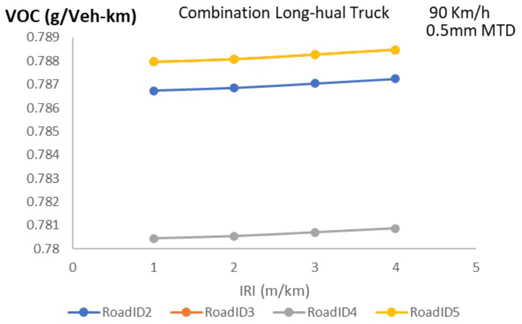












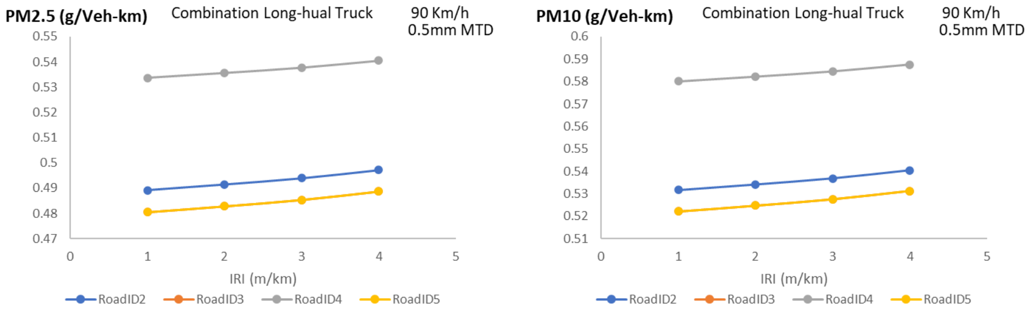


Figure 7.21 Effect of roughness on different pollutant emission from heavy duty (combination trucks) traveling on 1km of an urban freeway.

7.4.2 Regression Analysis and Models

7.4.2.1 Energy Consumption

After considering the general form of the regression model proposed in equation Eq. 7.22, the model coefficients were estimated by performing a series ordinary least square fittings using the regression model proposed. It found that a good fit could not be obtained when all the variables are considered in one model (see Figure 7.22). A decision was reached to consider MTD as a categorical variable and the model was fit for each block of MTD. The new form of the regression for each level of MTD is as shown in equation Eq. 7.23.

$$\text{E-Rate(ij)} = \frac{\boldsymbol{P_1}}{\boldsymbol{v}} + (\boldsymbol{a_1} \times \mathbf{IRI} + \boldsymbol{a_2} \times \mathbf{MTD} + \boldsymbol{a_0}) + \boldsymbol{b} \times \boldsymbol{v} + (\boldsymbol{c_1} \times \boldsymbol{IRI} + \boldsymbol{c_2} \times \boldsymbol{MTD} + \boldsymbol{c_0})\, \boldsymbol{v}^2 \quad \textbf{Eq. 7.24}$$

$$\textbf{E-Rate(ij)} = \frac{\boldsymbol{P_1}}{\boldsymbol{v}} + (\boldsymbol{a_1} \times \mathbf{IRI} + \boldsymbol{a_0}) + \boldsymbol{b} \times \boldsymbol{v} + (\boldsymbol{c_1} \times \boldsymbol{IRI} + \boldsymbol{c_0})\, \boldsymbol{v}^2 \qquad \textbf{Eq. 7.25}$$

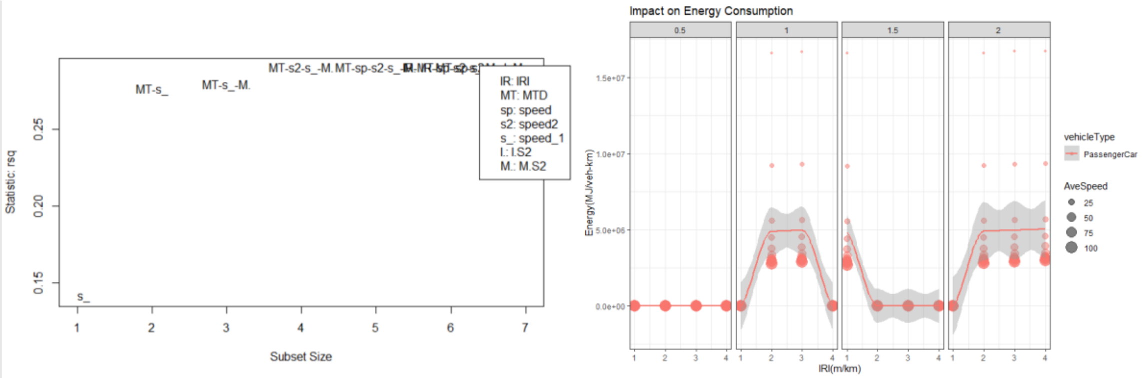


Figure 7.22 Effort to fit energy consumption rate data to the equation 7.22, the R-squared achieved was less than 0.3.

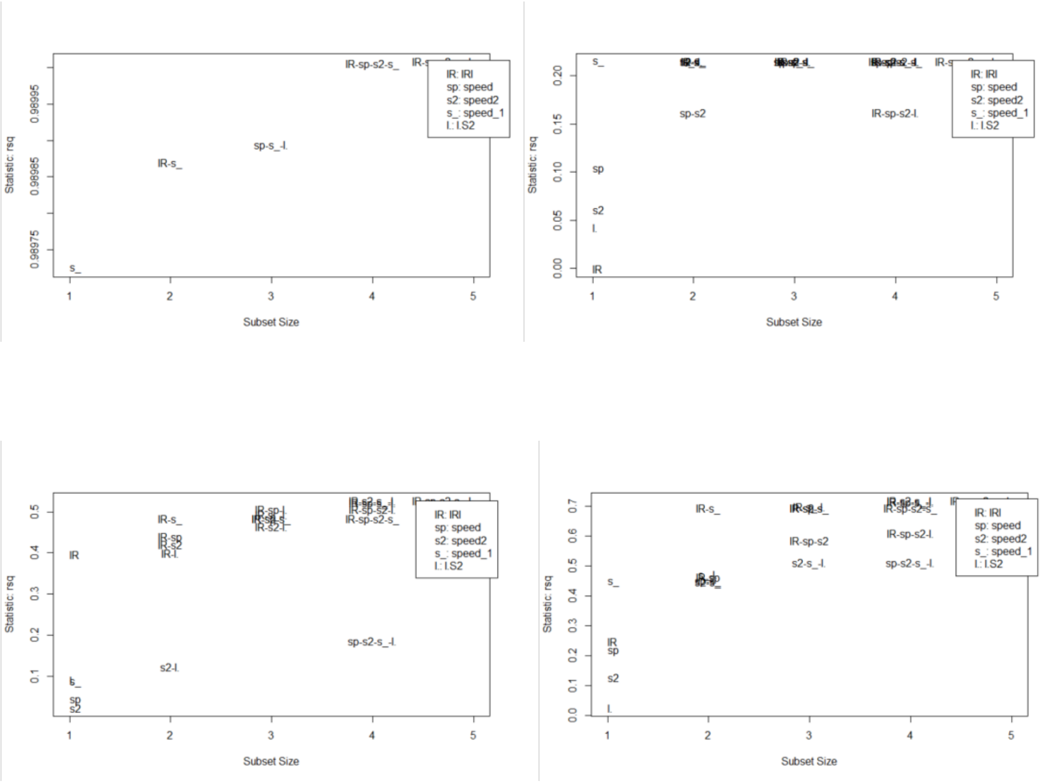


Figure 7.23 Visualization of fitted regression model equation 7.23 on the energy consumption data for urban freeway, four charts represent four levels of macrotexture (MTD = 0.5mm, 1mm, 1.5mm and 2mm) considered as different categories

Table 7.6 and Table 7.7 show the coefficients of the regression model in the form of equation 7.23.

Table 7.6 Proposed parameter values used in predicting energy consumption rate (J/veh-km) of seven vehicle types on urban freeway and their performance measure

Coefficients	Passenger Car	Passenger Trucks	Light Commercial Truck	Single Unit Short-haul Truck	Single Unit Long-haul Truck	Combination Short-haul Truck	Combination Long-haul Truck
a_0	4160	11950	12580	30890	24580	40800	42600
a_1	74.5	63.65	67.2	941.3	658.1	495.5	413.1
P_1	95110	250500	243900	1568000	1603000	703300	698000
b	-36.81	-106.5	-132	241.8	341.2	-124	-113.7
c_0	0.3373	0.9897	1.14	-1.103	-1.695	0.9919	0.8384
c_1	0.005779	0.00862	0.006316	-0.09562	-0.06404	0.01001	0.02329
Performance measure							
R^2	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Adjusted R^2	0.99	0.99	0.99	0.99	0.99	0.99	1
SE	656.7	1734	1764	8396	9136	4959	4841
F (5, 46)	937.8	938.8	892.4	1393	1202	882.1	911.5
P- value	2.2E-16	2.2E-16	2.2E-16	2.2E-16	2.2E-16	2.2E-16	2.2E-16

The model parameters were developed for four different classes of vehicles present in the MOVES software. As shown in the Table 7.6 and 7.7 the performance of the model using goodness-of-fit and error measures suggest the models are significant and can explain the relationships between the dependent variable and independent variables.

Table 7.7 Proposed parameter values used in predicting energy consumption rate (J/veh-km) seven vehicle types on urban arterial/collector/local road and their performance measure

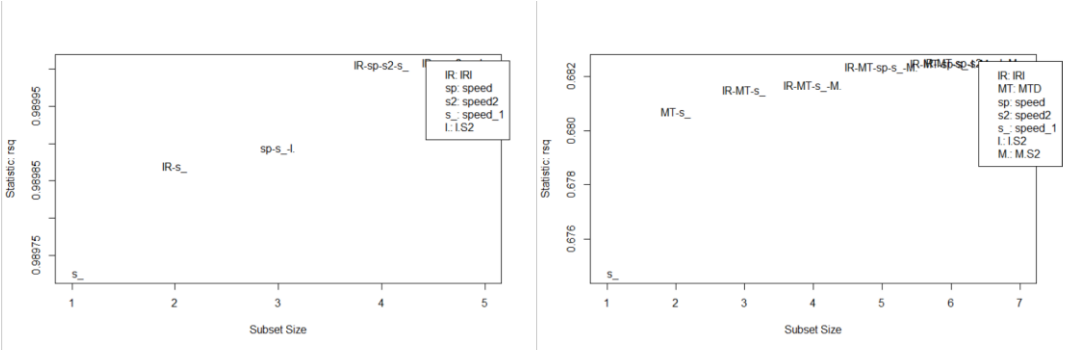
Coefficients	Passenger Car	Passenger Trucks	Light Commercial Truck	Single Unit Short-haul Truck	Single Unit Long-haul Truck	Combination Short-haul Truck	Combination Long-haul Truck

a_0	5511	15430	15360	35580	28250	41570	43750
a_1	100.5	76.92	84.54	1133	792.5	596.7	497.6
P_1	85340	226700	226700	1522000	1560000	708900	702400
b	-72.04	-195.7	-196.8	-73.67	17.25	-86	-72.88
c_0	0.5176	1.444	1.439	-0.5011	-1.018	0.08213	-0.1045
c_1	0.005607	0.009683	0.008239	-0.1151	-0.07712	0.01205	0.02802
Performance measure							
R^2	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Adjusted R^2	0.99	0.99	0.99	0.99	0.99	0.99	0.99
SE	566.6	1505	1504	7121	7876	4511	4444
F (5, 46)	1184	1183	1190	2045	1714	1118	1131
P- value	2.2E-16	2.2E-16	2.2E-16	2.2E-16	2.2E-16	2.2E-16	2.2E-16

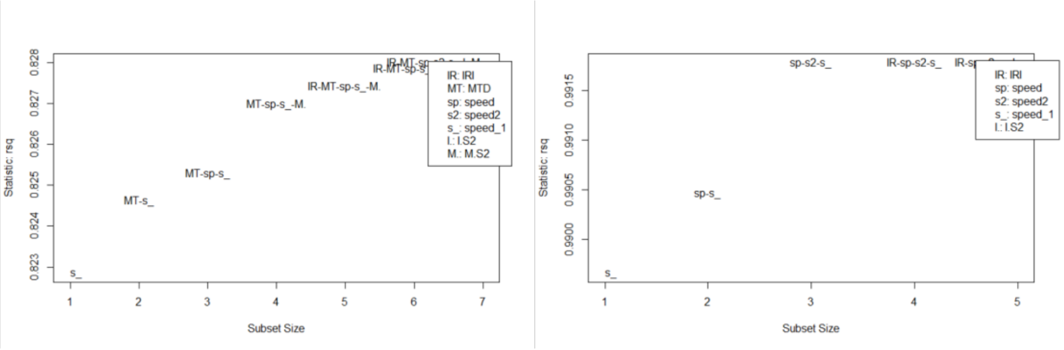
7.4.2.2 GHG Emissions

The emission rates data for the GHG emissions was analysed using the ordinary least squares to fit the data to the regression equations in Eq. 7.22 and Eq. 7.23. Figure 7.24 show the results of the effort given the subset of variables and the R-square for the model.

CO2 (A) (B)



N2O (A) (B)



CH4 (A) (B)

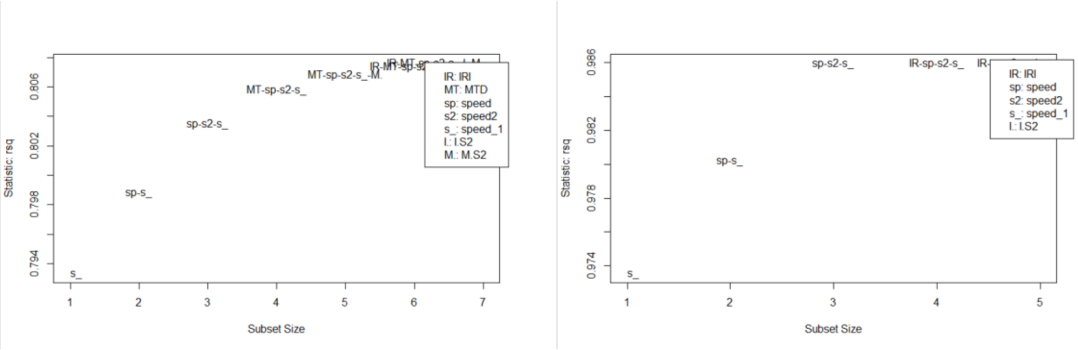


Figure 7.24 Effort to fit output data for GHG emission rates to the equation 7.22 and 7.23.

Regression models were also developed using same approach for all the pollutants and the table of all coefficients are available on Appendix D.

7.4.2.3 Environmental Damage Cost

As discussed in chapter 3, outcome-based indicators are vital to operationalizing environmental sustainability in pavement management. The EDC-IRI models are developed for each pollutant based on equation Eq. 23. Table 7.8 presents coefficients for the EDC-IRI models for the five atmospheric pollutants for two road groups of roadway functional class. The models are presented for easy application for large road network where the average speed on the road will be based on speed limits assigned to the roads. For example, most of the Ontario urban roads managed by MTO are with the speed limits of 80km/h and 100km/h. According to the model, at an average speed (80km/h) a unit increase in IRI (1m/km) can lead to \$0.03 and \$0.01 per kilometre of environmental damage for a passenger car and Truck emissions. This number may look small but when the number of vehicles and the vehicle-kilometre travelled are considered the large effect can easily be accounted. For example, section of highway 401 in Ontario of 8.7km, with AADT of 323650 and IRI of 1.68m/km, the excess emission from the vehicles will lead to \$57915 compared to a similar road with IRI of 1m/km.

Table 7.8 EDC-IRI equation for Urban roads in Ontario at speed limits for Freeway (100km/h) and Arterial Roads (80km/h)

Pollutants	**CO2**		**CO**		**NOx**		**SO2**		**PM2.5**	
Coefficients	a	b	a	b	a	b	a	b	a	b
Freeway										
Passenger Car	\$0.04	0.001	\$1.05	0.043	\$0.00	1.0E-05	\$0.00	7.5E-06	\$0.00	1.1E-05
Passenger Trucks	\$0.12	0.001	\$4.87	0.035	\$0.00	1.5E-05	\$0.00	8.5E-06	\$0.00	1.6E-05
Light Commercial Truck	\$0.11	0.001	\$4.58	0.032	\$0.00	1.3E-05	\$0.00	7.4E-06	\$0.00	1.2E-05
Single Unit Short-haul Truck	\$0.00	0.177	\$1.27	0.000	\$0.01	-3.8E-05	\$0.00	-3.8E-07	\$0.00	6.4E-03
Single Unit Long-haul Truck	\$0.51	0.000	\$1.23	0.000	\$0.01	-1.8E-05	\$0.00	4.5E-07	\$0.00	6.2E-03
Combination Short-haul Truck	\$0.40	0.005	\$0.84	0.002	\$0.01	1.2E-04	\$0.00	1.5E-05	\$0.01	2.1E-05
Combination Long-haul Truck	\$0.41	0.006	\$0.97	0.003	\$0.01	1.6E-04	\$0.00	1.7E-05	\$0.02	7.0E-05
Arterial, Collector and Local										
Passenger Car	\$0.04	0.001	\$0.45	0.036	\$0.00	1.0E-05	\$0.00	7.7E-06	\$0.00	1.1E-05
Passenger Trucks	\$0.10	0.001	\$3.40	0.036	\$0.00	1.4E-05	\$0.00	7.9E-06	\$0.00	1.5E-05
Light Commercial Truck	\$0.10	0.001	\$3.39	0.036	\$0.00	1.4E-05	\$0.00	7.8E-06	\$0.00	1.6E-05
Single Unit Short-haul Truck	\$0.40	0.004	\$1.28	0.003	\$0.01	7.6E-05	\$0.00	1.0E-05	\$0.02	6.4E-05

Single Unit Long-haul Truck	$ 0.38	0.003	$ 1.25	0.002	$ 0.01	5.5E-05	$ 0.00	7.6E-06	$ 0.02	5.1E-05
Combination Short-haul Truck	$ 0.39	0.006	$ 0.83	0.004	$ 0.01	1.5E-04	$ 0.00	1.7E-05	$ 0.01	9.9E-05
Combination Long-haul Truck	$ 0.41	0.006	$ 0.97	0.005	$ 0.01	1.7E-04	$ 0.00	1.7E-05	$ 0.02	1.2E-04

The speed has soon to have effect on the emission rate as discussed in section 7.4.2.1 and 7.4.2.2. It was also found that the EDC-IRI is speed dependant and can vary for individual EDC ($/km) of each pollutant or for total EDC ($/km) from all five pollutants. Figure 7.25 A and B show that the EDC ($/Km) of CO_2 emissions from a Passenger car and a Truck driving at lower speed have the highest values $0.2 and $1.62 respectively and reduces as the speed increase to $0.04 and $0.42 for passenger car and truck respectively. At lower speed, the change in EDC($/km) of CO_2 is less than 1 cent with change in IRI from 1m/km to 4m/km for both passenger car, a cent increase in EDC$ of CO_2 as the IRI increase is only evident at higher speed from 80km/h to 100km/h. Similarly, for trucks, the effect of IRI is evident at higher speed than lower speed. At lower speed, a cent increase in EDC$ of CO_2 is only found at 4m/km. The EDC ($/km) of CO emissions and shown in Figure 7.25 depicts an upward curve where the lowest EDC ($/km) is found at an average speed and IRI of 50km/h and 1m/km for passenger car, 90km/h and 1m/km for a Truck. Again, these variations will be well suited to estimate the impact of congestion on high-volume road, more so to inform expected work zone impacts when planning and programming road maintenance policy for road highly trafficked road networks. In Figure 7.26, SO_2 and NOx follow similar pattern as CO_2 but very low compared to CO_2. The highest values for EDC($/km) of SO_2 are $0.0013 and $0.0047 for passenger car and truck respectively, driving at low speed. For NOx, the highest estimates are at the low speed, $0.0004 and $0.06 for passenger car and truck respectively. The $PM_{2.5}$ EDC ($/km) follow similar upward curve pattern for passenger car, where the lowest value ($0.0004) is found at average speed 50km/h. For Truck $PM_{2.5}$ EDC ($/km) highest value $0.13 is found at 5km/h and 1m/km, while the lowest value $0.015 is found at 100km/h and 1m/km.

Figure 7.27 shows the total EDC($/km) from all five pollutants considered here. CO has the highest value so its influence on the total values can be seen in the similar upward cover in Figure 7.27A for passenger car; the highest total EDC($/km) value is $2.31 at low speed (5km/h) and high roughness (4m/km); the lowest values is $0.79 at medium speed (40km/h) and low roughness (1m/km).

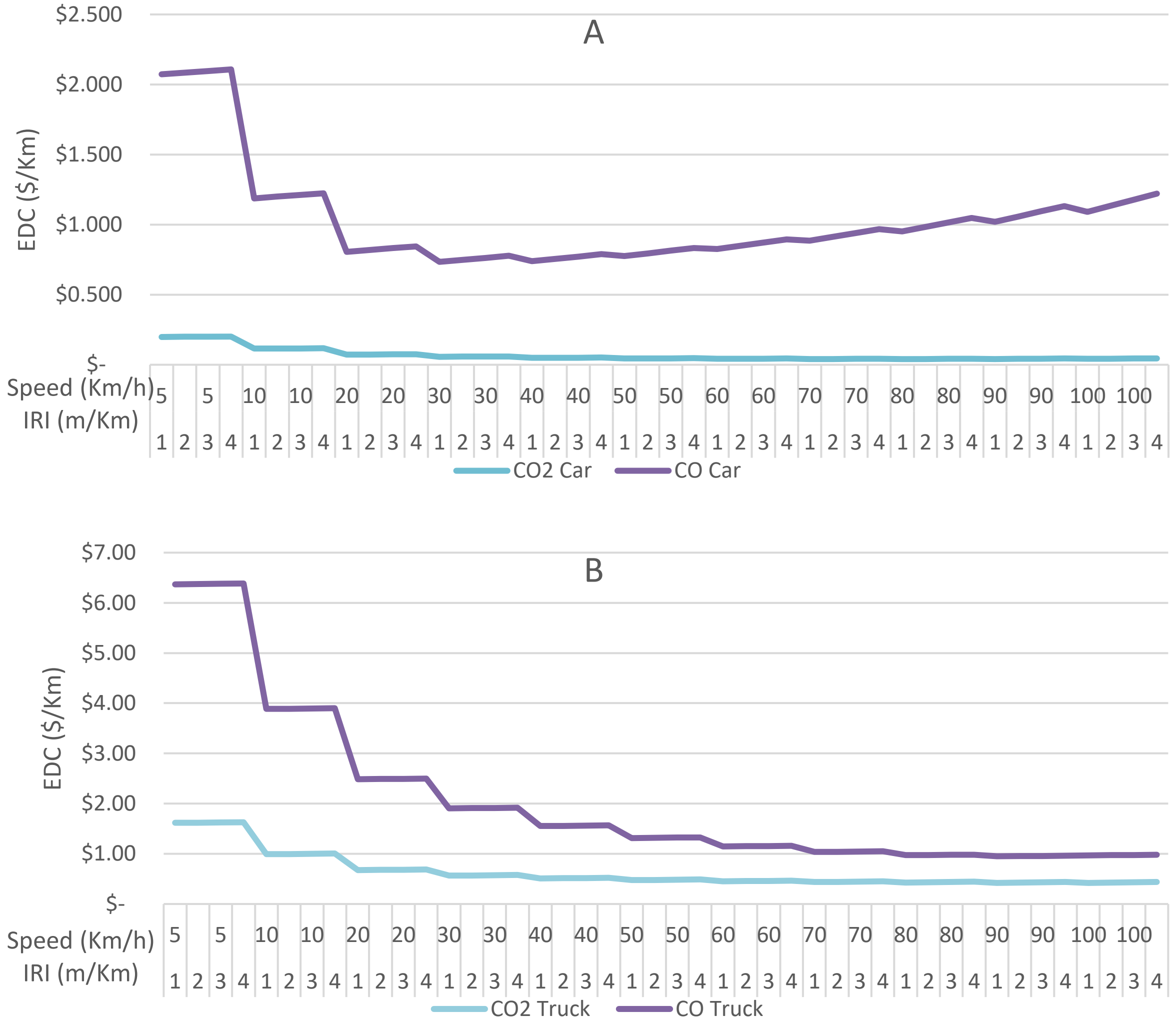


Figure 7.25 Environmental Damage Cost (EDC) of CO_2 and CO emissions per Km traveled by a Passenger car (A) and a Truck (B)

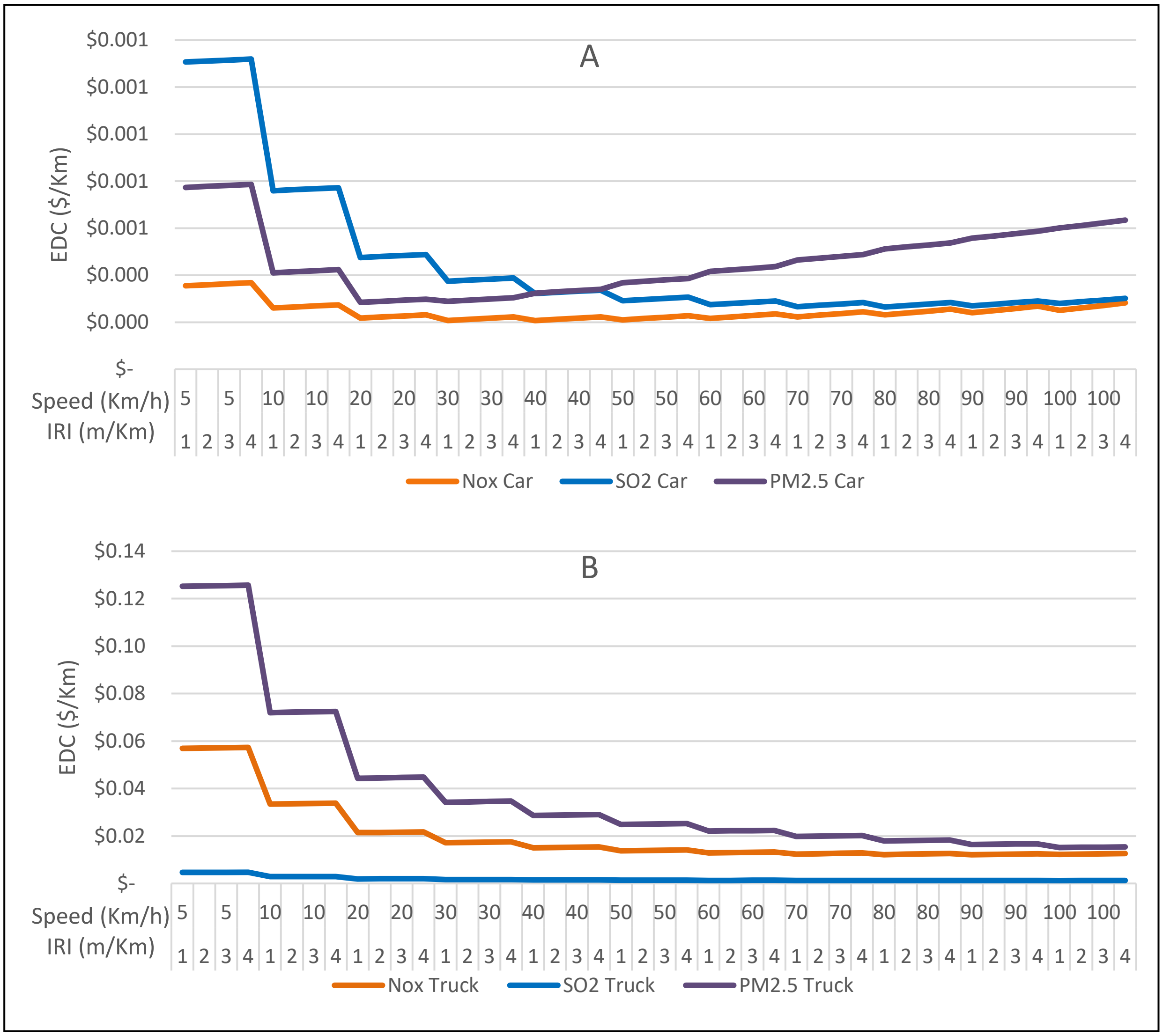


Figure 7.26 Environmental Damage Cost (EDC) of NOx, SO_2 and $PM_{2.5}$ emissions per Km traveled by a Passenger car (A) and a Truck (B)

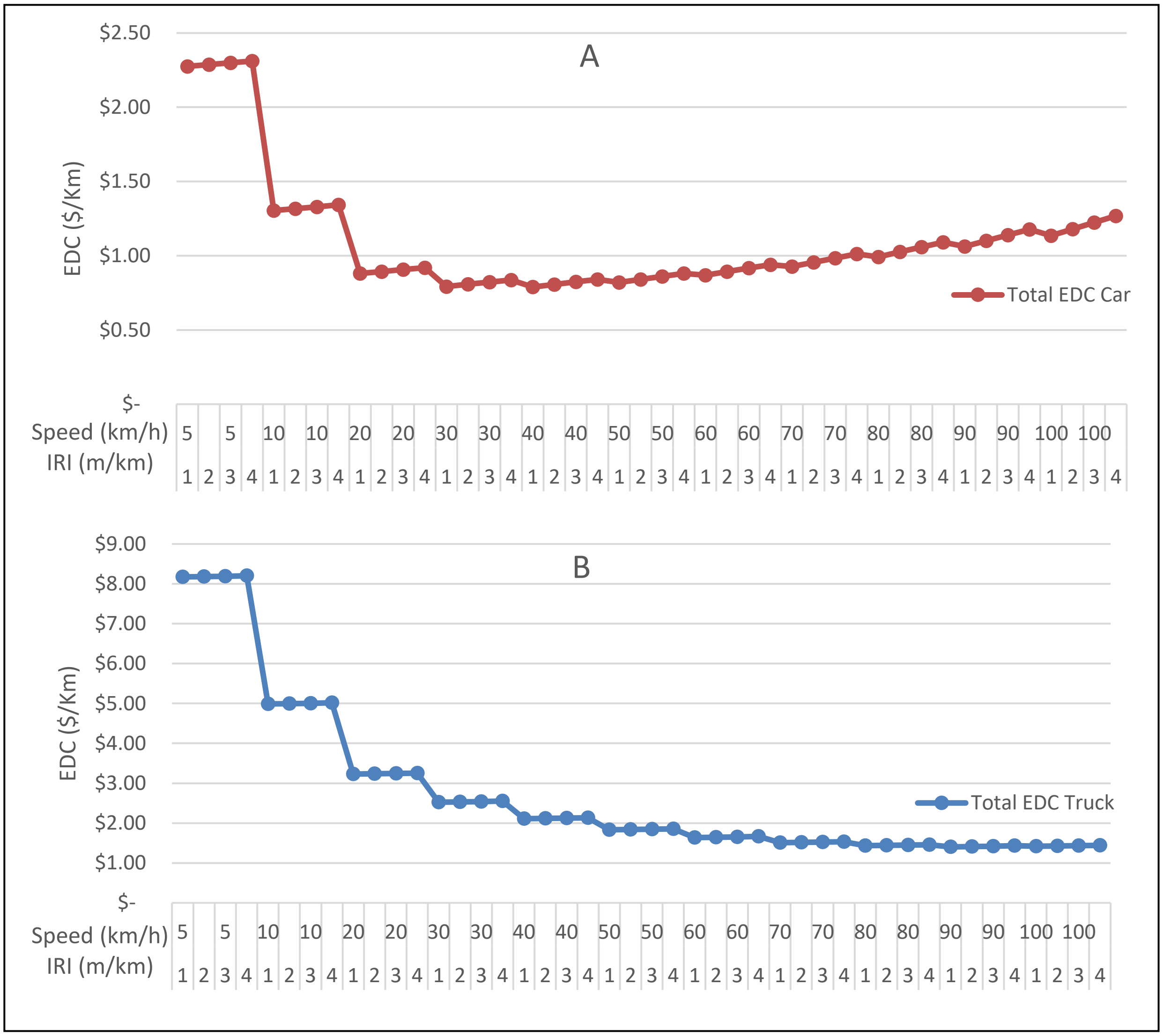


Figure 7.27Total Environmental Damage Cost (EDC) per Km traveled by a Passenger car (A) and a Truck (B)

It is clear from Figures 7.25 to 7.27 that EDC is vehicle speed dependant, so the IRI effect can be explained better by considering the effect of another independent variable vehicle speed. The best fit model for Car and Truck EDC for all read types were determined. Table 7.9 presents the regression output for an EDC-IRI-Speed model for a freeway, given by the equation

$EDC\ (\$/Km) = \beta_0 + \beta_1 \times IRI + \beta_2 \times V + \beta_3 \times V^2$ Eq. 7.26

Where;

EDC ($/Km) = environmental damage cost (2010CAD$) of five pollutants (CO2, CO, NOx, SO2 and PM2.5) per Km travel of a vehicle type on a certain road class with roughness range (IRI) at a certain speed (V)

IRI = road roughness in m/Km

V = speed of the travelling vehicle in Km/h

β_0 = model intercept coefficient

β_1, β_2, β_3 = model coefficients for IRI, Speed and Speed^2

The coefficients of the regression model for EDC($/km) of a passenger car and a truck are shown in Table 7.9. The multiple R-squared is the absolute value of the correlation coefficient of the dependent variable and independent variables, and R-squared reflects the proportion of variance in the dependent variable explained by the independent variables. As shown in Table 7.9, there is a strong correlation between dependant variable (EDC) and independent variables (V, IRI and V^2) given that multiple R-squared for the two models are 0.8 and 0.9. R-squared at 0.6 and 0.8 shows that over 60% and 80% of the variance in EDC is explained by IRI, V and V2 in the model for passenger car and trucks respectively. The residual error is only 35% and 13% of the Passenger car EDC ($/km) model and Truck EDC ($/km) model respectively.

Table 7.9 Regression Summary Output for Total EDC ($/km) for Passenger car and Truck driving on a Freeway

Regression Statistics for EDC ($/km) of a Passenger Car			
Multiple R	0.80		
R Square	0.64		
Adjusted R Square	0.62		
Standard Error	0.25		
Observations	44		
ANOVA			
	df	*SS*	*MS*
Regression	3	4.696	1.565
Residual	40	2.564	0.064
Total	43	7.260	

	Coefficients	*Standard Error*	*t Stat*
β_0	1.892	0.137	13.781
β_1	0.023	0.034	0.685
β_2	-0.042	0.005	-8.357
β_3	0.0004	4.692E-05	7.669
Regression Statistics for EDC ($/km) of a Truck			
Multiple R	0.93		
R Square	0.87		
Adjusted R Square	0.86		
Standard Error	0.77		
Observations	44		
ANOVA			
	df	*SS*	*MS*
Regression	3	152.856	50.952
Residual	40	23.473	0.5868
Total	43	176.329	
	Coefficients	*Standard Error*	*t Stat*
β_0	7.385	0.415	17.777
β_1	0.009	0.103	0.088
β_2	-0.178	0.015	-11.836
β_3	0.001	0.0001	8.745

7.4.3 Discussion of Validation and Comparison to Other Models

The coefficient of determination (R-squared (R^2)) obtained for all models are between 0.91 and 0.99, which indicate that the models are significant and useful, in that over 90% of the observed variation in the dependent variable can be explained by the model's inputs. P-values (<0.001) show that the independent variables (speed, speed^2, speed^{-1} and IRI) has some correlation with the dependent variable. Figures 7.25 and 26 shows the rate of energy change per unit change in IRI estimates in the current study versus other studies in literature. Figures 7.25 and 26 illustrate the estimates base on models Eq. 7.23 with coefficients in Table 7.5 and MOVES simulation output data for passenger car and a heavy-duty truck versus the models developed by Ziyadi et al. (2018) and Chatti and Zaabar

(2012) at different traveling speeds (70km/h, 72km/h(40mph) and 100km/h). The results indicate a stronger interaction between IRI and energy consumption at higher speeds.

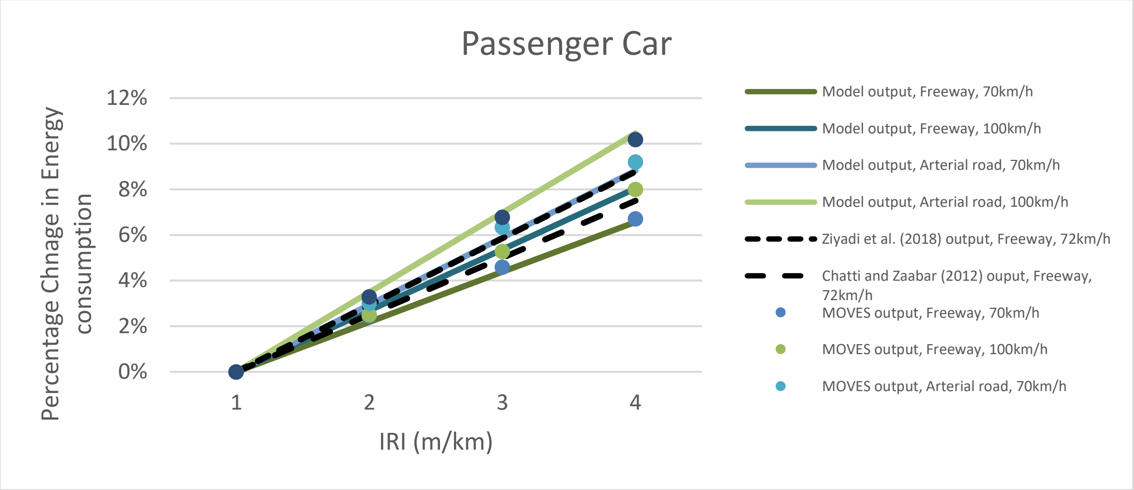


Figure 7.28 Percentage change in energy consumption rate with increasing IRI and speed for a Passenger car

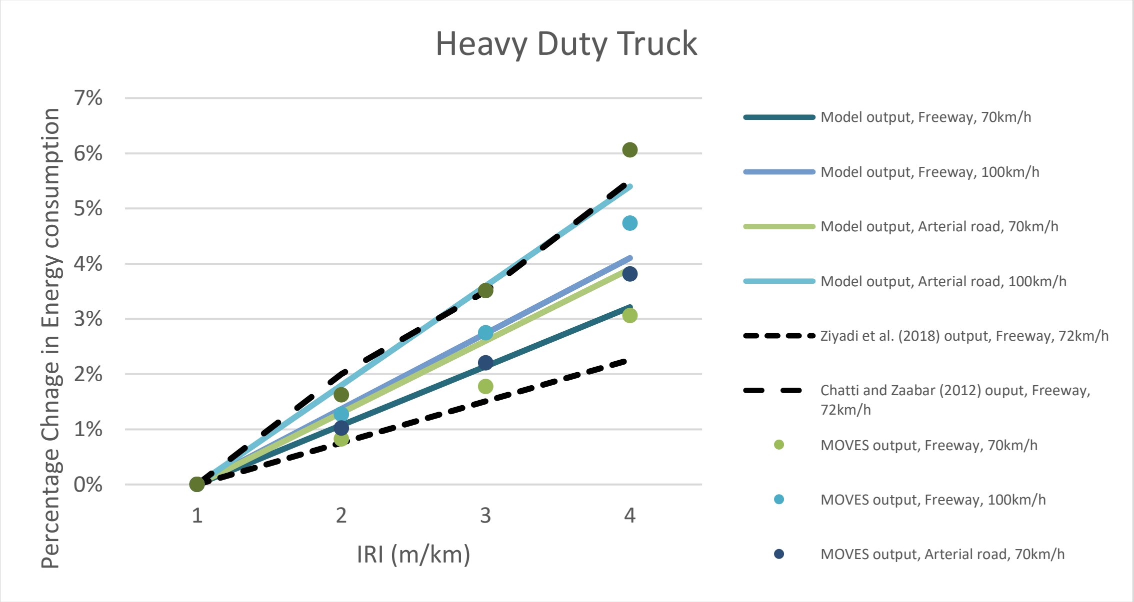


Figure 7.29 Percentage change in energy consumption rate with increasing IRI and speed for a Heavy-duty Truck

7.5 Conclusion

This chapter introduced an analytical model developed to evaluate the pavement surface condition effect on vehicle energy consumption and related emissions for seven different classes of vehicles on four classes of roadways reflecting regional road network and regional on-road transportation. The models are intended for LCA applications, particularly use-stage of the pavement life cycle, where energy consumption and air pollution associated with the vehicles using the roadways can contribute significantly. The model represents vehicle's energy consumption and emission of harmful pollutants considering on-road conditions.

The model is based on regional data, and the analytical vehicle specific power. It estimates energy consumption as well as the emission of twelve pollutants:

To define the contribution of the pavement-vehicle interaction on the environmental system, in terms of rolling resistance, the understand the effects of road surface characteristics on rolling resistance was estimating the coefficient A and C in MOVES (relating rolling resistance to pavement surface properties) and the effect of rolling resistance on the vehicle power demand overcome that resistant force was estimated by running MOVES simulation for four levels of IRI and four levels of MTD (relating traffic energy demand/fuel consumption to the rolling resistance due to road roughness and texture).

A PVI model proposed offers advantages for easy integration and implementation into pavement LCA tools to evaluate the use-stage energy and environmental footprints related to pavement surface conditions. This model address on gap for integration of LCAs into network-level pavement management, the model can be used to inform maintenance management strategies of a road network that maximises the reduction of road traffic emissions and excess fuel consumptions. Subsequently, the model can be used to assist decision makers for developing sustainable pavement-management system. According to the simulation data analysis, passenger vehicles on freeways are highly sensitive to roughness and speed. For a passenger car, one unit change of IRI (1m/km) results in an average increase in fuel consumption of 1% and 2% at low speeds and high speeds respectively. Trucks are more sensitive to IRI change; and one unit change in IRI on average results in 2% and 3% increase, respectively, in fuel consumption of Heavy -duty truck at low speeds. The results are in line with reported values from the literature, percent change in fuel consumption for one unit change of IRI under various conditions is 0.1% to 6%. The range found in the current study is between 0.5% and 3% according to models developed here, indicating consistency of the model.

Due to the limitation to fit the data into an all-encompassing representation of MTD and IRI, a large number of models have been developed, which also maybe become computationally demanding, so future studies can investigate how these models can be streamlined. Also, future studies can investigate impact of other factors not included. The results from the limited number of factors investigated here, suggest that there are model significant variables the PVI relation that can not be explained in current model.

The proposed output-based environmental damage cost (EDC) models provide relationship covering environmental impacts of road surface and speed and the associated with air pollutants of five atmospheric pollutants Carbon dioxide (CO2), Carbon monoxide (CO), Nitrogen oxides (NOx), Sulphur dioxide (SO2) and Particulate matter 2.5um (PM2.5) emissions from various vehicle types. According to the model, at an average speed (80km/h) a unit increase in IRI (1m/km) can lead to \$0.03 and \$0.01 per kilometre of environmental damage for a passenger car and Truck emissions. This number may look small but when the number of vehicles and the vehicle-kilometre travelled are considered the large effect can easily be accounted. For example, section of highway 400 in Ontario of 8.7km, with AADT of 323650 and IRI of 1.68m/km, the excess emission from the vehicles will lead to \$57915 compared to a similar road with IRI of 1m/km.

Chapter 8

Sustainable Pavement Management Evaluation

8.1 Introduction

Environmental assessment alone does not encompass the more modern, broader vision of sustainability as fairness, enhancing well-being across generations (Clark and Harley 2020). Sustainable pavement management, more broadly, would involve capturing the impacts on technical, economic, and social factors and their relationships and relating factors to the goals, influence, and interactions of pavement management stakeholders (Jeon and Amekudzi, 2005; Oltean-Dumbrava, Watts, and Miah, 2014). This chapter proposes an approach to incorporate environmental indicators into pavement management while considering the interactions with other factors in a sustainable pavement management framework. The literature gap identified in section 2.4.2, with regards integrating LCA into pavement management, is also addressed by providing information regarding how to apply LCA principles and thinking in light of the availability of input data (metrics identified in Chapter 3 and models developed in Chapter 7) which can reflect regional difference in pavement and road network operation. Project level management is considered in section 8.2 while network-level management is in section 8.3.

8.2 Sustainability Evaluation at Project-Level Management

This study proposes a framework (Figure 8.1) for sustainability evaluation in order to incorporate sustainability considerations in to project-level pavement management decision making.

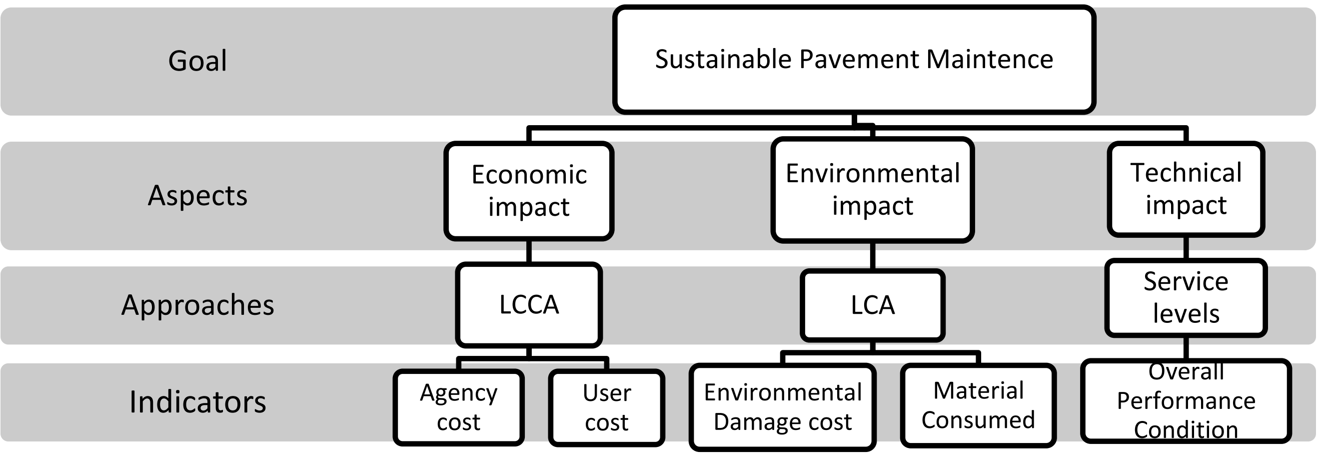


Figure 8.1 Proposed framework for incorporating sustainability in Project-level pavement management

A case study of a project-level pavement management plan for York Region's Highway 48 road based on test section data from the Federal Highway Administration (FHWA) Long Term Pavement Performance (LTPP) InfoPave database is investigated with the proposed framework. The information for the Highway 48 test segment under that LTPP project is show in Table 8.1.

Table 8.1 Data from LTPP for test segment on Highway 48 (source (FHWA 1992)**)**

LTPP SHRP_ID	87 – AA01, AA02, AA03, AA61, AA62, BA01, BA02, BA61, BA62
LTPP experiment group	Warm Mix Asphalt Overlay of Asphalt Pavement
Pavement Type	Flexible
Functional Class	Urban Minor Arterial
Climate zone	Wet, Freeze
Location	York region, Ontario
Average IRI (2015)	1.05 m/km

One section of 1km land road is selected for the project level sustainability evaluation. The full segment is considered for network analysis. The goal of the project-level study is to determine sustainability impacts resulting from different management plans and the timing of treatment application. The conventional pavement preservation plan for arterial roads in Ontario is explored and compared with a theoretical maintenance plan which includes only green maintenance strategies such as Cold-In-Place Recycling using Bitumen Emulsion (CIR) and Full Depth Reclamation (FDR). In order to compare these maintenance programs under a sustainable approach, three aspects are considered in the evaluation: environmental, technical and economic; and four sub-criteria. These criteria and their sub-criteria are assessed in the decision-making process using a multi-criteria decision method (MCDM): Analytic Hierarchy Process (AHP) to show how to integrate many sustainability aspects in pavement management and how the weights applied to each criteria can change the outcome of the decisions.

8.2.1 Application of Proposed framework

Project-level analysis of a sample case study of Highway 48 pavement segment in Ontario is considered for the application of the proposed framework in Figure 8.1. The general information and the performance data measured at different points of the road segment are presented in Table 8.2, while the geographical map showing the road segment and point of measurements is available in Appendix E. Two scenarios of maintenance plans were investigated, as shown in table 8.2:

- Scenario 1 is based on the conventional maintenance plan for arterial roadways
- Scenario 2 is a maintenance plan based on application of environmentally friendly maintenance strategies. In this theoretical maintenance plan, green maintenance strategies such as Cold-In-Place Recycling using Bitumen Emulsion (CIR) and Full Depth Reclamation (FDR) replace the traditional strategies: HMA M&O and HMA Mill and 2-lift Overlay.

Table 8.2 Two Scenarios of Preservation and Maintenance plans for the Road network

	Scenario 1 (Conventional preservation plan)	**Scenario 2 (Green Plan)**
Year	**Treatment**	
10	5% Crack seal + Mill 40mm and Patch 40mm	5% Crack seal + Mill 40mm and Patch 40mm
15	10% Spot Repair + Mill 40mm and Patch 40mm	10% Spot Repair + Mill 40mm and Patch 40mm
20	Mill (40mm) & Overlay (40mm)	CIR (50mm) + thin Overlay 40mm
30	5% Thin overlay (40mm)	
33		FDR (90mm) + overlay 40mm
35	Two lift M &O (binder 19mm and surface 12.5 FCI)	
40	50% crack seal	50% Crack seal
43	5% thin overlay (40mm)	
45		Micro surfacing
48	Two lift M &O (binder 19mm and surface 12.5 FCI)	

The typical time period considered for pavement design for a highway road project in Ontario is 50 years. The proposed framework to select the best road network maintenance program for the highway will follow this time period. In order to compare these maintenance programs under a sustainable approach, three aspects are considered in the evaluation: environmental, technical and economic; and five sub-criteria. These criteria and their sub-criteria are assessed in the decision-making process by the use of a multi-criteria decision method (MCDM): Analytic Hierarchy Process (AHP). The aim of this case study is to better understand how to integrate sustainability aspects in pavement management. The following sections provide details of data collected and used in the sustainability evaluation of the selected maintenance plans. The main assumptions made in the analysis and limitations are highlighted.

8.2.1.1 Data and Source of Data

The main source of data is the FHWA LTPP InfoPave, which is FHWA's LTPP database for all pavement LTPP data collected under the program for material structure, climate data, traffic loading, and performance data of pavement sections across the USA and Canada since 1989 (FHWA 1992). The selected test sections considered in this project are located on the Highway 48. The road section was resurfaced in 2016 and has been in the LTPP program since 2014. The details of the road sections, pavement structure, material type, location on HWY 48, the performance details such as IRI and fatigue cracking measure in 2016 are shown in Figure 8.2. The study by ARA (ARA 2011) provided the conventional pavement preservation plan for an arterial road (see Appendix D) which is adopted in this the current study as the base case maintenance program that can be employed by MTO on the Highway 48 road section. Data for unit costs, material use and emissions of maintenance strategies were collected from available literature and reports including MTO quantification of sustainability report by (Chan & Tighe, 2010) and research projects done at the Center for Pavement Technology.

8.2.1.2 Methods and Assumptions

8.2.1.2.1 Economic, Environmental and Technical Evaluations of Maintenance strategies and plans

Technical Performance Evaluation:

The overall performance is measured by Riding Comfort Index (RCI) and IRI

Given the purpose of this analysis, some considerations made in this analysis include:

- The deterioration rate for the pavement was assumed to be 0.05m/km of the IRI per year. Similar assumptions have been made in a previous study (J. M. Bryce, Flintsch, and Hall 2014) of network –level pavement management sustainability assessment. Based on this, the assumed deterioration rates for IRI and RCI were predicted for 50 years, as shown in Figure 8.2 for IRI.

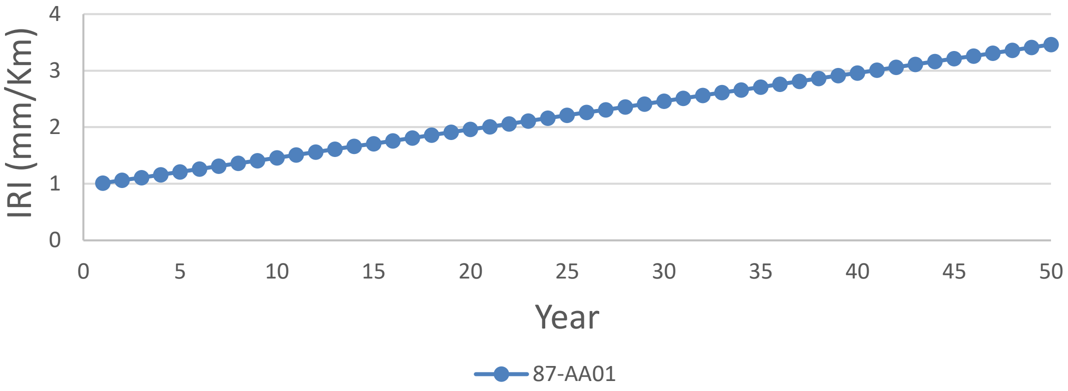


Figure 8.2 Predicted deterioration of IRI for 50 years without any preservation or maintenance treatments

- Assumptions made concerning impact of maintenance strategies on the overall condition were determined by treatment effects on RCI. The expected time to maintenance and the impact of maintenance treatment is given by the RCI threshold from the MTO manual (MTO 2013) and the expected changes on RCI from the TAC guide (TAC, 2013). The RCI values were estimated based on the equation obtained from (Jannat 2017) as shown below:

$$RCI = \text{Max}\,(0, \text{Min}\,(10, 8.5 - 3.02 \times \ln(IRI))) \qquad \textbf{Eq. 8.1}$$

Economic Performance Evaluation:

For agency cost evaluation, unit costs for the selected treatments were collected from available literature on material costs in Ontario (Alkins et al. 2008; Chan 2010; Chan et al. 2010) and the total cost was calculated for the treatment applied in Scenario 1 and Scenario 2. To analyze and compare the two scenarios, a discount rate of 5% was used to bring the cost to net present value. Below shows the formula used to calculate the agency cost for the treatment plan over 50 years.

$$\boldsymbol{NPV_{Total}} = \left[\sum\left(\boldsymbol{C} \times \left(\frac{\mathbf{1}}{\mathbf{1}+\boldsymbol{i}}\right)^{\boldsymbol{n}}\right)\right] \qquad \textbf{Eq. 8.2}$$

Where: C = cost of treatment ($); i = discount rate (5%); n = nth year of implementation.

Environmental Performance Evaluation

For environmental evaluation, life cycle emissions and material use of each type of treatment was calculated and measured as environmental damage cost and total material use. As each of the pollutants considered have different effects on human health and the environment, their emissions cannot be directly compared with each other. So, the social cost of emissions is adapted for valuation of emission to assign a dollar value to the resulting damages from emissions. The Environmental Cost of Atmospheric Releases estimates for Ontario developed by Nasir (2018) for the valuation of the effects of several greenhouse gases and air pollutants was used, with marginal social costs per Mg of emission as reference in chapter 6 of this thesis

8.2.1.2.2 AHP Decision Making Analysis

AHP offers the advantage of incorporating subjective judgments in an easy-to-understand procedure when the number of alternatives are limited. It allows for the consideration of both qualitative and quantitative criteria in the evaluation. The basic steps of AHP are as follows:

1. Identify the decision to be made, called the “goal.” Structure the goal, criteria, and alternatives into a hierarchy. The criteria may be contained in more than one level to provide additional structure to complex problems.

2. Perform pairwise comparisons for the alternatives. Pairwise comparisons are an evaluation of the importance or preference of a pair of alternatives. Comparisons are made for all possible pairs of alternatives with respect to each criterion. The comparison is done with each pair of alternatives given a value according to Table 8.3. These values are placed in a pairwise comparison matrix (PCM).

Table 8.3. The value system (A) for pairwise comparison of alternatives on each sub-criteria (B)

(A) AHP Value Scale

Value	Interpretation
0.2	Strong preference/importance B over A
0.33	Moderate preference/importance B over A
1	Equal preference/importance A and B
3	Equal preference/importance A and B

5	Strong preference/importance A over B

(B) AHP Criterion Scale

	0.2	0.333	1	3	5
Agency Cost ($)	X>300K	300K <=X<=0	Equal	0 <=X<= -300K	X< -300K
Technical Aspects (RCI/IRI)	X> -1	-1 <=X<=0	Equal	0 <=X<= 1	X> 1
Virgin Material Consumed	X>600T	600T <=X<=0	Equal	0 <=X<= -600T	X< -600T
Environmental impact ($)	X>300K	300K <=X<=0	Equal	0 <=X<= -300K	X< -300K

3. Calculate priority weights for the alternatives by normalizing the elements of the PCM and averaging the row entries.

4. Perform pairwise comparisons for the criteria. Similar to the process in Step 2 of comparing the alternatives, all pairs of criteria are now compared with the use of the AHP value scale. Similar to Step 3, a PCM is determined, and priority weights are calculated for each of the criteria. Alternative priority weights are multiplied by the corresponding criteria priority weights and summed to give an overall alternative ranking.

8.2.1.2.3 Limitations

A limited number of indicators were considered to measure performance in the three aspects of sustainability highlighted in proposed framework. Given the limitations due to the methodological approaches and tools adopted, data and modeling functions were lacking to characterize some impacts.

In the current work, the user cost was not included in the economic impact analysis due to limited information on the length of the road sections. Limitations of the project analysis were mainly due to availability of data. Thus, traffic delay was not considered, and the user cost and the emission caused by traffic delays during maintenance operations were also not included in the accounting of sustainability impacts of maintenance programs. Other challenges include the time constraints and limited work zone data to include traffic delay impacts such as those considered by Min et al. (2021) and adopted in a case study on other rehabilitation design for concrete roads (see section 5.2.2.3 of this thesis document). This analysis included a sensitivity analysis in the AHP analysis to capture the effects of the level of importance weights given to the three aspects of sustainable pavement management considered in this study.

8.2.2 Results and Discussion

The case study results for sustainability evaluation in project level management presented here to show results in response to the individual aspects of sustainability first, then the combine evaluations through ranking maintenance plans that should inform decision making in sustainable pavement management.

8.2.2.1 Technical Impact

The main approach used for technical aspect is the service level which is measured by the overall pavement condition of the road network. Technical impacts of maintenance plans are shown in the Figure 8.3 and Figure 8.4, indicating the riding comfort experienced by the road network usages over the 50-year time period for Scenario 1 and Scenario 2.

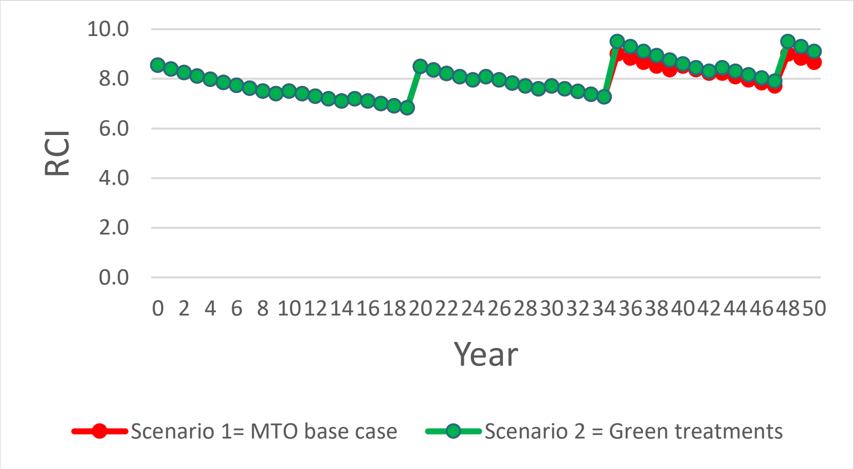


Figure 8.3 Technical impacts of the two scenarios of maintenance plans for HWY 48, service levels measure based on RCI over a 50-year time period

Figure 8.3 displays the results of technical performance analysis of the road network in terms of RCI, while Figure 8.4shows the impacts on IRI growth. Overall, the effect of the maintenance strategies and plans show a similar pattern in the two scenarios. Scenario 2 results to a better performance overall that Scenario 1. The main reason is that the increase in RCI by the FDR maintenance is higher than the traditional alternative of HMA mill and 2-lift overlay in Year 35 which impacts the overall performance of the pavement network. The FDR returns the pavement RCI to 9.5 which reduces the IRI to 0.72mm/Km but the HMA M&O returns the pavement condition RCI to 9 equivalent to IRI value of 0.85 mm/Km.

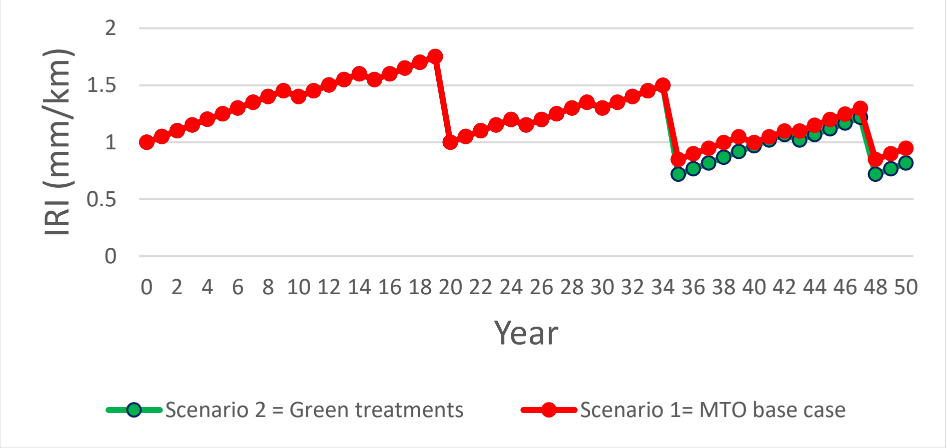


Figure 8.4. Technical impacts of the two scenarios of maintenance plans for HWY 48, service levels measure based on IRI over a 50-year time period

8.2.2.2 Environmental Impact

The environmental impacts of the maintenance strategies investigated in the two scenarios are measured by the amount of virgin material consumed and compared as shown in Figure 8.5. The total material consumed in the two scenarios are shown in Table 8.4. Comparing Scenario 2 to Scenario 1, almost 50% of material savings is achieved. Adopting a maintenance program based on green solutions will save over 25% of the environmental damage cost from the traditional counterpart. Almost 50% of the material consumption can be reduced considering that the green technologies adopted in the greener maintenance plan are using less virgin material. This is essential when we considering the increasing issue with material availability and high cost of material hauling.

Table 8.4 The total material consumed in the two maintenance scenarios 1 and 2

	Scenario 1 Maintenance Plan	Scenario 2 Maintenance Plan
Total Material consumption	5902.4 tonnes	3992.8 tonnes

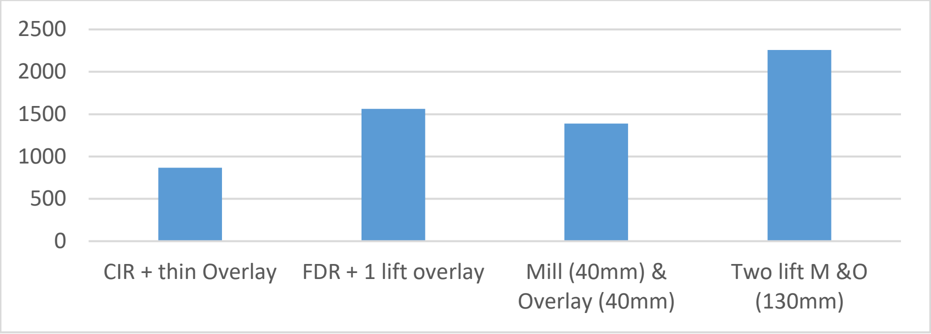


Figure 8.5. Material consumed in application of maintenance strategies, CIR and FDR are used in Scenario 2, while M&O techniques are used for Scenario 1

Environmental impacts are based on social costs of emission estimates and material savings from application of treatments due to the limitations highlighted in section 8.2.1.2.3. Environmental impacts use and operation of the road network such as emissions due pavement –vehicle interaction and maintenance traffic delay were excluded in the results presented. Given that environmental damages from material production and construction activities are the current global focus for defining policies towards sustainability development goals, the results are adequate for a conservative sustainability management decision. Figure 8.6 shows the environmental damage cost estimated for the maintenance strategies and the total environmental damage cost due to emissions for each maintenance plan is shown in Table 8.5.

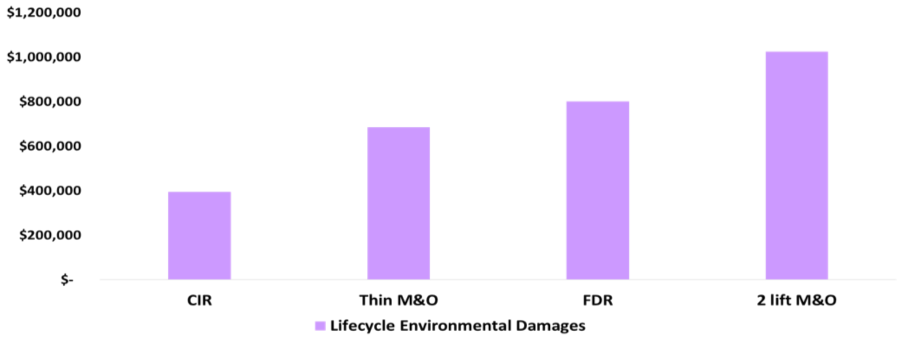


Figure 8.6. Environmental impacts of rehabilitation measured by cost of environmental damage

Table 8.5. The total environmental damage cost for the two scenarios of maintenance plans

	Scenario 1 Maintenance Plan	Scenario 2 Maintenance Plan
Environmental damage cost	$2,750,000	$2,000,000

8.2.2.3 Economic Impacts

Based on the treatments applied during the selected years, the total agency cost for the maintenance plans in net present value are summarized in Table 8.6. These values are a result of adding all the net present values of the treatments at the time of implementation respectively. Although this analysis shows that Scenario 2, the "Green" maintenance plan, is $38,153 more expensive than Scenario 1, this is only an increase of 7% than the standard MTO plan. See Appendix D for a more thorough calculation.

Table 8.6. The total environmental damage cost for the two scenarios of maintenance plans

	Scenario 1 Maintenance Plan	**Scenario 2 Maintenance Plan**
Total Treatment cost	$574,506	$612,659

8.2.2.4 Ranking Maintenance Plans

From the AHP analysis, we summarized our findings for agency cost, technical aspects, material consumed and environmental damage cost in Table 8.7 and use the AHP methodology to create the AHP criterion scale as explained in Table 8.3.

Table 8.7 Summary Table

	CIR + Thin Overlay (A)	FDR + One Surface Life (B)	Mill and Overlay 40mm (C)	Two lifts (Binder & Surface), Mill & Overlay (D)
Agency Cost ($)	900,000	850,000	350,000	1,450,000
Technical Aspects (RCI)	8.5	9.5	8.5	9
Virgin Material Consumed (Tonne)	868	1564	1389	2257
Environmental damage cost ($)	400,000	800,000	650,000	1,050,000

From AHP criterion scale and pair wise comparison of each alternative, we developed AHP pairwise comparison table (see Appendix E). The priority ranking was assessed based on set preference of each alternative and level of importance of the criteria.

The priority or rank of alternative is very sensitive to the importance weights allocated to the criteria and sub-criteria. Figure 8.7 shows the effect of the importance weights on the ranking of alternatives, in each option as labeled in figure 8, 40% of the importance weight was allocated to one or two of the criteria considered. The sensitivity analysis is further discussed in section 8.2.2.5.

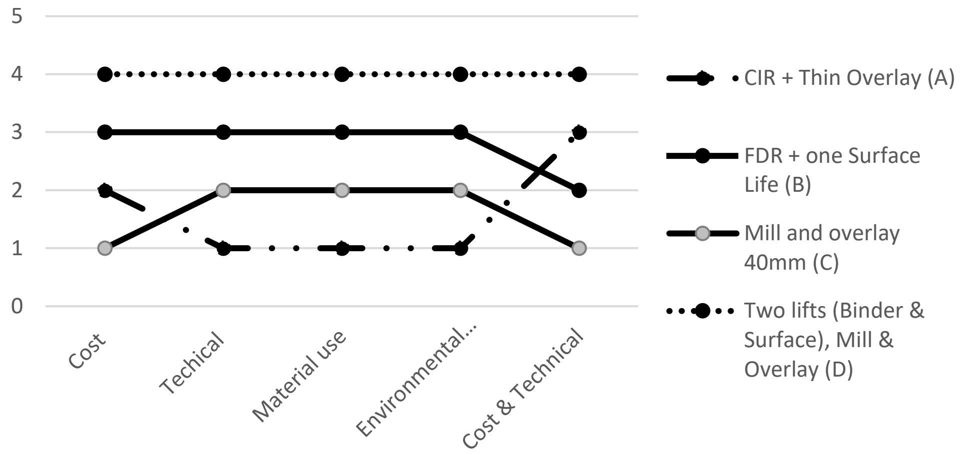


Figure 8.7. Ranking of maintenance treatment considering five options of allocating over one-third of the importance weights to one or two sub-criteria

A simple AHP criterion scale and pairwise comparison table can easily be adopted by an agency to compare alternatives. The results in Figure 8.7 can provide guidance to agencies regarding the effect of the importance allocated to a certain criterion or set of criteria on the results for making sustainable decisions regarding pavement management. The priority weights for the alternatives can be calculated as explained in the step 3 in section 8.2.1.2.2. This method can help the agencies to find out the priority for different alternatives to reflect agency policy and overall goal.

8.2.2.5 Sensitivity Analysis

As per the calculated data we performed a sensitivity analysis by assuming different preferences/policy for any individual agency or to see the difference in the outcome if there is a change in the need of the decision maker/agency.

Option 1- If the agency cost has more importance than other factors then Mill and Overlay (40mm) become the first choice for the agency as per the AHP method.

Indicators	Importance factor	Treatment Options	Results	Priorities
Agency Cost ($)	40%	CIR + Thin Overlay (A)	0.291	2
Technical Aspects (RCI/IRI)	20%	FDR + one Surface Life (B)	0.245	3
Virgin Material Consumed	20%	Mill and Overlay 40mm (C)	0.357	1
Environmental damage ($)	20%	Two lifts (Binder & Surface), Mill & Overlay (D)	0.107	4

Option 2- If the technical aspects has more importance than other factors then CIR + Thin overlay become the first choice for the agency as per the AHP method.

Indicators	Importance factor	Treatment Options	Results	Priorities
Agency Cost ($)	20%	CIR + Thin Overlay (A)	0.286	1
Technical Aspects (RCI/IRI)	40%	FDR + one Surface Life (B)	0.275	3
Virgin Material Consumed	20%	Mill and overlay 40mm (C)	0.285	2
Environmental damage ($)	20%	Two lifts (Binder & Surface), Mill & Overlay (D)	0.154	4

Option 3- If the consumption of virgin has more importance than other factors then CIR + Thin overlay become the first choice for the agency as per the AHP method.

Indicators	Importance factor	Treatment Options	Results	Priorities
Agency Cost ($)	20%	CIR + Thin Overlay (A)	0.350	1
Technical Aspects (RCI/IRI)	20%	FDR + one Surface Life (B)	0.232	3
Virgin Material Consumed	40%	Mill and overlay 40mm (C)	0.307	2
Environmental damage ($)	20%	Two lifts (Binder & Surface), Mill & Overlay (D)	0.111	4

Option 4- If the environmental impact has more importance than other factors then CIR + Thin overlay become the first choice for the agency as per the AHP method.

Indicators	Importance factor	Treatment Options	Results	Priorities
Agency Cost ($)	20%	CIR + Thin Overlay (A)	0.352	1
Technical Aspects (RCI/IRI)	20%	FDR + one Surface Life (B)	0.227	3
Virgin Material Consumed	20%	Mill and overlay 40mm (C)	0.309	2
Environmental damage ($)	40%	Two lifts (Binder & Surface), Mill & Overlay (D)	0.112	4

Option 5- If the cost and the technical aspects has more importance than other factors then Mill & overlay become the first choice for the agency as per the AHP method.

Indicators	Importance factor	Treatment Options	Results	Priorities
Agency Cost ($)	40%	CIR + Thin Overlay (A)	0.221	3
Technical Aspects (RCI/IRI)	40%	FDR + one Surface Life (B)	0.292	2
Virgin Material Consumed	10%	Mill and overlay 40mm (C)	0.337	1
Environmental damage ($)	10%	Two lifts (Binder & Surface), Mill & Overlay (D)	0.150	4

8.3 Network-level Sustainability Evaluation

As discussed in Chapter 2 of this thesis, LCA can be integrated into PMS, either directly through: integration of inventory data, impact models and assessment reporting; or indirectly through inclusion of LCA results into programming platform in PMS. The goal of this section is to show how available analysis input data that can reflect regional practice can be used to make better decisions to meet sustainability goals for transportation. Additionally, this section aims to recommend how this research can be implemented into broad public infrastructure management practice.

First the case study of HWY 48 road network is evaluated to show how the model developed in chapter 7 of this thesis can be adopted to inform environmental management of pavement surface condition and used as a strategy to improve environmental sustainability of the transportation sector. Previous studies have proposed carbon management of road condition as better short-term strategy for road network maintenance planning and programming. Environmental savings from pavement-roughness management are evaluated using a segment of HWY 48 in York Region, Ontario.

The second network-level case study, the regression models for emissions and environmental damage cost (EDC) are adopted to provide a convenient tool to upscale pavement section emissions to the network scale environmental impact. To this end, the components of the models are integrated with the Ontario Road network dataset obtained from the public databases provided by MTO, Government of Ontario, and Government of Canada (City of Toronto 2013; Government of Canada 2021; Government of Ontario 2020; MTO 2004, 2016) are used to perform a network-level analysis. A geographical reference tool QGIS (QGIS Development Team 2020) was adopted to show the spatial disaggregation of findings.

8.3.1 Application of Proposed Models

Two network level evaluations are completed to show (1) how available environmental analysis input data that can be used to make decisions towards achieving sustainability goals, (2) how the PVI environmental impact regression models from chapter 7 of this thesis can be used on a road network analysis to inform road public infrastructure management practice on maintenance planning and programming.

8.3.1.1 Data and Source of Data

The first network-level analysis of a sample case study of Highway 48 pavement segment in Ontario is considered for the application of the proposed models in chapter 7. This road network analysis can be considered a corridor/segment analysis since all section have similar surface type, traffic range, road class, and all on a road of total length approximately 14km. The general information and the performance data measured at eight points of the road segment were presented in Table 8.1 and the IRI prediction for 25 years is shown in Figure 8.8, and the geographical map showing the road segment and point of measurements is available in Appendix E.

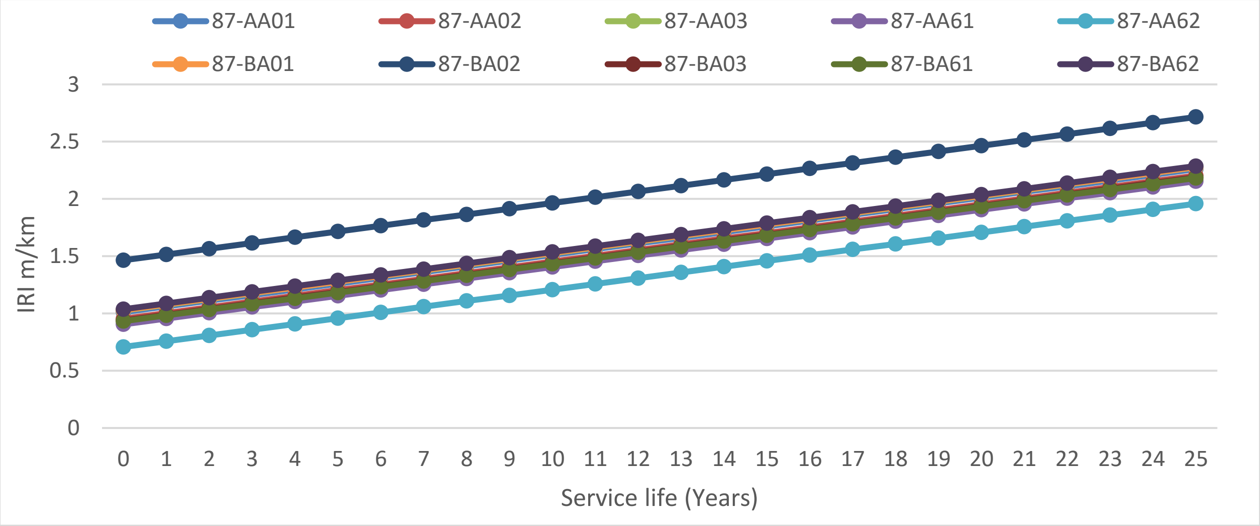


Figure 8.8 2014 Predicted IRI of road section on Highway 48

The second network-level analysis of the Ontario Road network managed by the MTO depicted by the map in Figure 8.9 shows the location of the roadways while Figure 8.10 shows the pavement condition index for different road sections as reported by MTO for the year 2014. There are 1822 road section on over 18,000km (single lane). The road condition indicator- pavement roughness (IRI), vehicle speed and traffic counts (AADT) are the inputs to estimate roughness-induced energy and pollutant mass/km emitted by vehicle types. The distribution of the IRI data and AADT data for all road sections are shown in Figure 8.11 (A) and (B).

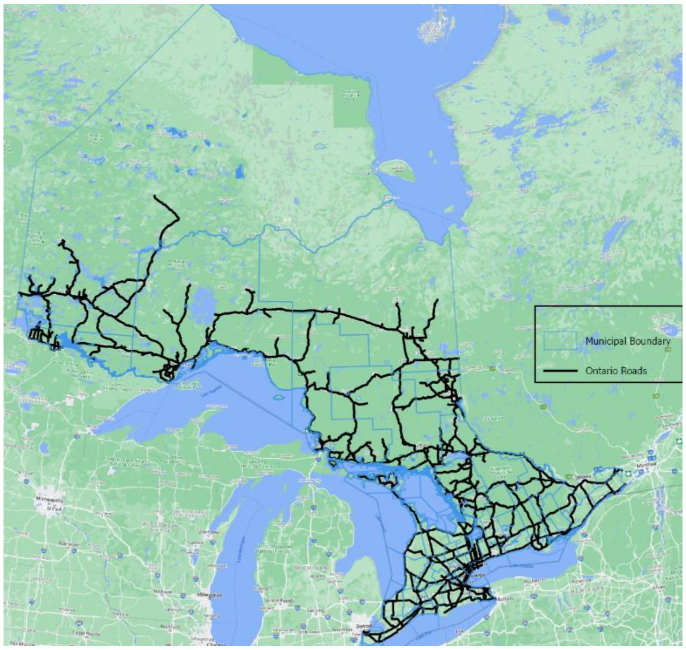


Figure 8.9 Locations of the Ontario Road network managed by the MTO.

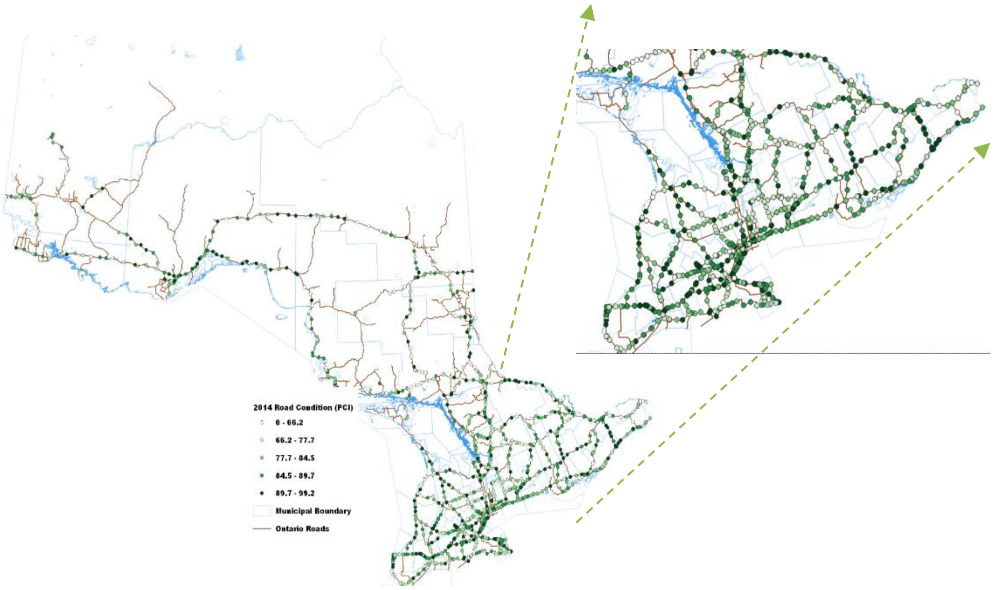


Figure 8.10 Presentation of the 2014 Pavement Condition Index (PCI) of all the road sections reported in the MTO public data

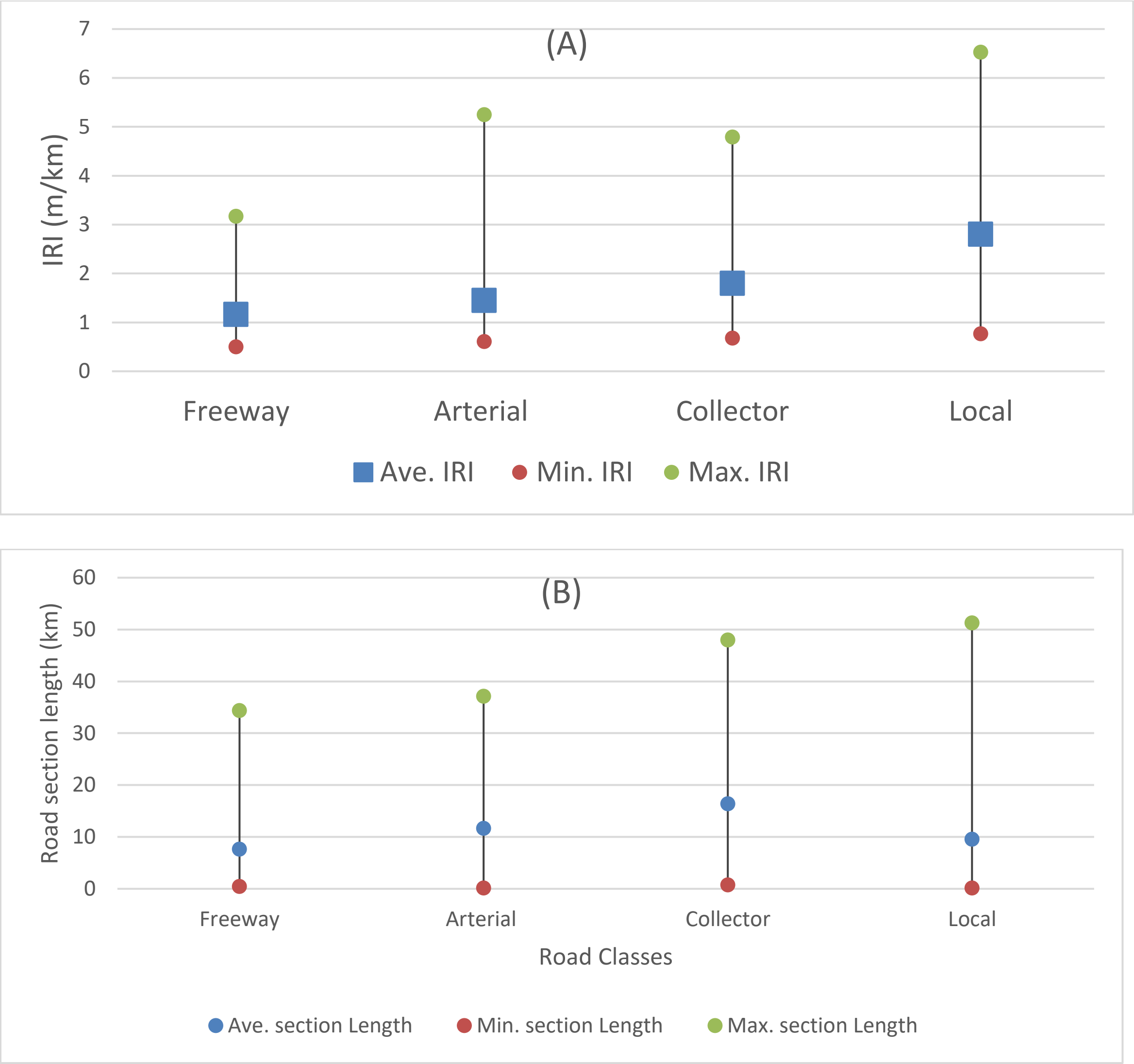


Figure 8.11Distribution of the road network road roughness data (A) and section length (B) in the four road classes

8.3.1.2 Method and Assumptions

For HWY 48 segment analysis, three maintenance policies were investigated. Firstly, a trigger level of 2.9m/km IRI based on a PCI of 55 trigger level for arterial roads in Ontario (see Table 7.4) is considered. Secondly, the trigger value is 1.9m/km which is the assigned trigger value for freeway maintenance by the MTO. The third trigger level is 1.4m/km which is based on the practice observed for a section of HWY 48 in the road condition public database published by MTO. In 2016, a section of HWY 48 had an IRI 1.4m/km and PCI 77.2. Same section is reported to have increase PCI at 87.5

and IRI 0.65m/km in 2017, which shows a maintenance treatment has been applied to the road section. Thus, the lower trigger value of 1.4 is investigated to account for the potential environmental savings from roughness management. For the predicted performance in this study, none of the sections reached and IRI level of 2.9m/km which means the first maintenance scenario can be considered a “Do-nothing” maintenance policy aside the frequent rout and seal every 3 to 5 years. Two maintenance programs are compared: the conventional Mill and Overlay (M&O) versus the recycling technique, Cold-In-Place recycling (CIR). The environmental impact data for the maintenance strategies were collated from Nasir (2018 and Min (2020). The EDC ($/km) values for Ikm-1lane road rehabilitation by M&O and CIR are $20,998 and $12,168 respectively. The EDC (4/km) for capital rehabilitation or reconstruction at the end of the analysis is considered for the Do nothing scenario, and its values is $2310162. These treatments are applied at different year given the performance of the road section. Similar to Nasir (2018), a 3% discount rate is adopted and the present worth if each treatment applied is estimated. The EDC-IRI linear models from chapter 7 is adopted to estimate effect of change in IRI and a constant speed of 100km/h was assumed for all sections.

For the Ontario network, the vehicle traffic are assumed to travels at a free-flow speed of 100km/h on freeways and 80km/h on other road classes was assumed, so the effect of roughness (IRI) and traffic counts (AADT) was used to estimate the environmental damage cost for each road section at EDC ($/km) (See equation Eq. 7.23 and Table 7.7). Although an analysis of road congestion effect can be conducted, for simplicity it is assumed that the traffic volume will not reach the capacity of the road within the analysis period and hence no congestion is expected. The EDC$ per section was also estimated using the total length for each section (see Figure 8.11 (C)). The QGIS tool is used to show the results on a map.

8.3.2 Results and Discussion

8.3.2.1 Environmental Sustainability Performance of HWY 48 Maintenance Strategy and Roughness management.

Figure 8.12 depict the possible maintenance timing based on the IRI prediction and trigger values for conservative case 1.9m/km and proactive case 1.4m/km

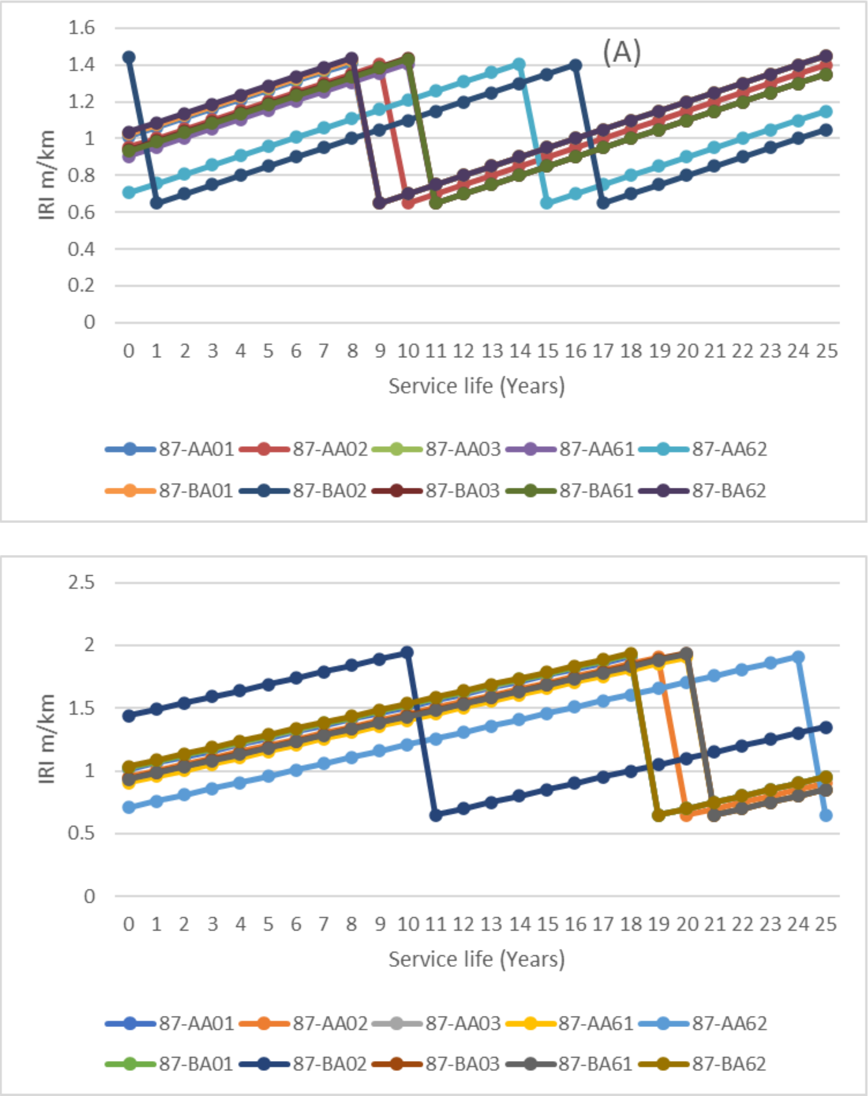


Figure 8.12 Maintenance Timing for HWY48 section for trigger level 1.4m/km (A) and 1.9 (B)

Reducing the trigger value will result in more frequent rehabilitations which is bound to involves environmental burdens from materials and construction of the rehabilitation activity. Thus, the system boundary was defined also to include environmental impacts from materials and construction of overlay activities. Figure 8.13 shows the potential savings from the different maintenance policies over the 25-years analysis period, It illustrates the effect of pavement roughness effect on the overall environmental impacts under the conventional M&R policy with trigger value 2.9 and compares it with the decrease trigger value policies effects. Potential environmental savings due to decreased pavement-roughness management policies are show vary from 10% to 18% depending on the policy. While M&R accounts for about 15% of the potential total EDC savings, potential savings from pavement roughness can be up to 17%, depending on maintenance policy. Arguably, savings from pavement roughness management could be more compared to the choice of a green M&R strategy over a conventional M&R.

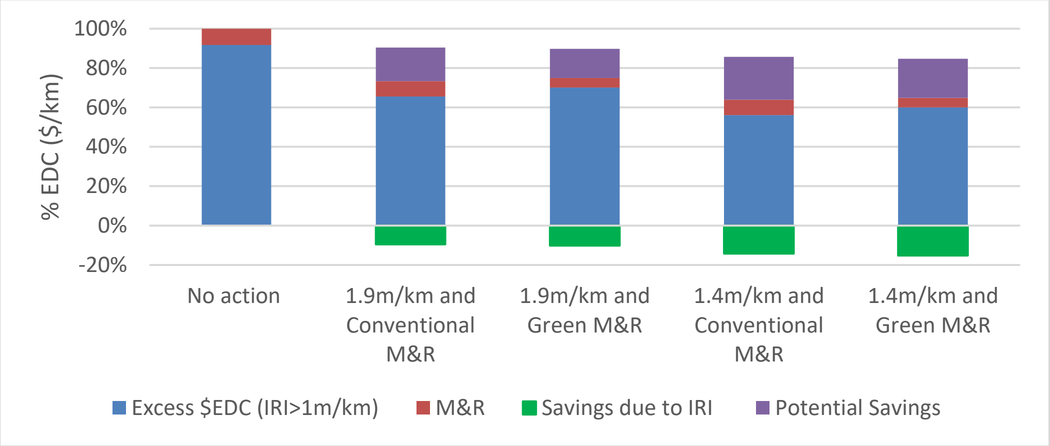


Figure 8.13 Potential EDC ($/Km) savings from IRI management and timely implementation of M&R strategies on 1km 1-lane road of HWY48 sections in this study

Decrease in the IRI trigger value by only 0.5m/km (from 1.9 to 1.4m/km) would decrease CO_2 emissions impacts by up to 10% for the 25-years analysis year (Figure 8.14). This result shows potential near-term GHG emission savings from pavement roughness management. Figure 8.14 shows CO_2 emissions can decrease with improved roughness level. Within the low roughness range, the total CO_2 reduction can be further reduced when green M&R strategies are adopted.

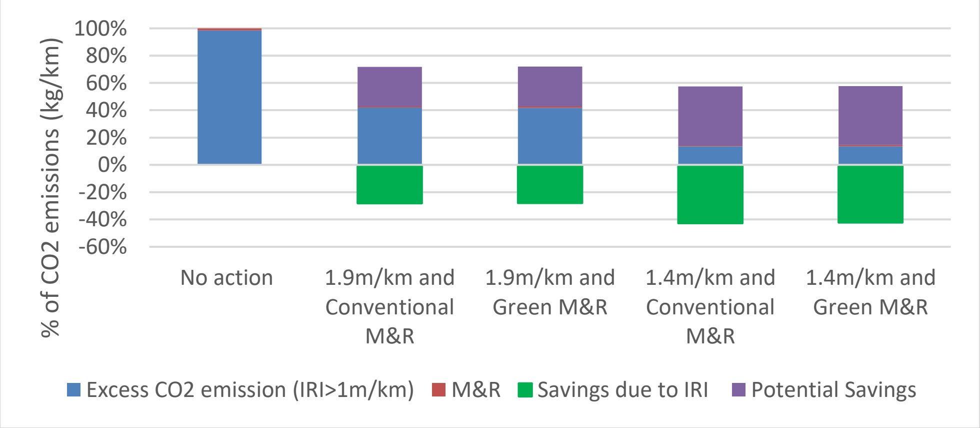


Figure 8.14 Potential CO_2 emissions savings from IRI management and timely implementation of M&R strategies on 1km 1-lane road of HWY48 sections in this study

8.3.2.2 Environmental Sustainability Performance of Ontario Road Network

Figure 8.15 shows the pavement roughness effect on the overall CO_2 emissions (kg/km) travelled on the 1822 section of Ontario network. Higher environmental emission values are estimated for the high-volume roads in the southern part of Ontario. Total energy use and emissions from a highway network is directly dependent on the number of vehicles using the system.

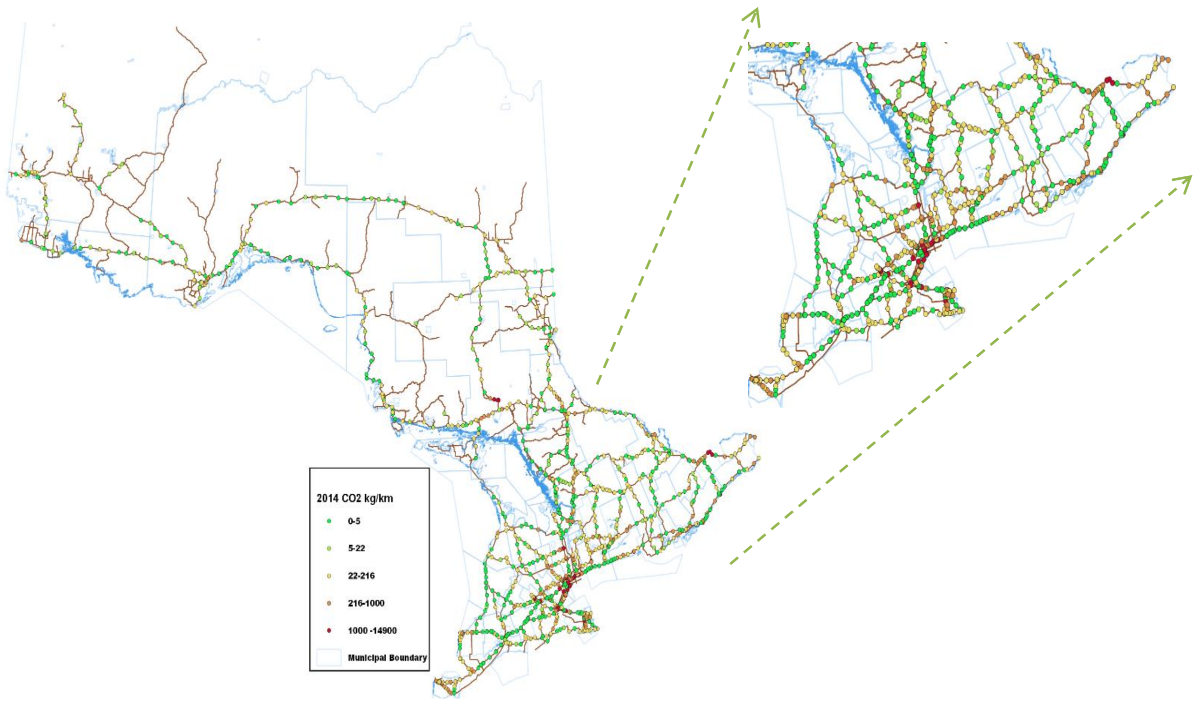


Figure 8.15 Excess CO2 emission from both passenger cars and trucks using Ontario Roads

Figure 8.16 disaggregates the results for excess CO_2 emissions (kg/km) and excess EDC ($/km) of CO_2 emissions, at IRI >1m/km, by the road classes and vehicle types. From this figure, it can be seen that the largest contributions of emissions are from trucks (heavy-duty vehicles) on freeways, similar results were found Wang et al (2020) for the freight damage investigation of Ontario Road network. This can be attributed to the road class having a larger traffic AADT (see Figure 8.11 for distribution). Additionally, vehicle types, the trucks make up of about 40% of the vehicle population in the model and each truck emits about 55% more than each passenger car.

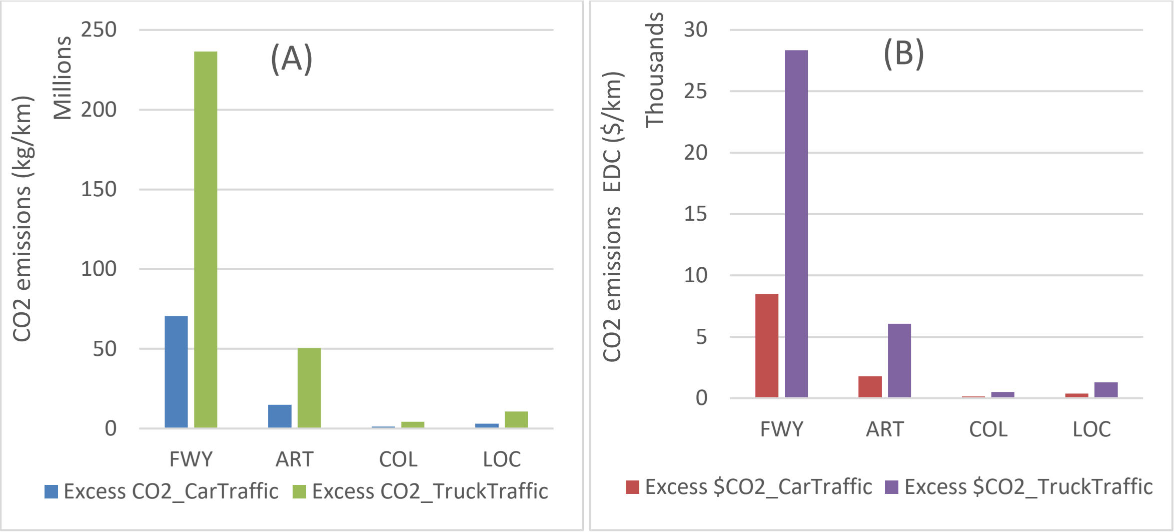


Figure 8.16 Excess CO$_2$ emissions (kg/km) (A) and Excess EDC ($/km) of CO$_2$ emissions (B) from passenger car and truck traffic using Ontario Roads

Figure 8.17 shows the CO$_2$ emission from traffic by section, produced from the baseline estimates. The CO$_2$ emission of Ontario roads due to road condition (IRI>1m/km) in 2014 is 2216.03 tonnes. The vehicle emissions occur largely in the southern part of Ontario along the highway 400 series roadways since there is a high traffic volume and more vehicle activity. A section of Highway 401 creates the highest emissions of 62.38 tonnes of CO$_2$ emission from 40,700 vehicles travelling on the road section with roughness of 2.7m/km. The high vehicle activity and traffic volume on the roadway results to higher emissions.

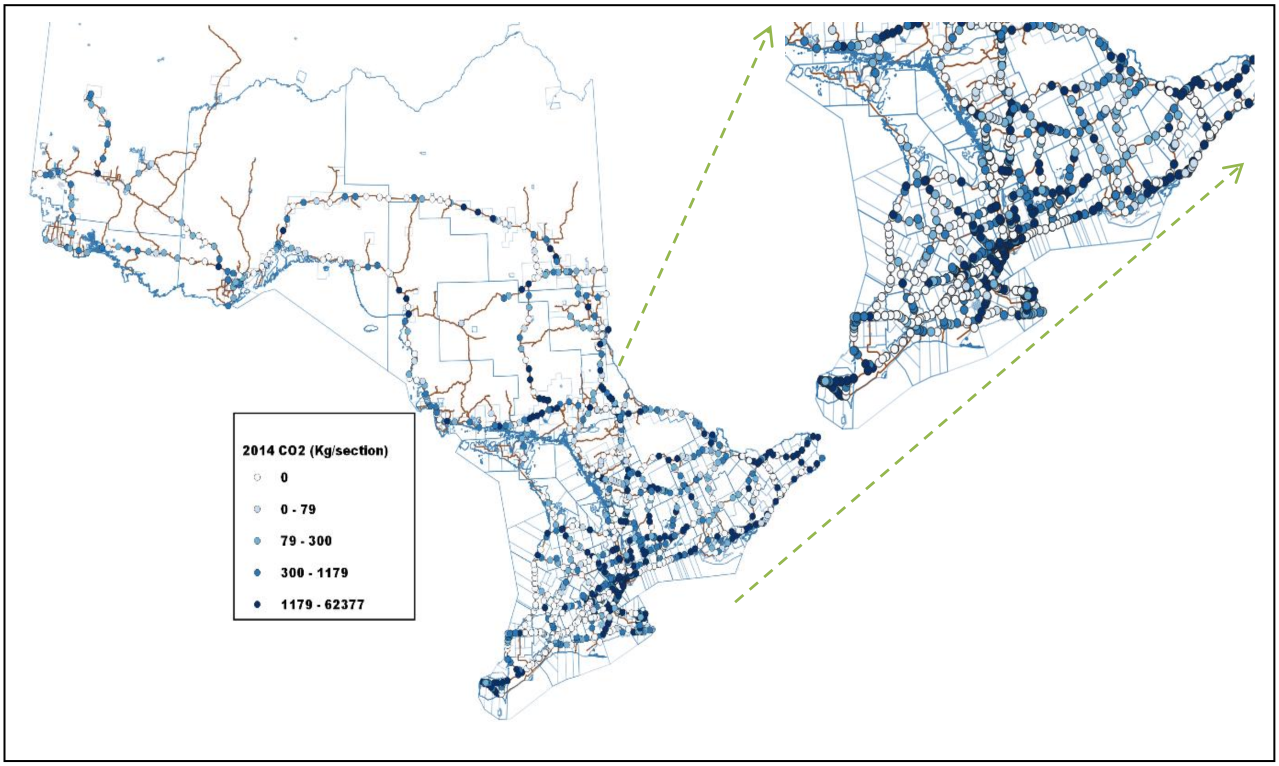


Figure 8.17 Excess CO_2 emissions (kg/section) due to road surface condition (IRI> 1m/km) of Ontario Roads

Figure 8.18 shows the environmental damages (2010CAD$/section) by road sections, produced from the baseline estimates of damages of CO_2, SO_2, NOx, CO and $PM_{2.5}$ emissions per section of Ontario Roads due to road condition IRI >1m/km. The total damages in the region due road condition is $2.6 Million (2010CAD). The damage occurs largely in the southern part of Ontario. Like the results presented in Figure 8.17, the 400series roadways cause are the highest road sections with regards to the damages per section. This may be attributed to the higher AADT and vehicle activity. So maintenance effort for sustainable pavement and transportation can use these can kind of results to inform decisions that include environmental performance metric of the road condition to ensure that the environmental damages can be reduce form transportation by the chosen policy or plan. Similarly, it was found that the traffic volume plays a big role in the EDC$ estimated. When equivalent length road sections were compared, the higher traffic road had much higher emissions. For example, consider two sections: a road section on highway 401 with a traffic of 407,040 AADT, road conditions PCI at 85.6 and IRI 1.69; versus a road section on highway 7 with a traffic of

94,600 AADT, road conditions PCI at 85.06 and IRI 2.12; both sections are freeway asphalt roads about 4.2 km in length. The highway 401 road section generated a damage cost $32,000. The highway 7 road section generated an excess of 11 tonnes of CO_2 emissions and the environmental damage cost was $13,000.

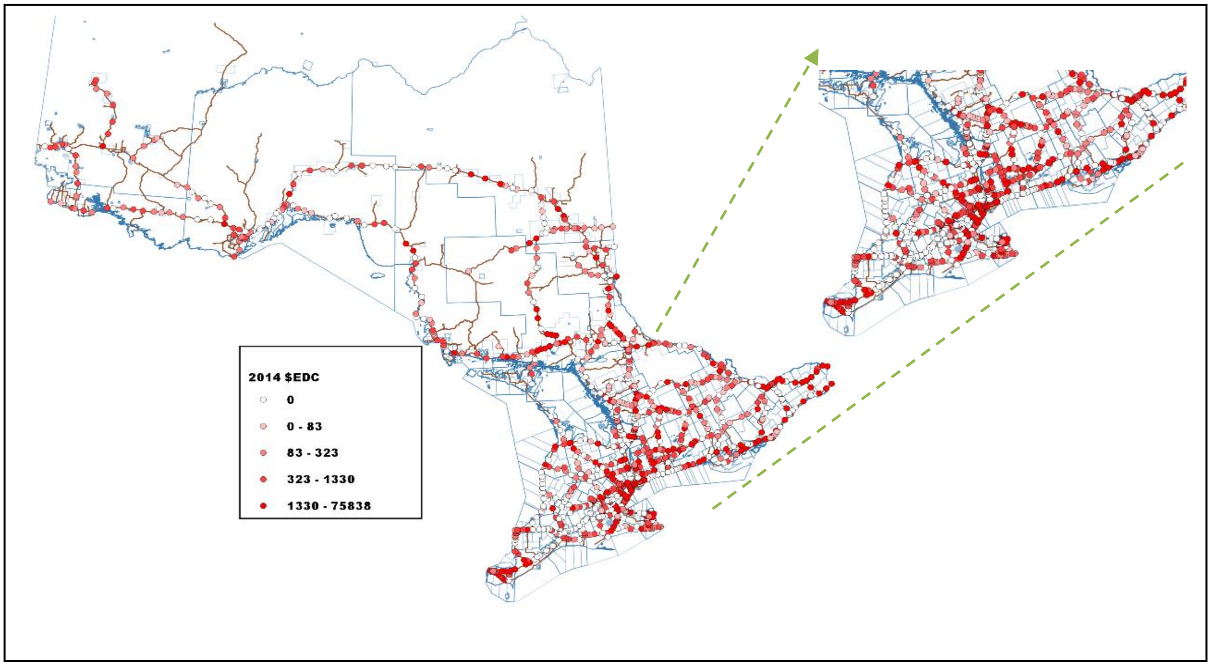


Figure 8.18 Environmental Damage Cost ($/section) due to road surface condition (IRI> 1m/km) of Ontario Roads

8.4 Recommendations and Conclusion

This study has analyzed the integration of sustainable criteria in project and network-level pavement management decisions. A framework for sustainability evaluation was proposed for project-level evaluation and a sample case study was adopted to show the applicability of the proposed framework. Traditional maintenance solutions based on mill and overlay (M&O) and preservation plan for 50 years planning time-period were analyzed, then compared to green maintenance strategies and maintenance program using cold-in-place recycling (CIR) and full-depth-reclamation (FDR). The AHP decision making technique is explored to integrate technical, environmental and economic evaluation. Impacts of using the maintenance solution were obtained and compared, including a sensitivity analysis on the importance of sustainability criteria in the sustainable evaluation of maintenance alternatives.

For network level evaluations, two case studies are used to show how the environmental impact of pavement surface condition can be evaluated and used to inform decision making in maintenance planning and programming. The emission in kg/km for passenger cars and truck for cars travelling on HWY48 are estimated integrated into five maintenance policies which are compared to estimate the savings from road roughness management with savings from integrating recycling (green) treatment techniques.

The project-level case study, the economic impact analysis shows that it is not a huge strain on the costs when it comes to selecting sustainable treatments for maintenance as opposed to standard treatments. At net present value, the cost difference is $38,153, which is only a 7% difference. Ideally, choosing “Green” maintenance plans would effectively have bigger environmental impact than it does economically. Adopting a maintenance program based on green solutions will save over 25% of the environmental damage cost from the traditional counterpart. Almost 50% of the material consumption can be reduced considering that the green technologies adopted in the greener maintenance plan are using less virgin material. These factors reduce the challenges with material availability and high cost of material hauling. The analysis also show that technical performance of the green maintenance plan is better than the traditional preservation plan. The results from this study show that CIR is equivalent to M&O in performance (as measured by the increase in RCI) and FDR better than the 2-lift M&O alternative. Although, M&O as the more commonly used practice (TAC 2013), when green innovative new technologies greater benefits can be gained including long-term performance, less new material use, reduced material cost and environmental damage for the whole road network. This study shows AHP inconsistent recommendations and ranking for techniques. That is, the sustainable ranking obtained depended on the importance level accorded to a particular criterion. This is an important finding, letting the agency understand the implication of criteria considered to decide how alternative are ranked. Further work needs to be done to identify existing barriers for the implementation of sustainable technologies in the pavement management of the road network.

Chapter 9

Conclusions and Recommendations

This chapter provides highlights and significance of research study done, while providing points for future studies.

9.1 Summary of Major Findings and Contributions

The main conclusions of this research can be concluded as follows:

- Measuring environmental sustainability allows pavement managers to improve accountability in the responsible use of ecosystems and resources and monitor their performance on environmental issues. A variety of input-based, output-based, and outcome-based indicators provided in the framework (chapter 4) for addressing seven environmental protection factors, and four natural resource management factors could help integrate environmental sustainability performance in pavement design and management decisions. Measures are provided for indicators including noise, air quality, waste, noise, habitat loss, toxics, and resource consumption (energy, materials, and water). Using the case of Ontario, measures listed are context-specific, and informed by values, influence, and purpose of pavement managers. This framework and its implementation can inform the development of broader and purpose-built sustainability assessment methods for pavement management.
- Pavement sustainability is a context–sensitive characteristic of pavement, which exist and function within the transportation system and environmental system. An accounting of interaction between pavement lifecycle and the surrounding systems is required to ascertain claims of strategies that profess sustainable practices for a particular pavement system (Van Dam et al. 2015). The use of RCWM must be evaluated in the particular context it is being used.
- System interactions can influence sustainability, Pavement characteristics influence the PVI, vehicle fuel consumption and emissions. Regional models and data to account for these interactions is needed to inform pavement management strategies and reduce the effects on the transportation emissions which are considered the main source of traffic related health challenges.

- A PVI model to quantify the environmental impact of pavement condition is proposed model in this thesis. It offers advantages for easy integration and implementation into pavement LCA tools to evaluate the use-stage energy and environmental footprints related to pavement surface conditions. This model addresses on gap for integration of LCAs into network-level pavement management, the model can be used to inform maintenance management strategies of a road network that maximises the reduction of road traffic emissions and excess fuel consumptions. Subsequently, the model can be used to assist decision makers for developing sustainable pavement-management system. According to the simulation data analysis, passenger vehicles on freeways are highly sensitive to roughness and speed. For a passenger car, one unit change of IRI (1m/km) results in an average increase in fuel consumption of 1% and 2% at low speeds and high speeds respectively. Trucks are more sensitive to IRI change; and one unit change in IRI on average results in 2% and 3% increase, respectively, in fuel consumption of heavy -duty truck at low speeds. The results are in line with reported values from the literature, percent change in fuel consumption for one unit change of IRI under various conditions is 0.1% to 6%. The range found in the current study is between 0.5% and 3% according to models developed here, indicating consistency of the model.
- A sustainable pavement evaluation framework is presented and applied to a case study of a project section from HWY48 roadway in Onatrio. Findings shows that choosing "Green" maintenance plans effectively have bigger environmental impact than it does economically. A maintenance program based on green solutions will save over 25% of the environmental damage cost from the traditional counterpart. Almost 50% of the material consumption can be reduced considering that the green technologies adopted in the greener maintenance plan are using less virgin material. These factors reduce the challenges with material availability and high cost of material hauling. The analysis also shows that technical performance of the green maintenance plan is better than the traditional preservation plan. In summary, by adopting green innovative new technologies, greater benefits can be gained including long-term performance, less new material use, reduced material cost and environmental damage for the whole road network. However, the sustainable ranking of technologies based on the three dimensions of sustainability will depended on the importance level accorded to a particular criterion. This is an important finding, letting the agency understand the implication of criteria considered to decide how alternatives are ranked.

- The PVI model was demonstrated using the road condition data for the Ontario Road network. Main findings showed that the impact of road surface condition on fuel consumption and environmental cost was higher for road sections with higher traffic volume, even when the road condition measures of the section met the Ministry's target. For example, a road section on highway 401 with a traffic of 407,040 AADT, road conditions PCI at 85.6 and IRI 1.69 in 2014 generated excess 26 tonnes of CO_2 emissions and the environmental damage cost was $32,000 daily. For examprison, a road section on highway 7 with a traffic of 94,600 AADT, road conditions PCI at 85.06 and IRI 2.12 in 2014 generated an excess 11 tonnes of CO_2 emissions and the environmental damage cost was $13,000 daily.

9.2 Recommendations for Future Work

The following are recommended for future study:

- The Environmental evaluation framework proposed in this thesis consists of a list of environmental indicators and potential measures. Environmental indicators alone do not encompass the more modern, broader vision of sustainability as fairness, enhancing well-being across generations (Clark and Harley 2020). Further, they do not account for interactions and feedbacks that occur within Earth's dynamic human-natural system that will affect pavements and their sustainability. Supporting sustainable pavement management more broadly involves capturing these relevant factors and relationships. Transportation-focused literature in particular points to properties of both frameworks and indicators that future work could enhance. These include, for example, expanding beyond environmental sustainability, capturing interactions among indicators, including long-term effects, and relating indicating indicators to the goals, influence, and interactions of actors within a pavement management organization and across its stakeholders (Sdoukopoulos et al. 2019; Jeon and Amekudzi 2005; Zheng et al. 2013; Pei et al. 2010; Oltean-Dumbrava, Watts, and Miah 2014). Such additional effort could enhance the value of the factors and data contained herein, which offer one approach based on recent science to evaluate environmental sustainability of pavements across their lifecycle within the Ontario context.

- There is still limited knowledge regarding the environmental sustainability performance related to the evolution of pavement’s functionalities, for instance energy harvesting. Many of such innovative technologies are already implemented or in their pilot stage.. Although it may seem more cost effective where pavement’s function can also be extended, the effect of extending the pavement function on its key sustainability factors need to be quantified before they should be considered for implementation, such that the environmental burden is transferred from one system to another. Future studies can investigate viability of implementing them in Canada in term of sustainability performance.
- Potential impacts of all innovative GHG mitigation measures can be quantified, and all lifecycle phases should be included
- A field study can improve knowledge of potential trade-offs between adaptation and mitigation and broader scopes could be considered with more performance criteria beyond those considered in chapter 6 of this thesis
- This research applied the sustainable evaluation framework to a road section and only considered environmental performance in network level evaluation. A field study can improve the road condition environmental impact models. Future work can include other factors not considered. Evaluation of the impact of road network condition can be extended to other criteria such as noise, albedo effect (heat island) and runoff effects.

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Appendices

Appendix A

Supplementary Data for Chapter 3

Atmospheric Emissions

Construction Phase: Pavement Associated Emission Factors

Of each of these life-cycle stages, studies generally agree that material production dominates the overall lifecycle impacts. Thus, for a streamlined analysis, we present emissions factors associated with production of the various raw materials used in the pavement development process. These numbers derive from the Carnegie Mellon Environmental Input-Output Life Cycle Assessment model (Carnegie Mellon University Green Design Institute, 2018). Note that the factors have the units of kg of air pollutant or GHG per dollar of economic output in the economic sector required to produce the materials.

Carnegie Mellon University Green Design Institute. (2018). Economic Input-Output Life Cycle Assessment (EIO-LCA) Canada 2002 (105 sectors) Producer model. Retrieved July 22, 2018, from http://www.eiolca.net

Table 10: Emission factors from raw material use in pavement

Sector	**CO_2 (kg/$)**	**CO (kg/$)**	**NO_2 (kg/$)**	**SO_2 (kg/$)**	**PM_{10} (kg/$)**	**Hg (kg/$)**	**Pb (kg/$)**
Asphalt paving mixtures and blocks	0.35	1.59E-03	1.18E-03	1.02E-03	7.1E-04	3.88E-08	2E-06
Ready-mixed concrete	0.14	1.6E-04	2.4E-04	5.5E-04	4.5E-04	3.88E-08	2.1E-06
Blast furnaces and steel mills	0.1	1.55E-03	7E-05	6.4E-04	3E-05	4E-05	1.57E-05
Sand and gravel	0.07	9E-05	1.1E-04	3E-05	1.7E-04	4.05E-11	3E-07
Bitumen	1.04	7.1E-04	9.6E-04	1.66E-03	1.4E-04	3.88E-08	1.8E-06
Cement	0.78	1.31E-03	2.18E-03	2.47E-03	1.6E-04	3.88E-08	3.7E-06
Concrete Additives	0.11	1.68E-03	4.9E-04	1.27E-03	2.9E-04	3.88E-08	2.7E-06
Asphalt Emulsion	1.04	7.1E-04	9.6E-04	1.66E-03	1.4E-04	3.88E-08	1.8E-06
Water	0.01	2E-05	2E-05	1E-05	0	4.67E-10	1.2E-06
Electric Services (Utilities)	0.12	3E-05	2.6E-04	6E-04	3E-05	4.67E-10	1.9E-06

The emission factors shown in table 10 can be combined with the amount invested in raw materials to estimate the associated pollutant, greenhouse gas, and toxic emissions released. The relative dollars amounts per materials required will depend on the type of infrastructure (e.g., asphalt vs.

concrete). For a project-level comparison of full life-cycle emissions associated with various asphalt and concrete highways, refer to (Nasir, 2018).

On-road (Operation Phase: Vehicle Emission Factors)

The development of highway infrastructure will influence travel and thus the emissions released.

Table 11: Greenhouse gas emission factors for light and heavy duty vehicles

Speed (kmph)	Light-Duty Vehicles Emission Factors				Heavy-Duty Vehicles Emission Factors			
	CO_2 (kg/km)	CH_4 (kg/km)	N_2O (kg/km)	CO_{2e} (kg/km)	CO_2 (kg/km)	CH_4 (kg/km)	N_2O (kg/km)	CO_{2e} (kg/km)
10	0.69	1.29E-05	2.24E-05	0.70	2.40	1.18E-04	9.26E-06	2.41
30	0.32	5.57E-06	6.84E-06	0.32	1.20	3.98E-05	2.83E-06	1.21
50	0.25	4.66E-06	4.03E-06	0.25	1.04	2.50E-05	1.66E-06	1.04
70	0.25	5.49E-06	2.87E-06	0.25	0.92	1.92E-05	1.182E-06	0.92
90	0.24	5.18E-06	2.23E-06	0.24	0.86	1.55E-05	9.18E-07	0.86

Table 11 above presents emission factors in kg of greenhouse gas emitted per kilometer of travel at different speeds. The data is derived from inputting Canadian and Ontario specific data into US EPA's Motor Vehicle Emission Simulator (MOVES) (Wang, 2018). Emission rates for each type of vehicle have been aggregated using vehicle distribution based on Ontario vehicle registration. Vehicle type emission factors have been segregated into two broad categories, namely, light-duty (LDVs) and trucks (including medium duty vehicles (MDVs) and heavy duty vehicles (HDVs). It can be seen from the above table that emission factors are higher at lower speeds, therefore, depending on weather conditions and the guidelines for vehicle travel along highways in Canada, emission factors may vary significantly. The data presented in table 11 can be used to estimate the environmental impact in terms of GHG emissions from potential vehicle travel on highways intended to be developed in the territorial north of Canada.

Table 12: Air pollutant emission factors for light and heavy duty vehicles

Speed (kmph)	**Total HC (g/km)**		**CO (g/km)**		**NO_x (g/km)**		**SO_2 (g/km)**		**Hg (g/km)**		**PM_{10} (g/km)**		**$PM_{2.5}$ (g/km)**	
	LDV	**HDV**	**LDV**	**HDV**	**LDV**	**HDV**	**LDV**	**HDV**	**LDV**	**HDV**	**LDV**	**HDV**	**LDV**	**HDV**
10	0.173	1.43	3.67	8.43	0.34	10.22	0.013	0.023	7.31E-08	2.05E-08	0.184	1.95	0.033	0.74
30	0.069	0.53	1.88	4.67	0.221	4.86	0.006	0.012	7.31E-08	2.05E-08	0.092	0.672	0.016	0.297
50	0.051	0.351	1.69	4.08	0.222	3.95	0.005	0.01	7.31E-08	2.05E-08	0.054	0.422	0.012	0.213
70	0.048	0.256	2.055	3.36	0.25	3.41	0.005	0.009	7.31E-08	2.05E-08	0.037	0.281	0.013	0.163

90	0.044	0.197	1.98	2.85	0.26	3.166	0.004	0.008	7.31E-08	2.05E-08	0.025	0.191	0.01	0.13

Similar to table 11, the air pollutant emission factors for light and medium/heavy duty vehicles have been presented in grams per km travelled in table 12. The emission factors are seen to be higher at lower speeds. The associated documentation file 'Air Pollutant Emission Factors.xlsx' lists air pollutant emissions factors for LDVs and MDVs/HDVs over a wider speed range. Data in table 12 can be used to estimate the environmental impact in terms of air pollutant emissions from potential vehicle travel on highways intended to be developed in the territorial north of Canada.

Pavement (Operation Phase: Dust Emission Factors)

Dust emissions are generally attributable to unpaved roads. As the northern transportation infrastructure investment project may involve the development of paved roads/airstrips in place of existing infrastructure (which may be gravel or unpaved roads), there may be a potential reduction in dust emissions. In this case, we refer to the methodology presented by Government of Canada's 'National Pollution Release Inventory' website (Government of Canada, 2008) for determining dust emission factors based on vehicle kilometers travelled on unpaved roads.

Outcome-Based Indicator: Marginal Damages

Emissions alone are difficult to compare across species, as their effects are varied and interrelated. While emissions are associated with various impacts, this relationship is nonlinear and dependent on complex atmospheric conditions and processes. This difficulty can be addressed by using the results of research used to estimate the marginal damages (MD) of emissions. Marginal damages represent the full social cost of an additional ton of emission, accounting, ideally, for nonlinear effects across multiple impact categories.

Here we rely on a literature review we previously conducted that is detailed in (Nasir, 2018), and summarized in Table 15. Five different methods to calculate marginal damages from atmospheric emissions were selected and applied in this work. These methods were chosen because they are comprehensive and state-of-the-art methods that provide North American or global MD estimates for atmospheric emissions. We evaluated these different MD methods to determine a range of estimates for emissions of CO_2, NOx, SO_2, CO, and $PM_{2.5}$.

To determine a set of values relevant for use for Canadian transportation applications, we made multiple adjustments to harmonize estimates across methodologies, including harmonizing the exposure-risk relationships, the risk valuations, and the treatment of the various effects of nitrogen oxides, including to fine particulate matter formation, ozone formation, and direct health effects. The results are in table 17. To apply these, we suggest applying the median values across all emissions for the most relevant real discount rate. For full details, refer to (Nasir, 2018), provided.

Table 17: Marginal damages ($2010 CAD/ metric tonne); adjusted for inflation, VSL, NO_x 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, 2.5% discount rate	$117	$72,533	$378,777	$45,684	$749
SCAR, 2% discount rate	$136	$72,533	$394,916	$46,138	$811
EASIUR		$36,518	$107,631	$31,588	

Median, 2.5% discount rate	*$117*	*$30535*	*$272779*	*$41155*	*$749*
Median, 2.0% discount rate	*$136*	*$30535*	*$272779*	*$54376*	*$811*

Alternative Outcome-Based Measurement Options

It should be noted that while there are many estimates for CO$_2$ available in literature, above we only considered methods that also included health-related impacts of air pollution. However, there are other options for pricing carbon in Canada, including using the Social Cost of Carbon (SCC) developed by the United States Government Interagency Working Group on Social Cost of Greenhouse Gases (Greenstone et al., 2013; Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, 2013). The recommended regulatory SCC for emissions in 2020 range from $12 to $123/ton (in 2007 USD), with a median value of $42/ton discounted at 3% (Government of Canada, 2016). Canada also has a regulatory price of carbon, which is specified in the Carbon Pollution Pricing Rule (Canada, 2018). Its specification varies by source and sector. This approach may be of interest to regulators and departments, and so may be appropriate to use for its salience, recognizing that a regulatory price might not reflect the external cost as determined by economists.

We highlight the MD approach in the previous section as it was developed specifically for a Canadian application. However, others have developed estimates of external costs related to transportation, including the ongoing internalization project focused on EU countries (van Essen, 2019). We provide the 2019 version of this report as an alternative source of external costs related to air pollution (in Chapter 4) and climate change (in Chapter 5), which are not dependent on emissions but on transportation-related activities. Numbers are provided for EU28 countries, but could be converted for Canadian purposes by adjusting for GDPPC/PPP and currency.

Limitations and Uncertainty

Marginal damages of emissions are highly uncertain, with large ranges present both across the literature, and within a given method (e.g., EASIUR damages have a relative percent error around -100% to +300% (Heo, Adams, & Gao, 2016b)). Further, there is uncertainty introduced by the fact that these values were assessed for other contexts. While this is the best that can be done for this project without a significant increase in scope, we note that concerns with the benefits transfer method are well documented in economic literature. Nonetheless, the marginal damage of emissions approaches cited here have been applied in national policy analysis in the U.S. (e.g., (U.S. Environmental Protection Agency, 2014)), and the benefit transfer method is preferred for external costs in the EU (van Essen, 2019), and is codified in benefit cost analysis guidance in Canada (Treasury Board of Canada, 2007).

Noise

Developing new and repairing existing highway infrastructure enhances the travel time, cost and reliability of on-road travel. However, reinforcement of highway infrastructure may increase on-road traffic flow volume leading to increased noise levels. Table 1 below shows the noise levels associated with common on-road vehicles. However, to compare the magnitude of noise generated by vehicles, noise levels generated by non-road activities (e.g. speaking, shouting etc.) have also been included in the table below.

Table 1: Noise level associated with common on-road activities and non-road activities (“Pavement Noise,” n.d.)

Threshold of human hearing	140

Diesel truck at 50 feet	90
Motorcycle passing by at 50 feet	85
Car travelling at 60 mph passing by at 50 feet	80
Heavy traffic at 300 feet	60
Loud shout	90
Normal conversation	60
Gas lawnmower at 3 feet	100

Table 2 below can be used as a measure to understand the change in noise levels with traffic volumes.

Table 2: Change in noise level with number of automobiles on road per hour

Number of automobiles	**Noise Level (dbA)**
1	60
2	63
4	66
8	69
16	72

According to the Maryland department of transportation, with the doubling of number of vehicles, the noise level is seen to increase by 3 dbA (Maryland Department of Transportation: State Highway Administration, n.d.). An average person can notice a change in noise level only when there is an increase of 3 dBA. In other words, if the noise level of a highway with a 5,000 vehicles per hour traffic volume is 80 dBA, then for the noise level to go up to 83 dBA, the traffic volume has to increase to 10,000 vehicles per hour.

A study carried out by the European Environment Agency established thresholds for noise levels above which there are increased chances of adverse health effects becoming prominent. Table 3 below presents the different adverse health effects and their respective threshold noise levels. This table can serve as a guideline for monitoring noise levels in communities close to highways and help in reducing chronic or acute health effects within them.

Table 3: Adverse health effects of noise

Effect	**Measurement Metric**	**Threshold Levels (dBA)**	**Severity of Effect**
Annoyance disturbance	L_{den}	42	Chronic
Self-reported sleep disturbance	L_{night}	42	Chronic
Learning, memory	L_{eq}	50	Acute, Chronic
Stress hormones	$L_{max, Leq}$	NA	Acute, Chronic
Sleep	$L_{max, indoors}$	32	Acute, Chronic
Reported awakening	$SEL_{indoors}$	53	Acute
Reported health	L_{den}	50	Chronic
Hypertension	L_{den}	50	Chronic
Ischaemic heart diseases	L_{den}	60	Chronic

The World Health Organization (WHO) sets noise level guidelines for outdoor residential noise as shown in table 4 below.

Table 4: Outdoor residential noise level guidelines set by WHO (Toronto Public Health, 2017)

Measurement Metric	Noise Level (dBA)

	Day	Evening	Night
Noise Duration	12 hour	4 hour	8 hour
Time of day	7:00-19:00	19:00-23:00	23:00-7:00
WHO Target Guideline	55 dBA		40 dbA

Tables 1 to 4 can serve as a qualitative guideline for assessing potential noise levels generated from an increase in traffic volume upon the development of new highway infrastructure.

Outcome Based Indicator: Environmental Cost of Noise

Table 9 lists the environmental cost of being exposed to different decibel bands of noise. There are two components to this cost, namely, 'the annoyance value' and 'the health value'. The value associated with annoyance is based off of a willingness to pay method, where participants of a survey are asked the amount they are willing to pay to change noise levels. The 'health value' is based on a health endpoint study carried out by the Department for Environment, Food and Rural Affairs in United Kingdom (Department for Environment, Food & Rural Affairs, 2014) that associates a cost value to impacts such as hypertension, productivity loss, etc. These references are drawn from the European Union's (EU) Handbook on external costs of transportation and are based on EU28 average values and were adjusted for Canada using the GDP per capita purchasing power parity (GDPPC/PPP) approach in the Handbook (van Essen, 2019). The costs in Table 9 have the units of CAD 2016 per bins of 5 dB(A) per person per year. Note that marine cost factors are not well documented in the literature and therefore not presented below.

L_{den} (db(A))	**Road Transport ($/person/year)**		
	Annoyance	**Health**	**Total**
50-54	23.17	4.96	28.13
55-59	46.34	4.96	51.3
60-64	46.34	9.93	56.27
65-69	89.37	14.89	104.26
70-74	89.37	21.52	110.89
≥75	89.37	29.79	119.16

The noise levels presented in the table above are representative of L_{den} which is the weighted average of total noise during the day, evening and night time, as described earlier in this section among the list of indicators used to measure sound levels. The above table can serve as a guideline for environmental cost associated with noise, provided that data on the total number of people exposed to it is available. These values are drawn from the EU handbook on the external costs of transportation, specifically Table 33. This report is provided as a reference for further details on noise cost factors specific to passenger and vehicle distance travelled for different transportation modes (mainly on-road, rail and aviation) (van Essen, 2019).

Ecosystem Services

Effect	**Road ($ per km per year)**	
	Highways	**Other Roads**
Habitat Loss	130,579	3,144
Habitat fragmentation	24,163	3,641
Total habitat damage	154,742	6,785

The values represent habitat damage costs applicable to the Canada (in CAD 2016 adjusted based on GDPPC/PPP) (van Essen, 2019).

Table 20 presents another way of calculating habitat damage costs based on the passenger km travel or vehicle type km travel. Cost factors for the on-road transportation modes are presented in $ per passenger km (pkm) and $ per vehicle km (vkm).

Table 20: Cost factors for habitat damage based on distance covered in transportation mode

Source	Cost Factors	
Passenger transport	**$ per pkm**	**$ per vkm**
Passenger car	9.1E-03	0.015
Passenger car – petrol	8.9E-03	0.015
Passenger car – diesel	9.3E-03	0.015
Motorcycle	5.5E-03	4.9E-03
Bus	1.6E-03	0.031
Coach	1.8E-03	0.036

Resource Management

Solid Waste/Hazardous Waste and Water Consumption

The construction of pavements generates solid waste and consumes water.

Output Based Indicator: Waste Generation, Water Consumption, De-icing Salt Usage Factors

According to the US EPA's 'Resource Conservation and Recovery Act' (RCRA), solid waste generated during the construction of pavements is classified under 'Construction and Demolition' (C&D) debris. The RCRA is a guideline that can be used to classify C&D debris into non-hazardous and hazardous waste. Some of the hazardous waste generated during the development of pavements (e.g roads, airstrips) include concrete, asphalt, wood, gypsum, and asphalt shingles (US EPA, 2019).

Table 18 lists the kg of RCRA hazardous waste generated per dollar invested in the different components/raw materials used in the pavement construction process. The amount of water required in gallons per dollar invested on raw materials has also been listed in the table below, derived from PaLATE (Horvath, 2007).

Table 18: Hazardous waste generated and water consumed for raw materials used in pavement construction

Sector	RCRA Hazardous Waste (kg/$)	Water Usage (Gallon/$)
Asphalt paving mixtures and blocks	0.14	3.79
Ready-mixed concrete	0.03	6.03
Blast furnaces and steel mills	0.05	66.26
Sand and gravel	0.02	2.15
Bitumen	0.38	9.14
Cement	0.02	22.27
Concrete Additives	0.29	18.71
Asphalt Emulsion	0.38	9.14
Water	0.04	2.01
Electric Services (Utilities)	0.02	0.81

The data presented in the above table can serve as a guideline to monitor the potential release of Hazardous waste

Energy / Electricity

Pavement materials

Sector	Energy (MJ/$)	Electricity (kWh/$)
Asphalt paving mixtures and blocks	77.47	0.69
Ready-mixed concrete	19.06	0.67
Blast furnaces and steel mills	31.55	1.26
Sand and gravel	15.45	1.02
Bitumen	21.77	0.86
Cement	44.94	1.96
Concrete Additives	20.05	0.84
Asphalt Emulsion	21.77	0.86
Water	7.96	0.23
Electric Services (Utilities)	129.02	0.15

Appendix B
Supplementary Data for Chapter 4

This appendix provides supplementary Tables and data from "Achebe Jessica, Saari Rebecca K. Tighe Susan L., (In-view). Greenhouse Gas Mitigation in Highway Design, Construction and Maintenance - Jurisdictional Scan. Final Report, HIIFP Project #2018-02"

Table A. 1 Strategies to mitigate GHG emission of Highway management at MTO

	Currently in Use	Not implemented
Administrative Policies and Programs	Policy updates to align with MTO's Statement of Environmental Values (SEV) update	Incentives/Disincentives for haul-to-waste materials for reducing or reusing
	Class Environmental Assessment (EA) amendment of MOECC Considerations of Change in EA Guidance	Incentives for Locally Sourced Materials
	Air Quality 5 Year Plan	Incentives for reduced deficiencies and/or warranty work
		Alternative Contract Models (Option A cast-in-place, Option B Precast)
		Review of aggregate by-laws for virgin materials
		Specify Material sources in design
Evaluations and measurement	Longer life assets to reduce rehabilitation and maintenance works	Performance Based Specifications & Testing
	LEED certification for buildings (maintenance depots, rest areas, truck inspection stations)	Prequalification considerations for Contractor & CA

	Smoothness	Selection Evaluation Criteria - RFPs, DBs, CMGCs
	GreenPave	Climate Change Experts on CA Team & Contractor Crew
		Environmental Product Declaration (EPDs)
		Standardizing GHG Calculation Methodologies
		Life Cycle Assessment
		Evaluation of GHGs at contract completion
Alternative material use	Innovative cement binders and supplementary cementing materials	400W to 500W Reinforcing Steel
	Rapid Set Concrete (Bridges and road)	100 % recycled materials
	Smog Eating Concrete	
	Timber Bridges	
	Recycled Materials	
Sustainable Technologies (roads and bridge)	Warm Mix Asphalt (WMA)	Reduced deck slab depth for Bridge designs
	Precast Concrete Pavement	
	Rapid Bridge Replacement	
	Cold Mix Asphalt	
	Hot-In-Place Recycling (HIR)	
	Cold-In-Place Recycling (CIR and CIREAM)	
	Full Depth Reclamation (FDR)	
Drainage and structural	Pervious Pavement to minimize rainfall runoff	Oversizing pipes/culverts to allow for future re-linings

	Bio-retention & Storm-water Management	
	Drainage Based on Predictive Rainfall	
	Retained soil system (RSS) walls	
	Mechanically stabilized earth (MSE)	
Material management (access and hauling)	Use of Rock within the Right of Way	Storage depots to be used by multiple jobs
	Balanced Earth Excavation and fill embankments	Standardization and Stockpile of commonly used precast elements (Culverts)
	Minimizing Double Handling of Materials	Reducing Packaging for Construction Materials (e.g.. Plastic & Pallets)
Traffic and Congestion mitigation	HOT / HOV Lanes (Including Policy Changes)	Plan Winter Construction Activities to offset summer operations
	Design Characteristics - Free flow considerations, roundabouts, Truck Climbing Lanes	
Traffic and Congestion mitigation - Expedite activities and Smart staging	Aggressive Closures (Full Closures)	24/7 Construction
	Construction detours, staging and timing to reduce congestion	Payment adjustments for reducing construction times and congestion queues
		Lane Rentals / Flexible Closures
		Real Time Modelling - Adjusting based on Traffic Conditions
Roadside vegetation	Trees & Landscaping	
Vehicle and Equipment	Scrubbers and catalytic converters on construction equipment exhaust to include traditional small tools	Anti-Idling Software & Mechanisms

	Electric / Hybrid - Vehicles & Equip	Using Local Electrical Grid to Minimize use of Generators
	Electric Vehicle Charging Stations	Age Limits & Mechanical Fitness for vehicles and equipment
	Electric Ferries	
	Alternative Fuels - hybrid diesel equipment	
	Fuel Efficiency & Alternative Fuels	
Energy savers	LED Lighting	
	LED Traffic Signals	
	Solar & Wind - Counting Stations, Signs, Northern Airports	
	Solar Powered Cathodic Protection	
Congestion mitigation- queue prevention	Accelerated Vehicle Collision Removal	Communication of traffic patterns through variable message signs
	Toll Roads	Increased communication on social media
	511 Integration	Partnering with Google / Waze

Table A. 2 GHG mitigation Measures during Highway Infrastructure Planning and Design

Category	**GHG Mitigation Measure**	**Ontario**	**Canada**	**USA**	**UK**	**Netherlands**	**Scandinavia**	**O/Europe**	**Australia**	**Others**
Administrative – Planning	GHG emission in Environmental Assessment Guideline	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Programs and Policies	Environmental Protection Requirement for GHG during Highways Designs and Construction	🟥	🟩	🟩	🟩	🟩	🟩	🟩		
	GHG mitigation in short/long-term Air Quality plan	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Aggressive tree planting scheme	🟨	🟩	🟩	🟩					
	Rapid installation of charging stations on highway program	🟩		🟩	🟩					
	Low carbon refuelling infrastructure scheme	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
	Inclusion of GHG assessment in annual report and road plans						🟩	🟩		
	Inclusion of climate change forecast data/scenario in road plans	🟨		🟩	🟨	🟩	🟩		🟩	
	Sustainability/LEED certification for buildings	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
	Sustainability rating evaluation tool	🟩		🟩					🟩	
	Life Cycle Assessment (LCA) tool	🟥		🟩	🟩	🟩	🟩			
	Standardized GHG accounting method	🟥		🟨	🟨	🟩	🟩	🟩		
	HOT / HOV Lanes (Including Policy Changes)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Toll Road	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Low emission zone	🟩		🟩	🟩	🟩	🟩	🟩		
	Congestion charging (pricing or tax)	🟥			🟩	🟩	🟩	🟩		
	Scheme to award GHG mitigation innovations	🟥	🟩	🟩	🟩					
	Guides for Assessing and Mitigating Greenhouse Gas Emission of Transportation Projects	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

	Academy program for sharing Knowledge and training	🟥		🟩	🟩					
Procurement procedure	Green Procurement Policy		🟩	🟩	🟩	🟩	🟩	🟩		
	Environmental appraisal of project based on GHG	🟥				🟩	🟩	🟩		
	Requirement for GHG and energy use accounting	🟥	🟩	🟨		🟩	🟩	🟩		
	Life Cycle Assessment requirement for projects	🟥				🟩	🟩			
	GHG in prequalification considerations for Contractor & CA	🟥				🟩	🟩			
	GHG as selection evaluation criteria - RFPs, DBs, CMGCs	🟥				🟩	🟩			
	Climate change experts on CA Team & Contractor Crew	🟥								
	CO_2 emissions certification scheme for contractors	🟥								
	Evaluation of GHGs at contract completion	🟥	🟩	🟨						
	Incentives for reduced deficiencies and/or warranty work	🟥								
	Alternative Contract Models (Option A cast-in-place, Option B Precast)	🟥								
	Performance Based Specifications & Testing	🟨	🟨	🟨				🟨	🟨	
Project development and design	Restrict project within the existing right of way							🟩		
	Green bridge design	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Timber bridge design	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
	Reduced deck slab depth for Bridge designs	🟥								

	Smart Highway Design	🟥			🟨	🟩				
	Design strategies for Longevity	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	
	Design with local and recycled materials	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
	Permeable pavement design	🟨		🟩	🟩	🟩	🟩	🟩	🟩	
	Modular pavement system	🟨		🟩	🟩	🟩	🟩	🟩	🟩	
	Bioretention & Stormwater Management	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Oversizing pipes/culverts to allow for future re-linings	🟥								
	Drainage design based on Predictive Rainfall	🟩					🟩			
	Turf and Root Reinforcement Mat technology	🟩		🟩			🟩			
	Accelerated Vehicle Collision Removal	🟩								
	Traffic management with Intelligent traffic systems (ITS)	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
	Plan Winter Construction Activities to offset summer operations	🟥								
	Innovative Highway Intersection design	🟥	🟩					🟩		
Design for Energy Generation	Solar Roads	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟨	🟩
	Solar highway barriers	🟥		🟩	🟩	🟩		🟩		
	Wind turbines along highways							🟨	🟨	🟨
	Piezo-technology in road construction	🟥	🟥	🟨						🟨
	Energy/Power transfer technology (pavement)- wireless charging	🟥	🟥	🟥	🟥	🟨	🟥	🟨	🟥	
	Energy/Power transfer technology (pavement)- wired charging	🟥	🟥	🟥	🟥	🟥	🟩			
	Energy/Heat transfer technologies (other structures)			🟩	🟩	🟩	🟩	🟩	🟩	
	Alternative and Recycled materials use	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Material Selection	Requirement to use high amount of recycled materials for road resurfacing (> 25%)	🟥		🟩				🟩		
	100 % materials recycling requirement	🟥		🟨	🟨	🟨		🟩		
	Reduce packaging for construction materials	🟥			🟩	🟩				
	Environmental Product Declaration (EPDS)	🟥				🟩	🟩	🟩		
Material Access and Haulage	Review of aggregate by-laws for virgin materials	🟥								
	Specify Material sources in design	🟥								
	Use of Rock within the Right of Way	🟩								
	Balanced Earth Excavation and fill embankments	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
	Minimizing Double Handling of Materials	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Incentives/Disincentives for haul-to-waste materials for reducing or reusing	🟥								
	Incentives for Locally Sourced Materials	🟥		🟩						
	Storage depots to be used by multiple jobs	🟥			🟩					
	Standardization and Stockpile of commonly used precast elements (Culverts)	🟥								

Colour code	
Currently in Use	🟩
Used Occasionally/Pilot Project	🟨
Not in Use	🟥
Unsure/NA	

Table A. 3 Alternative and recycled materials and technologies

Category	GHG Mitigation Measure	Ontario	Canada	USA	UK	Netherlands	Scandinavia	O/Europe	Australia	Others
Materials	RCA in pavement surface/structural layer							🟩		🟩
	Plastic roadways					🟨		🟨		
	Reusing Porous asphalt					🟩				
	Timber	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	RCA in base and sub-base	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Recycled glass	🟨	🟨							
	Bio-binders		🟩	🟩	🟩	🟩	🟩	🟩	🟩	
	Epoxy asphalt									
	RAP and RAS	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Crumb rubber	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Toner Recycling	🟥							🟩	
	Waste plastic bottles and bags	🟥	🟩							
	Innovative cement binders	🟩								
	Supplementary cementing materials	🟩								
	Pine resin of tall oil	🟥				🟩	🟩		🟩	
	Rapid Set Concrete (Bridges and road)	🟩								
	Smog Eating Concrete	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
	High modulus asphalt	🟥			🟩	🟩	🟩	🟩	🟩	
	Low energy asphalt	🟩								
	Zero brick									
	Warm mix asphalt	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
	Half-warm mixtures	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	

	Flash-Calcination technology	🟥								
	Retained soil system (RSS) walls	🟩								
	Mechanically stabilized earth (MSE)	🟩								
	400W to 500W Reinforcing Steel									
	Geo-polymer concrete			🟩	🟩	🟩	🟩	🟩		
	Bio-composite material			🟩				🟩		

Table A. 4 GHG mitigation strategies during Highway Infrastructure Construction

Category	**GHG Mitigation Measure**	**Ontario**	**Canada**	**USA**	**UK**	**Netherlands**	**Scandinavia**	**O/Europe**	**Australia**	**Others**
	Scrubbers and catalytic converters on construction equipment exhaust to include traditional small tools	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
	Electric / Hybrid - Vehicles & Equip	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
	Electric Vehicle Charging Stations	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
	Electric Ferries	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
	Alternative Fuels - hybrid diesel equipment	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	

Fuel Efficiency & Alternative Fuels	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
Anti-Idling Software & Mechanisms	🟥	🟨	🟩						
Using Local Electrical Grid to Minimize use of Generators	🟥	🟩	🟩						
Age Limits & Mechanical Fitness for vehicles and equipment	🟥			🟩	🟩	🟩	🟩		
Driver Behaviour programs	🟥	🟨	🟩						
Maintaining trucks and fleet		🟨							
Reduce aggregate stockpile moisture		🟨							
Improve dryer burner combustion efficiency		🟨							
Upgrade paving plant insulation		🟨							
Modernize dryers and restore worn flights		🟨							
More efficient hot-oil heater design		🟨							
Lower carbon fuels for dryer burners		🟨							
Slot dozing		🟨							
		🟨							

Table A. 5 GHG mitigation Measures during Highway Infrastructure Rehabilitation

Category	GHG Mitigation Measure	Ontario	Canada	USA	UK	Netherlands	Scandinavia	O/Europe	Australia	Others
Preservation techniques	Precast Concrete Pavement	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
	Rapid Bridge Replacement	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
	Removable urban pavement							🟩		
	Ultra-High Pressure water cutting	🟥			🟩					
	CIR and CIREAM	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	FDR	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	In-pace recyling WMA	🟩	🟩	🟩	🟩					
	Lime and cement stabilisation for capping	🟩	🟩	🟩	🟩					
	Saw cut and seal (concrete)	🟩			🟩					
	Crake and seal (HBM)	🟩			🟩					
	Cold recycled bitumen bound	🟩			🟩					
	Cold recycled cement bound	🟩			🟩					
					🟩					
Traffic and Congestion mitigation	Aggressive Closures (Full Closures)	🟥			🟩					

	Construction detours, staging and timing to reduce congestion	🟩		🟩						
	24/7 Construction	🟥								
	Payment adjustments for reducing construction times and congestion queues	🟥								
	Lane Rentals / Flexible Closures	🟨								
	Real Time Modelling - Adjusting based on Traffic Conditions	🟥	🟩	🟩	🟩	🟩	🟩	🟩		

Table A. 6 GHG mitigation Measures during Highway Maintenance

Category	**GHG Mitigation Measure**	**Ontario**	**Canada**	**USA**	**UK**	**Netherlands**	**Scandinavia**	**O/Europe**	**Australia**	**Others**
Energy savers	LED Lighting	🟩								
	LED Traffic Signals	🟩								
	Solar & Wind stations along highway	🟩								
	Solar Powered Cathodic Protection	🟩								
	Lighting optimization (dimming, trimming, switch-off)		🟨	🟨	🟨	🟩	🟩	🟩		
	Illuminating road paints			🟨	🟨	🟩	🟨	🟨		
	Solar pavement markings			🟩	🟩	🟩	🟩	🟩	🟩	

	Lighting removal				🟨	🟩	🟩	🟩		
	Part-night switch-off				🟨	🟨	🟨	🟨		
	Dimming				🟨	🟨	🟨	🟨		
	Trimming				🟨	🟨	🟨	🟨		
	Use Energy-saving lamps	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
	Use Less bright lamps	🟩				🟨	🟨	🟨		
	Lighting design optimization (road and tunnel)				🟨	🟨	🟨	🟨		
	Lighting all-out optimization				🟨	🟨	🟨	🟨		
	Use Retro-reflective sign lighting		🟩	🟩	🟩	🟩	🟩	🟩		
	Lighting switch off at tunnel threshold and exit zone				🟨	🟨	🟨	🟨		
	Optimize tunnel access zone luminance				🟨	🟨	🟨	🟨		
Congestion mitigation- queue prevention	Smart roadway technologies				🟩	🟩	🟩	🟩		
	Dynamic traffic management systems (real-time traffic and travel information)	🟥			🟩	🟩	🟩	🟩		
	Dynamic traffic management (variable message signs, lane control, shoulder use)	🟨			🟩	🟩	🟩	🟩		
	Dynamic congestion pricing/tolling	🟨			🟩			🟩		
	Freeway ramp Metering		🟨		🟩	🟩	🟩	🟩		

	ITS tools		🟨		🟩	🟩	🟩	🟩	🟩	
	Accelerated Vehicle Collision Removal		🟨							
	Solar or wind powered changeable message signs		🟨	🟩	🟩	🟩	🟩	🟩	🟩	
Roadside vegetation	Trees & Landscaping	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
	Use of native plants		🟩	🟩	🟩	🟩	🟩	🟩	🟩	

Survey and interview responses were used to identify the mix of strategies they have implemented and the mix of strategies still in the pilot stage. The list of adopted strategies is provided in Table A.7. The green shading indicates the strategies adopted in full-scale projects while the yellow shading indicates strategies still in the pilot/demonstration stage. The color coded strategies listed on Table A.7 reflect the differences in adoption stages amongst the agencies that responded to the online survey. For example, some strategies related to highway design such as Diverging Diamond Interchange (DDI) have been implemented in one jurisdiction, another jurisdiction is still in the pilot study stage of adopting this strategy.

Table A. 7 List of adopted strategies both full-scale projects and those in pilot stage

	Strategies	AT	MoIT	MI	NT	MoTS	MDOT	MTO
Highway Network and Project Design – Planning and Project	Air Quality Plan	🟨					🟩	Y
	Animal crossing corridors with greenery			🟨			🟨	Y
	Bio-retention and Storm-water management			🟩		🟩	🟩	Y
	Climate Change Experts on CA Team & Contractor Crew	🟨						N
	CO_2 emissions certification scheme for contractors	🟨				🟨		N
	Congestion charging (pricing or tax)	🟨						N
	De-icing Technologies (Bridges)						🟨	N

Diverging diamond interchange (DDI)	🟨		🟨		🟩	🟩	N
Drainage Based on Predictive Rainfall	🟩				🟩		Y
Environmental appraisal of project based on GHG							N
Environmental Product Declaration requirement	🟨						N
Environmental Protection Requirement for GHG	🟨					🟩	N
Fleet - Idle Limiters					🟩		N
GHG emission accounting/ carbon footprint tool	🟨						N
GHG emission consideration in Environmental Assessment (EA)					🟨	🟩	Y
GHG emission in Environmental Assessment (EA) Guideline	🟨		🟩			🟩	Y
GHG Selection Evaluation Criteria in RFPs, DBs, CMGCs	🟨						N
Green procurement policy	🟨		🟩				N
Green Procurement requirement in project procurement	🟨				🟨		N
High Occupancy Vehicle (HOT / HOV) Lanes	🟩	🟨				🟩	Y
Incentives for reduced deficiencies and/or warranty work	🟨					🟨	N
Inclusion of climate change forecast data/scenario in road plans	🟩				🟨		Y
Life cycle assessment (LCA) tool	🟨		🟨			🟩	N
Modular pavement systems (precast, removable and reusable)			🟨				Y
Performance Based Specifications & Testing	🟨				🟨	🟨	N
Pervious concrete pavement			🟨			🟨	Y
Porous asphalt pavement			🟨			🟨	Y
Prequalification considerations for Contractor & CA	🟨					🟩	N
Requirement for Greenhouse gas (GHG) and energy use accounting	🟨				🟨		N
Requirement for Life cycle assessment (LCA) in EIA for project	🟨		🟨			🟩	N

	Requirement to use locally sourced materials	🟨		🟩		🟩		N
	Requirement to use only recycled materials for road resurfacing		🟩				🟨	N
	Reserve strip between carriage way for future development	🟩		🟩			🟩	Y
	Restrict project within the existing right of way	🟩		🟩	🟨		🟩	Y
	Solar highway barriers					🟩		N
	Solar/Wind stand-alone hybrids for lighting or signage poles			🟩		🟩		N
	Solar-powered LED roadway lighting			🟩		🟩	🟨	N
	Specify Material sources in design			🟩				N
	Standardized GHG emission calculation methodology			🟨		🟨	🟩	N
	Sustainability Rating system/tool	🟨						Y
	Thin concrete pavement			🟨			🟨	N
	Timber bridge design			🟩				Y
	Turf Mat technologies			🟨				Y
	Wind turbines (structures and roadside)				🟨			N
Highway Infrastructure Design – Materials consideration	Allow over 40% recycled material in asphalt concrete mixture						🟩	N
	Allow over 40% recycled material in hydraulic concrete mixture						🟨	N
	Balanced Earth Excavation and fill embankments	🟩	🟩	🟩			🟩	Y
	Cold Mix Asphalt	🟩		🟩	🟩			Y
	Half-warm Mix Asphalt			🟩				Y
	High Modulus Asphalt			🟩				N
	Lightweight Concrete						🟨	Y
	Minimizing Double Handling of Materials	🟩		🟩	🟨		🟩	Y
	Rapid- set Concrete			🟩			🟨	Y

	Recycled concrete aggregate							Y
	Self-compacting Concrete		🟨	🟨				N
	Specify Material sources in design			🟩	🟩			N
	Storage depots to be used by multiple jobs			🟩		🟩		N
	Use alternative low - carbon materials		🟨	🟨				Y
	Use of general use limestone cement		🟨					Y
	Use of recycled materials, lowered RAP content levels			🟨				Y
	Use recycled materials	🟩	🟩	🟩	🟩	🟩		Y
	Use Rock within the right of way	🟩		🟩			🟩	Y
	Warm Mix Asphalt	🟩	🟩	🟩	🟩	🟩	🟨	Y
Highway Infrastructure Construction & Rehabilitation	Aerodynamic improvements Programs					🟨		N
	Aggressive Closures (Full Closures)	🟨					🟩	Y
	Cold In Place Recycling (CIR)	🟩						Y
	Construction detours, staging and timing to reduce congestion	🟨	🟩		🟨		🟩	Y
	Electric Ferries			🟩				Y
	Electric Vehicle Charging Stations			🟩	🟨			Y
	Evaluation of GHGs at contract completion	🟨						N
	Full Depth Reclamation (FDR)	🟩						Y
	Geo-synthetic Reinforcement in Pavement Systems	🟩	🟩		🟨			Y
	Geo-synthetic Separation in Pavement Systems	🟩	🟩		🟨			Y
	Hot In Place Recycling (HIR)	🟩	🟩					Y
	Incentives for Modernize Fleet and Equipment					🟩		N
	Low rolling resistance tires Programs					🟨		N
	Mechanical Stabilization of Subgrades and Bases				🟨		🟨	Y

	On-road vehicle fuel efficiency Programs					🟩		N
	Precast Pavement						🟩	Y
	Rapid Bridge Replacement						🟨	Y
	Storage depots to be used by multiple jobs					🟩		N
	Vehicle purchasing and right sizing policies			🟩	🟨	🟩		N
	24/7 Construction						🟩	N
	Payment adjustments for reducing construction times and congestion queues						🟩	N
	Lane Rentals / Flexible Closures						🟩	N
	Real Time Modelling - Adjusting based on Traffic Conditions						🟩	Y
Highway Maintenance &Operations	Communication of traffic patterns through variable message signs				🟨		🟩	Y
	Dynamic traffic management systems - variable speed limits						🟨	N
	High Tension Cable Barrier (HTCB)	🟩						N
	Increased communication on social media			🟩				Y
	Use of Intelligent transportation systems (ITS) technology	🟩					🟩	Y
	LED lighting and LED traffic signals	🟩	🟩	🟩		🟩	🟩	Y
	Lighting optimization (dimming, trimming, switch-off)						🟩	N
	Optimize tunnel access zone luminance						🟩	N
	Partnering with Google / Waze						🟩	N
	Renewable energy for lighting			🟩				N
	Use of Road Shoulder for traffic	🟨						N
	Toll Roads	🟨						Y
	Traffic calming – roundabouts	🟩						Y

	Use Retro-reflective sign lighting			🟩			🟩	Y

Note: AT =Alberta Transportation, MoIT = BC. Ministry of Infrastructure and Transportation, MI= Manitoba Infrastructure, NT= Northern Territories Transportation, MoTS = Ministry of Transportation Saskatchewan, MDOT = Michigan Department of Transportation, MTO = Ministry of Transportation Ontario; Y= Implemented, N = Not Implemented

Appendix C

Supplementary Data for Chapter 5

Table A. 8 LCA of PCIP compared to alternative practice

	Materials and Construction	Work zone	Total KgCO2 emissions
PCIP	474451	2679.2	477159
M&O	198743.9	1158.699	199903
FDR - GU	244,270	139043.9	383314
FDR- HRB1	179,331	62569.76	241901

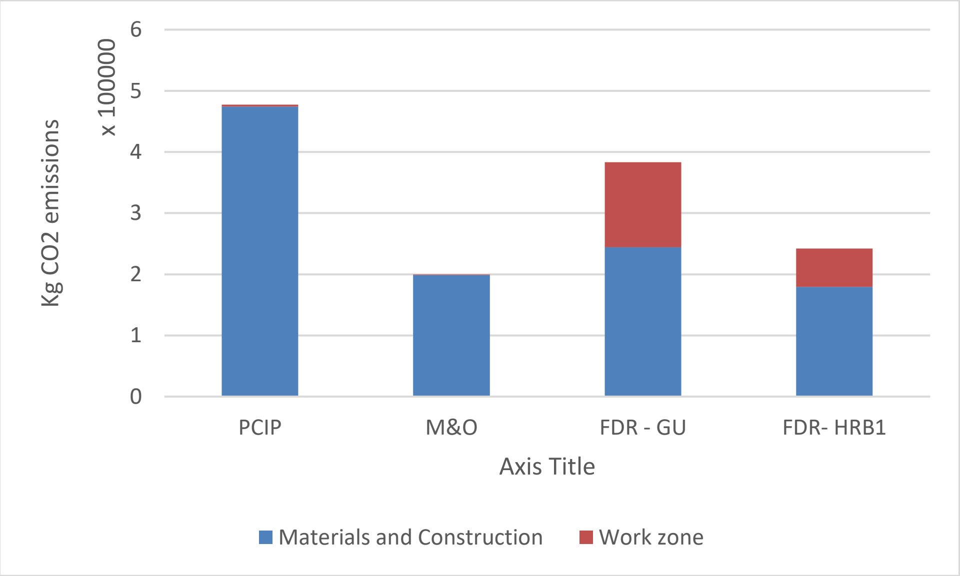


Figure A 1 Total CO2 emissions from Material, construction and work zone during pavement rehabilitation by PCIP, M&O, and FDR techniques

Appendix D

Supplementary Information for Chapter 7

Effect of pavement surface of fuel consumption and emissions

Table A. 9 Output Data on the MOVES rateperdistance table are based on the processes listed below

MOVES Output Table	Process ID and Process:
Rateperdistance when running	1: Running exhaust 9: Brakewear 10: Tirewear 11: Evap permeation 12: Evap fuel vapor venting 13: Evap fuel leaks 15: Crankcase running exhaust 18: Refueling displacement vapor loss 19: Refueling spillage loss

Table A. 10 MOVES default data for Coefficient A and C of select source types

Source Type ID	Source Types	beginModelYearID	endModelYearID	rollingTermA	rotatingTermB	dragTermC	sourceMass (metric tons)	fixedMassFactor (metric tons)
21	Passenger Car	1960	2050	0.156461	0.002002	0.000493	1.4788	1.4788
31	Passenger Trucks	1960	2050	0.22112	0.002838	0.000698	1.86686	1.86686

32	Light Commercial Truck	1960	2050	0.235008	0.003039	0.000748	2.05979	2.05979
52	Single Unit Short-haul Truck	1960	2013	0.627922	0	0.001603	8.53896	17.1
53	Single Unit Long-haul Truck	1960	2013	0.557262	0	0.001474	6.98448	17.1
61	Combination Short-haul Truck	1960	2013	1.53819	0	0.004031	22.9745	17.1
62	Combination Long-haul Truck	1960	2013	1.63041	0	0.004188	24.601	17.1

Table A. 11 Calibrated parameters from Chatti and Zaabar for select vehicle class in the HDM4 models

HDM-4 vehicle class	Number of Axles	CD	AF (m2)	CDAfront	NW	M(tons)	CR1	b11	b12	b13	Kcr2	FCLIM	p	CR2
Small/Medium	2	0.5	2.9	1.45	4	2.16	1	29.6	0.08	0.08	0.99	1	1.2	0.495
Four-wheel drive	2	0.5	2.9	3	4	2.5	1	29.6	0.08	0.08	0.99	1	1.2	0.5643
Light truck	2	0.6	5	3	4	4.5	1	29.6	0.08	0.08	0.99	1	1.2	0.5643

Medium truck	3	0.7	8.5	5.95	10	13	1.3	38.85	0.06	0.11	1.1	1	1.2	0.627
Heavy trucks	5	0.8	9	7.2	18	13.6	1.3	38.85	0.06	0.2	1.1	1	1.2	0.627

Table A. 12 Calculated values for Coefficient A with varying values for IRI and MTD

			A						
Group A Scenarios	IRI	MTD	21-Passenger Car	31-Passenger Trucks	32-Light Commercial Truck	52-Single Unit Short-haul Truck	53-Single Unit Long-haul Truck	61-Combination Short-haul Truck	62-Combination Long-haul Truck
A1	1	0.5	0.2	0.2	0.3	0.7	0.6	1.7	1.8
A2	2	0.5	0.2	0.3	0.3	0.7	0.7	1.8	1.9
A3	3	0.5	0.3	0.3	0.3	0.8	0.7	1.9	2.0
A4	4	0.5	0.3	0.3	0.3	0.8	0.7	2.0	2.1
A5	1	1	0.2	0.3	0.3	0.7	0.6	1.8	1.9
A6	2	1	0.2	0.3	0.3	0.8	0.7	1.9	2.0
A7	3	1	0.3	0.3	0.3	0.8	0.7	2.0	2.1
A8	4	1	0.3	0.3	0.3	0.8	0.8	2.1	2.2
A9	1	1.5	0.2	0.3	0.3	0.7	0.7	1.8	1.9
A10	2	1.5	0.2	0.3	0.3	0.8	0.7	1.9	2.0
A11	3	1.5	0.3	0.3	0.3	0.8	0.7	2.0	2.1
A12	4	1.5	0.3	0.3	0.3	0.9	0.8	2.1	2.3
A13	1	2	0.2	0.3	0.3	0.8	0.7	1.9	2.0
A14	2	2	0.2	0.3	0.3	0.8	0.7	2.0	2.1
A15	3	2	0.3	0.3	0.3	0.8	0.8	2.1	2.2
A16	4	2	0.3	0.3	0.3	0.9	0.8	2.2	2.3

Table A. 13 Calculated values for Coefficient C with varying values for IRI and MTD

Group A Scenarios	IRI	MTD	C						
			21-Passenger Car	31-Passenger Trucks	32-Light Commercial Truck	52-Single Unit Short-haul Truck	53-Single Unit Long-haul Truck	61-Combination Short-haul Truck	62-Combination Long-haul Truck
A1	1	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A2	2	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A3	3	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A4	4	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A5	1	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A6	2	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A7	3	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A8	4	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A9	1	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A10	2	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A11	3	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A12	4	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A13	1	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A14	2	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A15	3	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A16	4	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0

The excel work below contains all the output from MOVES simulation in Chapter 8 and all data analysis shown in the results section of Chapter 7

Microsoft Excel
Worksheet

Results

Data Visualization

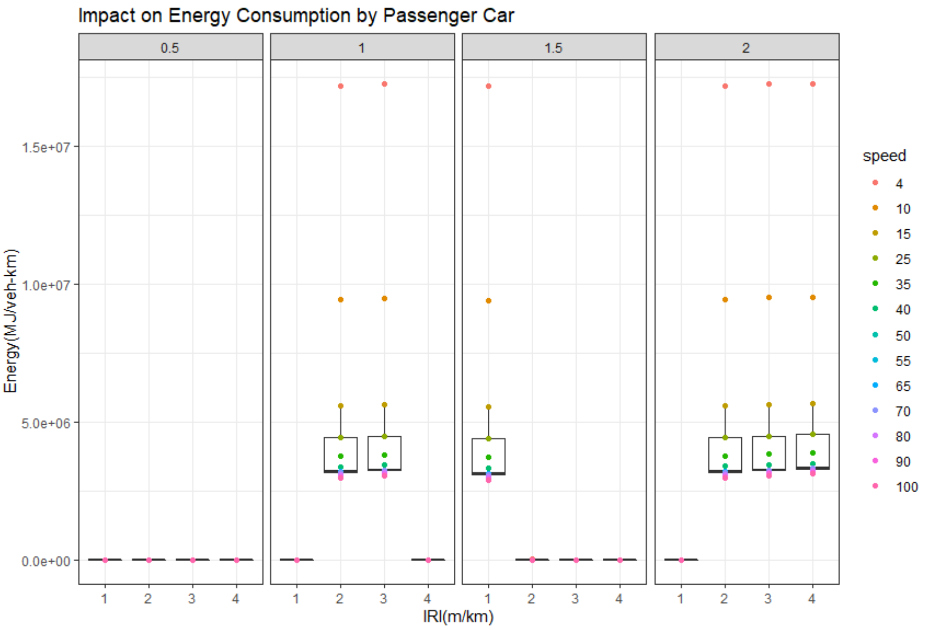


Figure A 2 Urban freeway (ID4)

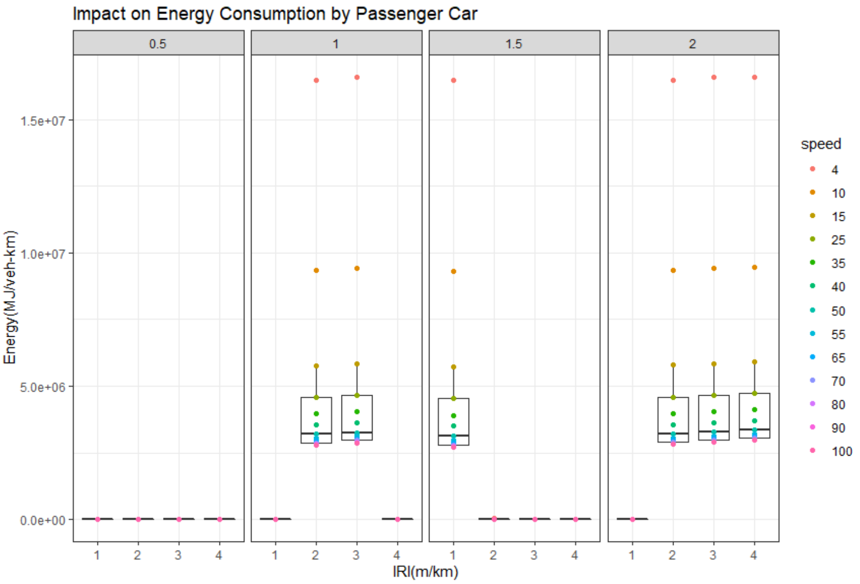


Figure A 3 Urban Arterial Road (ID5)

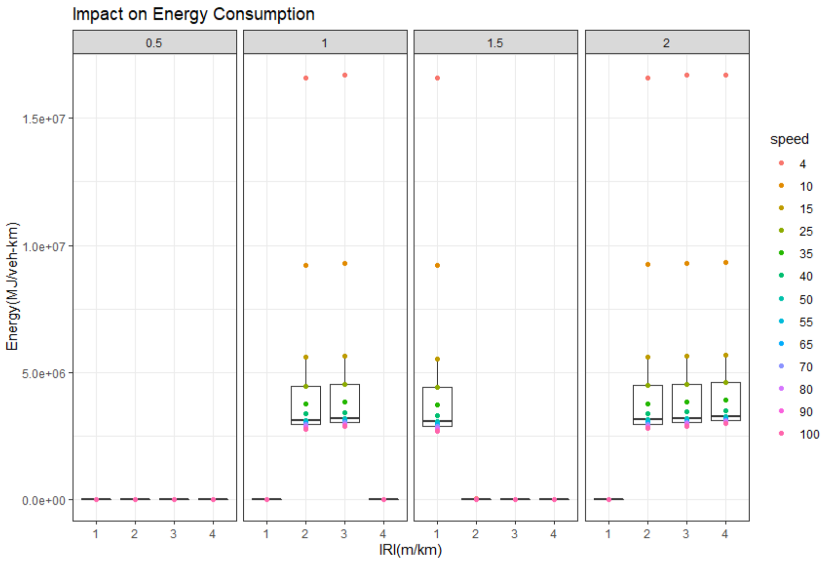


Figure A 4 Rural Freeway (ID2)

<u>Efforts to fit regression models</u>

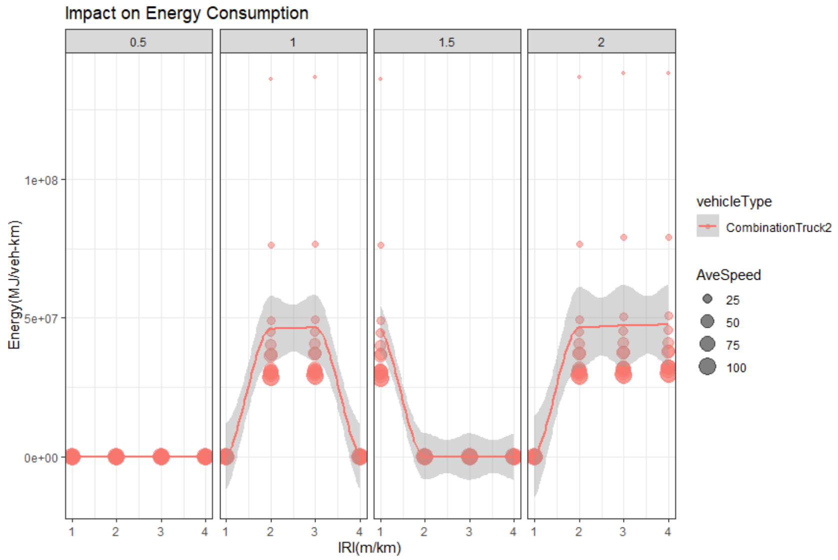


Figure A 5 Rural Arterial Road (ID3)

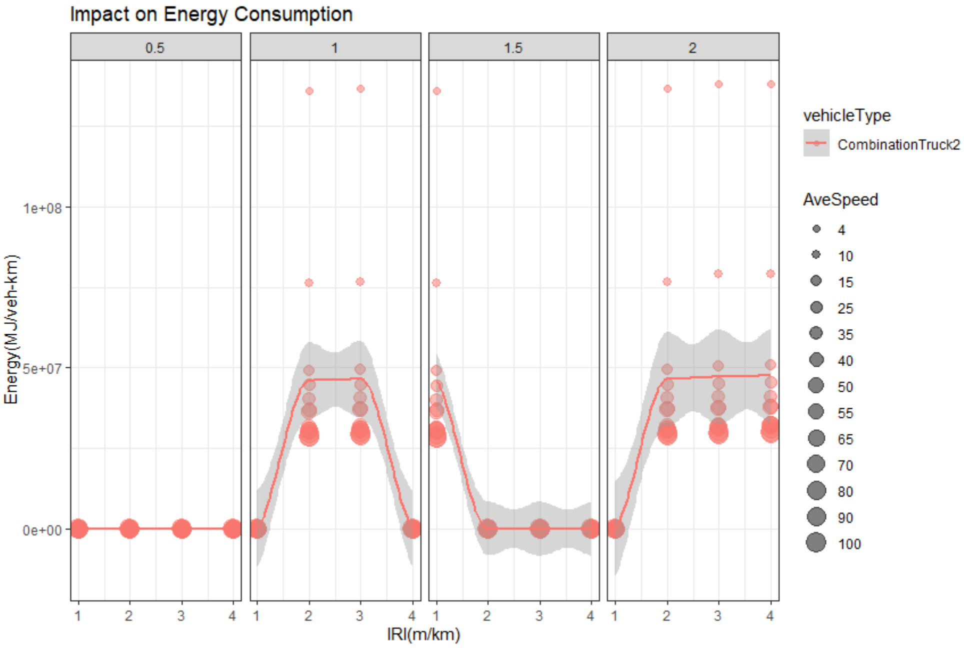


Figure A 6 Rural Arterial Road (ID3)

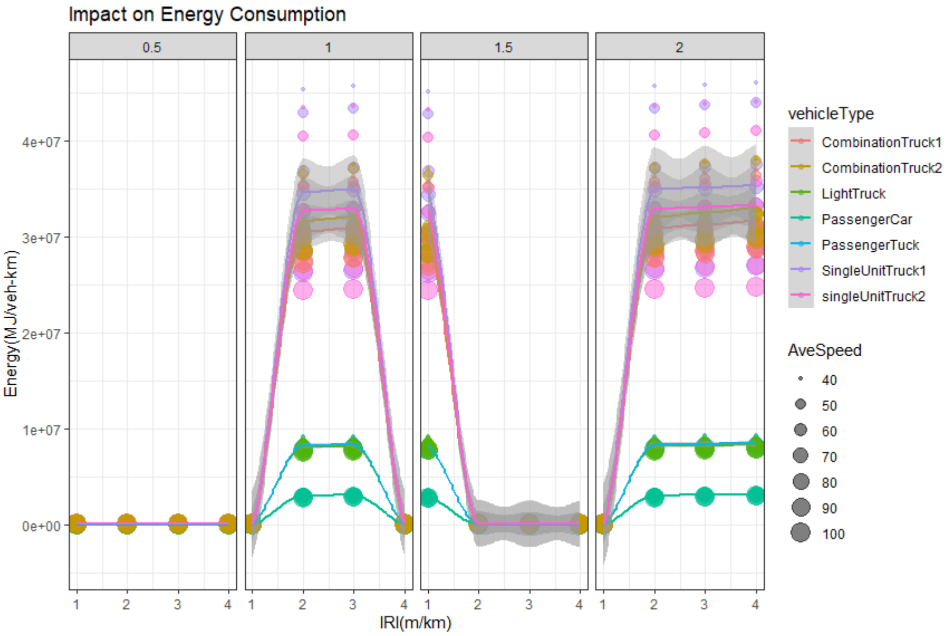


Figure A 7 Rural Arterial Road (ID3)

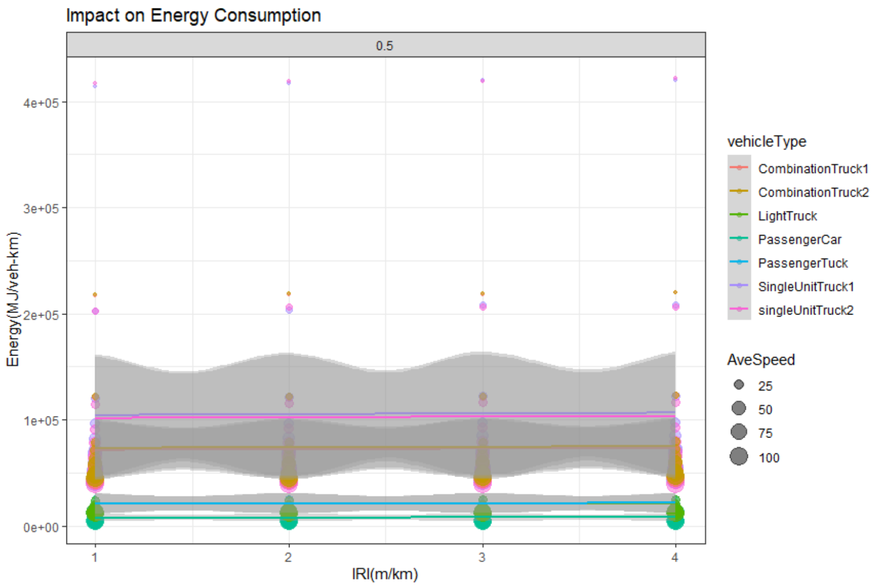


Figure A 8 Fitting the line for equation Eq.21 for energy-IRI prediction, for 0.5 MTD and various speed, for all vehicle types

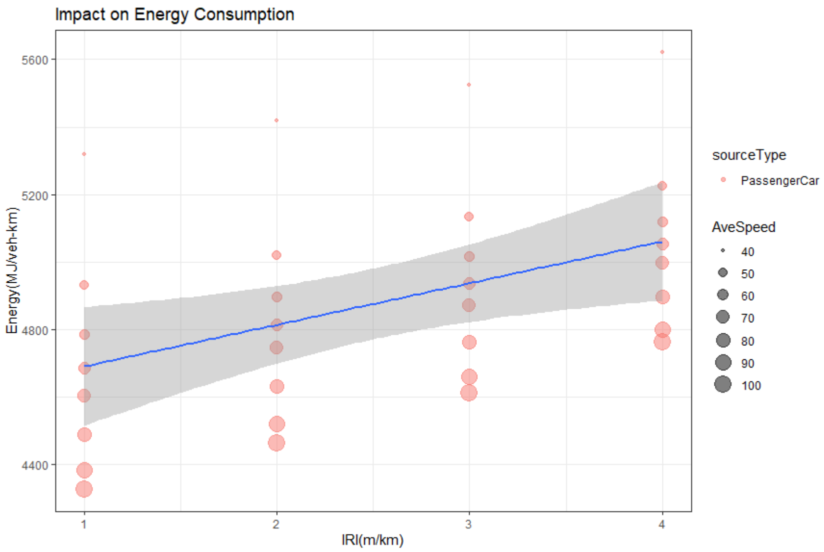


Figure A 9 Fitting the line for equation Eq.21 for energy-IRI prediction, for 0.5 MTD and various speed, for Passenger Car.

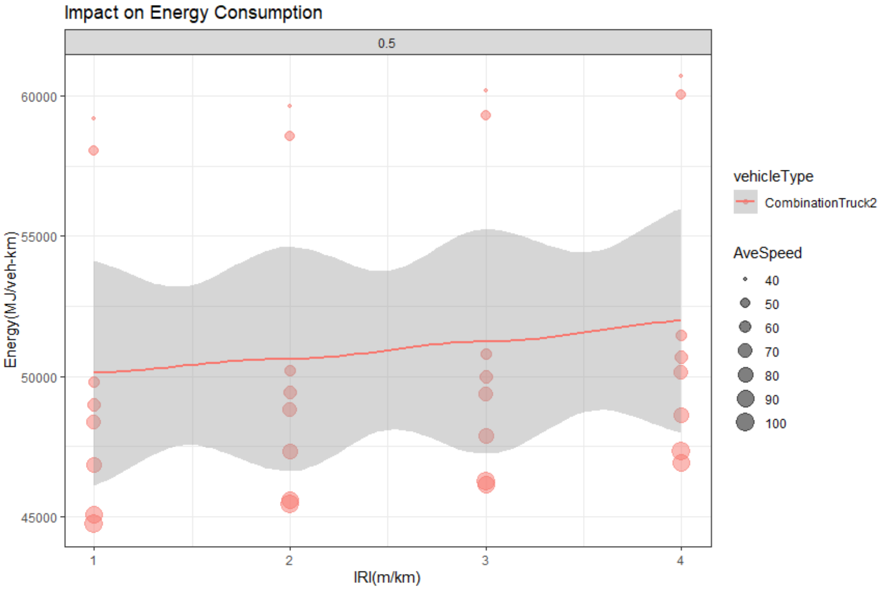


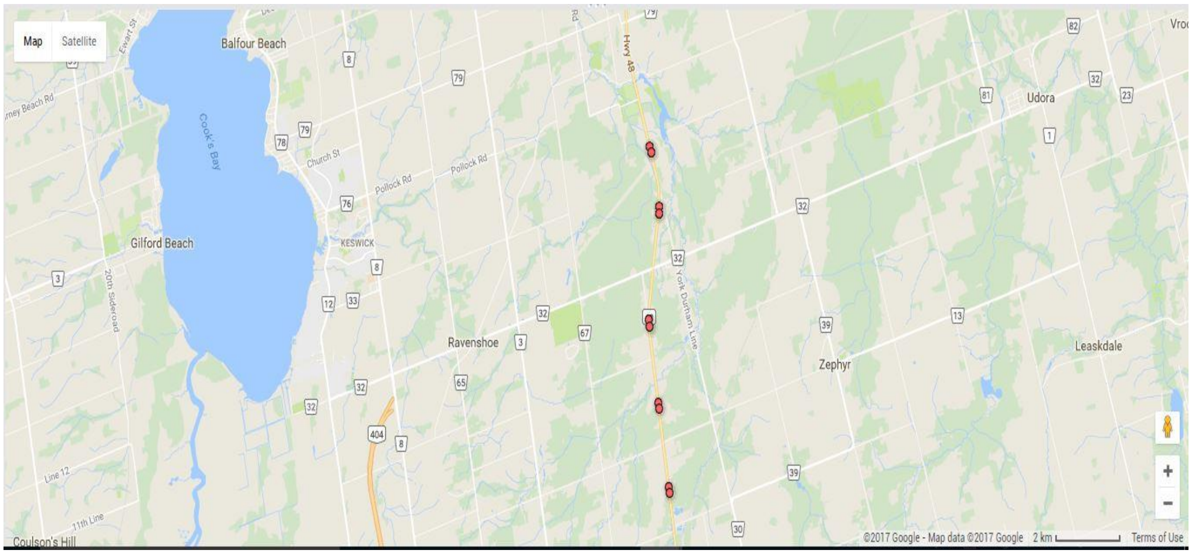
Figure A 10 Fitting the line for equation Eq.21 for energy-IRI prediction, for 0.5 MTD and various speed, for Passenger Car.

Appendix E

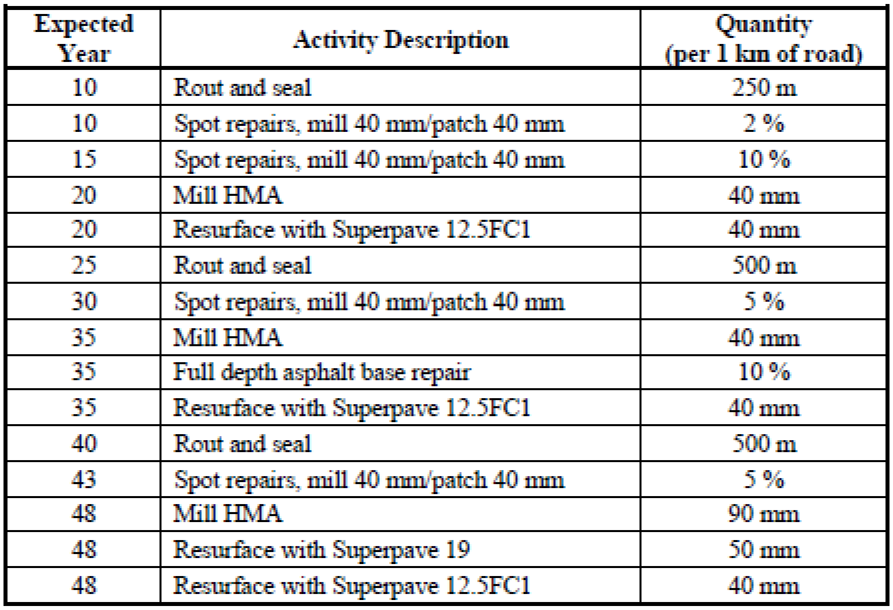
Supplementary Information for Chapter 8

Sustainable Pavement Management

Locations of the 10 test sections on Highway 48 (Google Map, 2020)



Typical Flexible Minor Arterial Pavement Preservation Plan (AADTT 1,000-1,500) adopted in Scenario 2 of the network analysis (source ARA (2011) (ARA 2011)**)**



Expected Year	Activity Description	Quantity (per 1 km of road)
10	Rout and seal	250 m
10	Spot repairs, mill 40 mm/patch 40 mm	2 %
15	Spot repairs, mill 40 mm/patch 40 mm	10 %
20	Mill HMA	40 mm
20	Resurface with Superpave 12.5FC1	40 mm
25	Rout and seal	500 m
30	Spot repairs, mill 40 mm/patch 40 mm	5 %
35	Mill HMA	40 mm
35	Full depth asphalt base repair	10 %
35	Resurface with Superpave 12.5FC1	40 mm
40	Rout and seal	500 m
43	Spot repairs, mill 40 mm/patch 40 mm	5 %
48	Mill HMA	90 mm
48	Resurface with Superpave 19	50 mm
48	Resurface with Superpave 12.5FC1	40 mm

Economic evaluation – Data and calculations

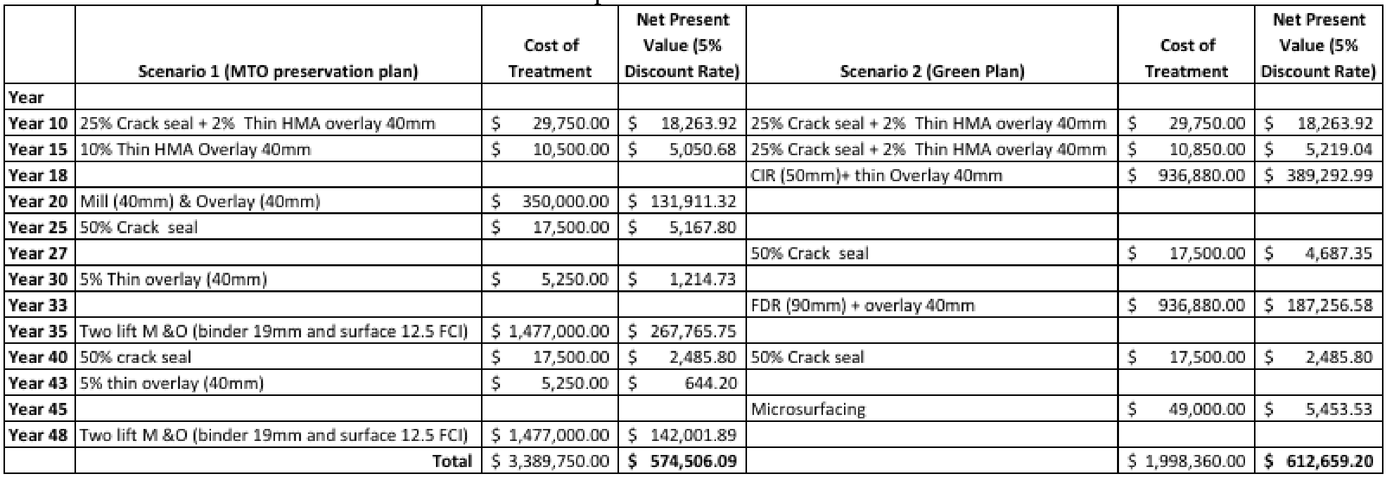
Road section data

Road Section	
Length (m)	1000
Width (m) (two lane)	7
Total Area (m2)	7000

Unit cost for treatment

Treatment	Unit Cost per quantity
Crack Seal	$5.00
Thin HMA Overlay (40mm)	$15.00
Mill (40mm)	$35.00
Binder (19mm)	$96.00
Surface (12.5 FCI)	$115.00
CIR (50mm)	$118.84
FDR (90mm)	$118.84
Micro-surfacing	$7.00

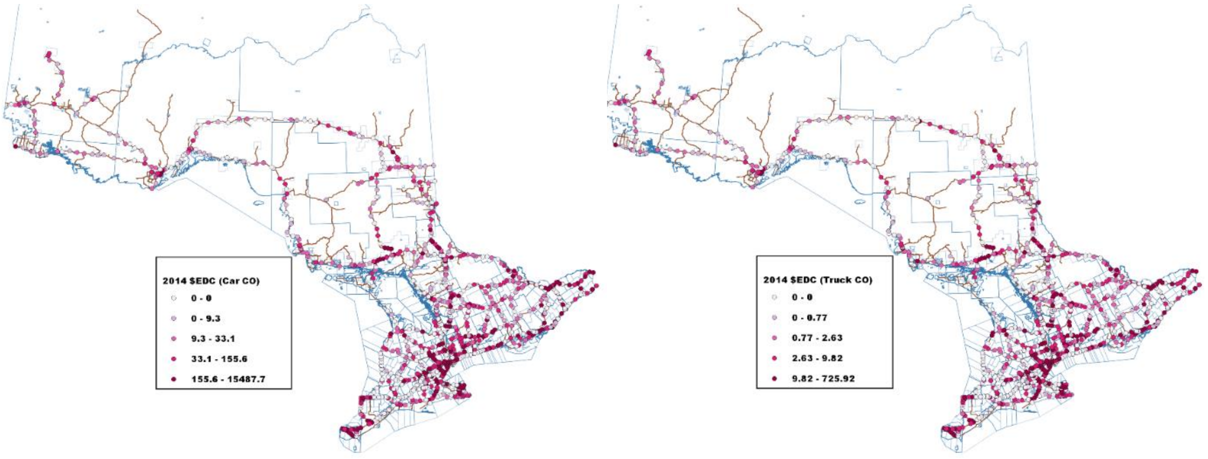
Net Present value calculation for the maintenance plans



	Scenario 1 (MTO preservation plan)	Cost of Treatment	Net Present Value (5% Discount Rate)	Scenario 2 (Green Plan)	Cost of Treatment	Net Present Value (5% Discount Rate)
Year						
Year 10	25% Crack seal + 2% Thin HMA overlay 40mm	$ 29,750.00	$ 18,263.92	25% Crack seal + 2% Thin HMA overlay 40mm	$ 29,750.00	$ 18,263.92
Year 15	10% Thin HMA Overlay 40mm	$ 10,500.00	$ 5,050.68	25% Crack seal + 2% Thin HMA overlay 40mm	$ 10,850.00	$ 5,219.04
Year 18				CIR (50mm)+ thin Overlay 40mm	$ 936,880.00	$ 389,292.99
Year 20	Mill (40mm) & Overlay (40mm)	$ 350,000.00	$ 131,911.32			
Year 25	50% Crack seal	$ 17,500.00	$ 5,167.80			
Year 27				50% Crack seal	$ 17,500.00	$ 4,687.35
Year 30	5% Thin overlay (40mm)	$ 5,250.00	$ 1,214.73			
Year 33				FDR (90mm) + overlay 40mm	$ 936,880.00	$ 187,256.58
Year 35	Two lift M &O (binder 19mm and surface 12.5 FCI)	$ 1,477,000.00	$ 267,765.75			
Year 40	50% crack seal	$ 17,500.00	$ 2,485.80	50% Crack seal	$ 17,500.00	$ 2,485.80
Year 43	5% thin overlay (40mm)	$ 5,250.00	$ 644.20			
Year 45				Microsurfacing	$ 49,000.00	$ 5,453.53
Year 48	Two lift M &O (binder 19mm and surface 12.5 FCI)	$ 1,477,000.00	$ 142,001.89			
	Total	$ 3,389,750.00	**$ 574,506.09**		$ 1,998,360.00	**$ 612,659.20**

AHP Pairwise comparison table for the maintenance treatment strategies

	AA	AB	AC	AD	BA	BB	BC	BD	CA	CB	CC	CD	DA	DB	DC	DD
Agency Cost ($)	1	0.333	0.2	5	3	1	0.2	5	5	5	1	5	0.2	0.2	0.2	1
Technical Aspects (RCI/IRI)	1	0.333	1	0.333	3	1	3	3	1	0.333	1	0.333	3	0.333	3	1
Virgin Material Consumed	1	5	3	5	0.2	1	0.333	5	0.333	3	1	5	0.2	0.2	0.2	1
Environmental Impact ($)	1	5	3	5	0.2	1	0.333	3	0.333	3	1	5	0.2	0.333	0.2	1



Excess environment damage cost associated with vehicle emission of CO from vehicle traveling on Ontario Roads with condition IRI >1m/km.