Quantifying Greenhouse Gas Mitigation Measures during Provincial Highway Design, Construction, and Maintenance Activities

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.

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Statement of Contributions

This research was conducted at the University of Waterloo by Qingyan Min under the supervision of Dr. Rebecca Saari. This thesis forms part of the project report under the Ministry of Ontario (MTO) 2018 Highway Infrastructure Innovation Funding Project (HIIFP). Specifically, Chapter 2 and a small portion of Chapter 3 of this thesis are previously presented in the first and second interim progress report of HIIFP Project #2018-01. Dr. Rebecca Saari and Dr. Ushnik Mukherjee provided guidance during each steps of the research, and also gave feedback and edited the project reports and this thesis.

Abstract

In response to the increasing need to address global climate change, departments of transportation have adopted and promoted diverse mitigation measures to reduce source and enhance sinks of the greenhouse gas (GHG) emissions associated with highway management. Quantitative evaluations of the applicable mitigation measures from infrastructure design, construction, operation, and rehabilitation, however, are often lacking. Quantification efforts assist the agency in understanding the magnitudes of the overall GHG reductions and the effectiveness of each mitigation measure.

This study proposes and develops a framework to track the current and emerging mitigation activities by the Ministry of Transportation in Ontario (MTO). Mitigation measures related to materials, transportation, lights, trees, and traffic were selected based on data availability, popularity of the mitigation measure, ease of quantification, the extent to which GHG emissions can be reduced by the practice, and potential for future adoption. The framework incorporates the records from MTO's Highway Costing System (HiCo) and builds on Ontario based emission factors and default activity values. Life-cycle GHG emissions and multi-year emissions impact are considered where applicable.

A standardized GHG mitigation tracking template, Province of Ontario Emission Tracker for Transportation (POETT) was designed based on the framework, and a case study was performed with 2017 HiCo data. The tool estimates that approximately 60 kilotonnes of GHG emissions were avoided in 2017 by MTO's mitigation activities. Overall, material recycling and other material substitution dominated the reductions by avoiding the production of new materials. The dominance of this measure reflects MTO's significant use of materials. The reduction value for each mitigation measure ranges from 1.04 tonnes carbon dioxide equivalent (CO_2e) from using LED high mast lights to 13,572 tonnes CO_2e from applying full-depth reclamation in place of traditional Mill & Overlay practice. Unit GHG emission reductions (e.g., kg/m^2 GHG reduced by in-place recycling) and the percentage reduction of the mitigation measures were also calculated. Within uncertainty, the results compared well with values obtained from emission quantification tools and literature. Compared to California Department of Transportation's mitigation of 161 kilotonnes CO_2e in 2013, these results suggest that MTO is making meaningful reductions of emissions in its purview. Given limits on data availability, this estimate is considered a lower bound. In the future, additional data collection efforts (including quantities of supplementary cementing materials and detailed traffic data) could be used to further validate and enhance MTO's capability in tracking GHG mitigation using POETT.

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List of Abbreviations

Tools	
asPECT	Asphalt Pavement Embodied Carbon Tool
CMEM	Comprehensive Modal Emission Model
CTCC	CUFR Tree Carbon Calculator
EIO-LCA	Economic Input-Output Life Cycle Assessment
GASCAP	Greenhouse Gas Assessment Spreadsheet for Capital Projects
GreenDOT	The Greenhouse Gas Calculator for State DOTs
GREET	Greenhouse Gases, Regulated Emissions, and Energy use in Transportation
MOVES	Motor Vehicle Emission Simulator
PaLATE	Pavement Life-cycle Assessment Tool for Environmental and Economic Effects
PE2	Project Emission Estimator
POETT	Province of Ontario Emissions from Transportation Tracker
ROADEO	ROADs Emissions Optimisation
Agencies, Programs, Organizations, and Regulations	
ADB	Asian Development Bank
Caltrans	California Department of Transportation
CAPCOA	California Air Pollution Control Officers Association
CMAQ	Congestion Mitigation and Air Quality Improvement
CPATT	Centre for Pavement and Transportation Technology
CUFR	Center for Urban Forest Research
FHWA	Federal Highway Administration
HiCo	Highway Costing System
IPCC	Intergovernmental Panel on Climate Change
MTO	Ontario Ministry of Transportation
NIR	National Inventory Report
NSSP	Non-Standard Special Provisions
OPSS	Ontario Provincial Standards

OTM	Ontario Traffic Manual
UNFCC	United Nations Framework Convention on Climate Change
Materials	
CIR	Cold In-Place Recycling
CIREAM	Cold In-Place Recycling with Expanded Asphalt
FDR	Full Depth Reclamation
FDR with EAS	Full Depth Reclamation with Expanded Asphalt Stabilization
HIR	Hot In-Place Recycling
HMA	Hot Mix Asphalt
NSSP	Non Standard Special Provision
RAP	Reclaimed Asphalt Pavement
RCM	Recycled Concrete Material
SCM	Supplementary Cementing Material
WMA	Warm Mix Asphalt
Transportation	
CNG	Compressed Natural Gas
EV	Electric Vehicles
FC	Fuel Cell
HDV	Heavy-Duty Vehicles
HEV	Hybrid Electric Vehicle
HHV	Hydraulic Hybrid Vehicle
ICEV	Internal Combustion Engine
LDV	Light-Duty Vehicles
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LS	Low Sulfur Diesel
PHEV	Plug-in Hybrid Electric Vehicle
RFG	Reformulated Gasoline
RNG	Renewable Natural Gas
VMT	Vehicle Miles Travelled
VKT	Vehicle Kilometers Travelled

Lights

HID	High-intensity Discharge Lamp
HPS	High Pressure Sodium Light
LED	Light-emitting Diode
MH	Metal Halide
MV	Mercury Vapor Lights
PSMH	Pulse Start Metal Halide
SV	Sodium Vapor Lamp

Trees

DBH	Diameter at Breast Height

Traffic

AADT	Annual Average Daily Traffic
AC	Asphalt Concrete
CO	Concrete
DIR	Direction
IRI	International Roughness Index
MPD	Mean Profile Depth

Chapter 1: Introduction

Transportation is the second largest source of greenhouse gases (GHGs) in Canada, contributing to 28% of carbon dioxide (CO_2) equivalent (CO_2eq or CO_2e) emissions (Environment and Climate Change Canada, 2017). Activities involving highway infrastructure development and the ensuing highway traffic congestion have a large impact on the climate system, mostly due to the production and processing of non-renewable materials for the pavement and the on-road vehicle emissions resulting from its use.

With the growing attention to climate change mitigation, transportation agencies have started to integrate greenhouse gas assessments into the transportation planning and contract selection process. This initiative enables implementing mitigation measures to reduce an agencies' carbon footprint. Among GHG mitigation measures, an agency has the most control over highway design, construction, and maintenance. Options to mitigate those emissions are myriad and rapidly expanding, and have been proposed, studied, or adopted across a variety of highway management jurisdictions, including Ontario. Current mitigation practices range from in-place pavement material recycling to tree planting and construction congestion mitigation (*Climate Change Strategy*, 2015).

Given the key role of transportation service providers in controlling activities contributing to GHG emissions and mitigation, they need the ability to track and assess these activities. Reporting requirements for GHGs are often the responsibility of national or subnational departments of environment. However, departments of transportation too have a role in tracking GHG emissions and mitigation, given their access to data and jurisdiction over highway infrastructure and use. To play this role, departments of transportation require tools and techniques that quantify their effects on emissions. In addition to reporting, tracking department-wide emissions or emission reductions assist in evaluating alternative mitigation measures and assessing the extent of emissions savings mitigation activities can achieve. This allows for more informed, effective, and sustainable decisions.

For over a decade, the Ministry of Transportation Ontario (MTO) has been committed to improving the sustainability of activities in its purview, including seeking to mitigate the atmospheric emissions of GHG that contribute to climate change (Ministry of Transportation, 2012). However, accurate and comprehensive tracking of these GHG mitigation efforts remains a challenge. The variety of activities, mitigation methods, tracking tools, and the emergence of new technologies and techniques complicate efforts to develop an internal process that is simple, yet accurate, transparent, relevant, comprehensive, and adaptable.

1.1 GHG Emission Sources and Mitigation Measures

GHGs in the atmosphere trap heat and lead to a warmer planet. GHGs including Carbon Dioxide (CO_2), Methane (CH_4), and Nitrous Oxides (N_2O) are generated primarily through the burning of fossil fuels for electricity, heat, manufacturing, and transportation, with CO_2 emissions being the most prevalent. Based on current technology and practices associated with highway infrastructure related activities, GHGs are generated from activities including design (choices about what to build), construction (how it is built), use, operations (ongoing activities required to enable use, e.g. lighting, trees), and maintenance (activities that provide and maintain serviceable roadways) throughout the lifetime of the highway infrastructure(Nasir, 2018; Yu & Lu, 2012). Most of the phases associated with the highway life cycle generate a large amount of GHGs, including the production of materials, vehicle activities that burn conventional fossil fuels, or lighting powered by electricity.

As opposed to emissions from highway use, transportation agencies and ministries have the most potential to control GHG emissions from infrastructure design, construction, operations, maintenance and rehabilitation. Despite the relative importance of construction, operation, maintenance, and rehabilitation activities, their individual contribution to emissions may vary with the transportation ministry's activities. For example, an analysis of 17 construction and rehabilitation projects by the British Columbia (B.C.) Ministry of Transportation and Infrastructure found a roughly equal contribution of GHG emissions from construction (160 kilotonnes), maintenance (100 kilotonnes), and rehabilitation (110 kilotonnes) activities for their 2010 activities. (British Columbia Ministry of Transportation and Infrastructure, 2011).

The MTO has made consistent efforts to mitigate climate impacts from highway related activities. GreenPave (S. Chan et al., 2013) is a well-known pavement sustainability rating system in Ontario that promotes pavement-related sustainability technology and processes, and assists in the selection of sustainable pavement designs and construction alternatives. In GreenPave, projects which achieve reductions in GHG emissions and energy consumption can each gain 3 points, and projects can gain 5 points by using recycled content. The MTO has also set "optimizing infrastructure design, capacity, and investment" as one of the strategic goals in the agency's sustainability implementation plan (Ministry of Transportation, n.d.). Some of the commitments related to the goal include generating renewable energy on MTO project sites, and considering sustainability when making policy and contract decisions. For provincial transportation projects, the MTO has an environmental guideline for assessing and mitigating the greenhouse gas emissions from on-road transportation (Ministry of Transportation, 2012). The guideline assists in the evaluation of GHG emissions from alternative technologies and methods used in transportation planning projects.

The MTO has considered and adopted a variety of mitigation measures in their projects. Among all options, material-related measures, such as recycled materials and HMA alternatives, are most often implemented because of their technical feasibility, cost effectiveness, and relatively short schedule for implementation. For concrete, a GHG reduction initiative has been included in OPSS PROV 1350 (Ready Mixed Concrete Association of Ontario, 2018). The provision requires a minimum of 10% GHG reduction, which can be achieved by the use of various Supplementary Cementing Materials (SCMs) and limestone filler (Van Dam et al., 2015). Several MTO activities reduce GHG emissions from on-road sources, even though they are often not considered as directly under an agency's purview. Congestion mitigation activities are commonly implemented because they reduce travel times, but can also potentially reduce GHG emissions(Figliozzi, 2011), particularly when referring to project work zones (as opposed to major projects designed to alleviate congestion, like highway expansion, which may induce additional travel demand and increase GHGs)(Handy & Boarnet, 2014). A transportation agency's efforts in promoting and funding congestion mitigation measures such as expedited construction, aggressive closure, and rapid road/bridge replacement during construction and maintenance phases can effectively reduce excess GHGs emitted from additional idling or operating vehicles at extremely low speeds (Barth & Boriboonsomsin, 2008). Similarly, improving pavement smoothness and building roundabouts instead of signal-controlled intersections both directly or indirectly reduce the GHG emissions from private and commercial vehicles that use the roads.

The MTO's tenders often also include items such as trees and LED lighting. The carbon sequestered by trees and electricity saved by the LED lights and signals can potentially lead to large GHG emission savings. Further, the placement of trees and LED lights could have long-lasting reductions depending on the items' lifetime.

Some activities that affect GHG emissions are not mitigation measures, but serve as administrative or decision support tools and instruments. The concrete NSSP (Non-Standard Special Provisions), for example, sets a concrete GHG reduction goal. Compliance with this goal can be included in a tracking template. Other administrative or policy options cannot be included for various reasons. For example, the decision to use tracking tools or LCAs in planning or design can help in identifying opportunities for mitigation but present a challenge in attributing actual reductions to this administrative approach, and doing so may lead to double-counting.

1.2 Need and Constraints for GHG Mitigation Tracking by Subnational Transportation Authorities

Global progress on addressing climate change has contributed to new knowledge and tools that help track mitigation of GHG emissions from highway management. Reporting guidelines have emerged to support policies established from global agreements (e.g., associated with the United Nations Framework Convention on Climate Change (UNFCC)) and provincial regulations (e.g., O. Reg. 390/18). Methods to report emissions have been formalized in a variety of emissions tracking tools. Several of these have focused specifically on highway management, such as GreenDOT (Gallivan et al., 2010) and PaLATE (Horvath, 2007). However, there remains no consistent process for tracking GHG mitigation efforts from highway design, construction, and maintenance (Grant et al., 2013).

While many jurisdictions have implemented measures that reduce life-cycle greenhouse gas emissions in transportation projects, only a few track agency-wide total emissions or reductions. Among the jurisdictions that do this tracking, the scope, method, level of detail and process vary. For example, Highway England (Highways England, 2015) collects its emission information by asking contractors to input material consumption and distance travelled into an Excel template and submit this on a quarterly or monthly basis. Asian Development Bank (2010) estimates the carbon footprint for road projects in India through calculating an overall (including on-road vehicle operations) emission per kilometer for four road types which is then extrapolated for the nation. California Department of Transportation (California Air Pollution Control Officers Association, 2010) quantifies emission reductions from mitigation strategies wherever sufficient data is available. Their analysis includes mitigation strategies such as cold in-place recycling, employee commuting alternatives, roadway lighting, etc.

For subnational authorities, such as the MTO, to track GHG mitigation efforts, several requirements and constraints emerge. Such a tracking template should be as comprehensive and as flexible as possible, given the broad and changing nature of their activities, and be able to utilize the available data and resources in their data repository. The process should be accurate, transparent, efficient, relevant, comprehensive, and adaptable. The process must be transparent and efficient to match resource availability and turnover. It must be relevant to reporting needs and relevant standards for GHG estimation across roadway design, construction, and maintenance. In addition to this, the process must be comprehensive in tracking emissions across a variety of highway related activities, and flexible enough to adapt to new and emerging technologies and practices.

1.3 Objectives

The goals of this study include: (1) review current literature and practice in tracking roadway-related GHG emissions and emission reductions achieved by the MTO, academia, and other jurisdictions (2) assess and evaluating the methods and data for quantifying GHG emissions and emission reductions in provincial highway-related practices (3) develop a standardized template, the Province of Ontario Emissions from Transportation Tracker (POETT), that is customized for Ontario to better track emissions associated with highway activities, sources, types of GHG emissions, life-cycle emission reductions, and annual reductions (4) evaluate the potential range and effectiveness of emission reductions from mitigation activities.

The developed tool, POETT, is described in Chapter 3. Its main function is to capture various existing and future GHG mitigation methods and to quantify the emission reductions achievable accurately. Alternatives for specific key functions are identified, including: (1) various estimation techniques and tools to review, (2) the scope of mitigation measures to include, and (3) possible improvements to existing tools. The goals of the tool are to (1) capture the Ministry's current activities to reduce GHG emissions, (2) assist the Ministry in understanding the extent of impact each mitigation activity can have and (3) evaluate the impact of potential new activities and changes. The GHG tracking template aims to balance accuracy, comprehensiveness, relevance, flexibility, transparency and efficiency.

Requirements of the tool specify, among other things, key functions, constraints, and performance. They are developed based on best practices in the literature (including data and literature provided by MTO), existing tools (including MTO's calculators), lessons from other jurisdictions (via HIIFP-2018 Topic 2 Greenhouse Gas Mitigation in Highway Design, Construction and Maintenance - Jurisdictional Scan), regulations and guidelines, and, most importantly, the requirements and resource-constraints of the MTO, which varied over the course of the project.

The tool is designed for the MTO's climate change personnel to quantify and report annual GHG emissions and emission reductions within the Ministry. To customize the tool for the MTO's needs, the study looks at Ontario specific data including HiCo data and examples of MTO projects that are used to identify the typical material, design, duration, and equipment choice, so that GHG emissions and mitigations can be estimated through material use quantities. The tool also allows user input including alternative equipment, fuel, and designs that override default values to provide a more accurate accounting when adequate data are available.

1.4 Thesis Organization

The remainder of this thesis is organized into five Chapters. Chapter 2 provides a literature review. The literature review begins with identifying and presenting the tools that are relevant to quantifying GHG reductions in the transportation sector. Following this, the literature review assesses the scope, the level of detail, and establishes baseline emissions gathered from other tools, journal articles, and reports. A short introduction of each mitigation category is also presented.

Chapter 3 presents the development of the POETT. The chapter covers the selection process of mitigation activities that were included, the development of the annual emission quantification method, the data collection process, and detailed methods and equations used for the quantification for each mitigation activity.

Chapter 4 presents the results and discussion. It focuses on GHG reductions associated with each mitigation activity and the annual emission reductions achieved by the MTO in 2017 based on the available data on active projects. For each mitigation measure, the unit GHG emission reductions (e.g., kg $CO2_e$/tonne WMA consumed) is calculated and compared with the results obtained from other calculation tools and literature. Sensitivity analysis is conducted for selected mitigation measures to examine the changes in emission reductions due to variations in structural design and the analysis period.

Chapter 5 concludes the report. Key recommendations, limitations, and avenues for future work are discussed.

Chapter 2: Literature Review

2.1 Tools for GHG Quantification

To understand current practices for quantifying highway-related emission reductions, a detailed review of the available tools addressing road infrastructure life cycle emissions and on-road transportation was performed. Pavement-related GHG emissions tools include MTO's internal GHG calculator (Ahmed, 2018), PaLATE 2.0 (Horvath, 2007), PaLATE 2.2 (University of Washington, 2011, p. 2), GreenDOT (ICF international, 2010), FWHA's Infrastructure Carbon Estimator (F. Gallivan et al., 2014), ROADEO (The World Bank, 2011), Highways England Carbon Tool (Highways England, 2015), GasCAP (Noland & Hanson, 2014), PE-2 (A. Mukherjee, 2013), and Athena Pavement LCA (Athena Sustainable Materials Institute, 2018). Transportation and traffic related tools are presented, 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 (*GHGenius 5.0d*, 2019). In addition, the CUFR Tree calculator (USDA Forest Service et al., n.d.) is reviewed for tree-related calculations. The tools reviewed vary in scope, items quantified, comprehensiveness, data requirements, and accuracy. For example, the Infrastructure Carbon Estimator and ROADEO tool can operate on less detail at the planning stage, while Athena, PaLATE, and GasCAP are data intensive and project specific. As a result, understanding the existing quantification tools allows us to identify and select the relevant data, functions, and items for quantification at the annual, Ministry level.

2.1.1 Pavement-related Calculations

MTO's Emission Reduction Tool

The MTO's internal calculation tool is an Excel-based tool developed by (Ahmed, 2018) for estimating CO_2 reductions based on the contracts awarded by the agency. It is customized to MTO and linked to its HiCo database. The tool includes GHG emission reductions from precast concrete, 24/7 construction, CIR/CREAM, HIR, FDR, lights, and trees, etc. The resulting GHG savings are expressed as the equivalent number of passenger cars removed and acres of forest sequestering carbon for one year.

In its calculation, the MTO's internal tool adopts multiple internal calculation workbooks and Ontario specific requirements. For example, the calculation for warm mix asphalt uses the emission factor (in kg CO_2/tonne) obtained from another MTO calculator (Corrin's calculator, as indicated in the tool). Components from tools such as GreenDOT and PaLATE 2.0 are also adopted for certain parts of the calculations.

PaLATE

The Pavement Life-cycle Assessment Tool for Environment and Economic Effects (PaLATE) is an Excel-based life cycle assessment tool for estimating the environmental effects of pavements and roads developed by the Consortium on Green Design and Manufacturing, at the University of California, Berkley (Horvath, 2003). The tool requires detailed information on roadway design, equipment, and dimensions, and models the material extraction and production, construction, maintenance, and the end-of-life phase of the roadway. Once the user inputs the data on the volume required for the layer of the design or M&RR activities, the tool estimates the emissions related to construction material, equipment, and transportation of the material to the site.

A newer version of the tool, PaLATE V2.2 has been created by University of Washington (Muench, 2011). The tool is a modification of PaLATE 2.0. It provides a simplified interface and a modification for the life cycle inventory in Greenroads. This version of the tool calculates the energy consumption and the Global Warming Potential for Greenroads projects. It provides updated emission factors from PaLATE 2.0 by using the Economic Input-Output Life Cycle Assessment (EIO-LCA) data based on 2002 NAICS Producer number, 2010 Transportation Energy Data Book Edition 29, and other literature.

PaLATE 2.0 and 2.2 are useful in calculating GHG emissions from materials, construction, maintenance, and disposal of the pavement. They provide a large database for material properties, emission factors, and equipment information. However, they have been developed specifically for the United States and are not designed for comparing mitigation strategies, thus requiring separate calculations.

The UW research team has several tools from which data and calculations are drawn. One tool is the adapted version of PaLATE developed by CPATT (Nasir, 2018). Adapted PaLATE offers improved emission calculations using updated and locally relevant data (e.g., material specifications, densities, costs, and equipment details provided by the MTO), and additional pavement management processes. Emissions factors in this tool have been updated. For example, the tool replaces the 2002 Economic Input Output Life Cycle Assessment (EIO-LCA) data used in PaLATE V2.2 with the Canadian EIO-LCA results from the same study, where possible.

GreenDOT

Greenhouse Gas Calculator for State Departments of Transportation (GreenDOT) is an Excel-based calculator tool developed in NCHRP Project 25-25/Task 58 (ICF international, 2010). The tool aims to assist state Departments of Transportation to estimate their CO_2 emissions in construction, maintenance, and operation activities. The tool enables estimating emissions for a baseline scenario and a mitigated scenario, which includes the impacts of various mitigation measures. The tool is also capable of capturing annual agency-wide emissions as well as emissions related to a specific project.

GreenDOT uses the calculation method and emission factors available from PaLATE 2.0 for its material, on-road, and off-road module, and added mitigation options such as raw material substitutes, Warm Mix Asphalt (WMA), and alternative fuel vehicles. The tool is able to capture electricity used on roadways including streetlights, traffic signals, and message signs, and provides mitigation options such as switching to more energy efficient appliances and reducing the appliances' hours of operation.

Additionally, the tool includes traffic smoothing strategies to estimate changes in CO_2 emissions on a roadway segment based on changes in average traffic speed. The emissions factors provided for this measure are derived from the U.S. Environmental Protection Agency's (EPA) Motor Vehicle Emission Simulator (MOVES) (US EPA, 2014). With user-provided data on road type, traffic composition, and the expected speed change, the effect of congestion-reducing strategies on CO_2 emissions can be estimated. The tool has been used by several state department of transportation for estimating CO_2 impacts.

Infrastructure Carbon Estimator

The Federal Highway Administration's (FWHA's) Infrastructure Carbon Estimator (2014) is an Excel-based tool that estimates the lifecycle energy and greenhouse gas emissions from the construction and maintenance of transportation infrastructure. The tool is a result of collaboration between ICF, Jack Faucett Associates, Inc, and Venner Consulting. The key functionality of this tool is that it allows the user to roughly estimate the energy usage and GHG emissions with a limited amount of inputs. As a result, it is particularly useful in informing planning and pre-engineering analysis when detailed facility dimensions, materials, and construction practices are not known. However, the tool is not suitable for pavement selection and engineering analysis.

In addition to the calculation of baseline emissions, FWHA's infrastructure Carbon Estimator covers mitigation strategies including alternative fuels, alternative vegetation management, alternative snow management, in-place recycling, etc. These mitigation strategies are represented in terms of baseline deployment and projected deployment as a percentage level. The tool also contains an "Impacts on Vehicle Operation" function that can approximate the GHG emissions due to construction delays and impacts of a smoother pavement.

ROADEO

The Greenhouse Gas Emission Mitigation Toolkit for Highway Construction and Rehabilitation (ROADEO) tool is an Excel-based GHG emissions evaluation and reduction tool developed by The World Bank (2011) for East Asian and Pacific countries. The tool is designed to evaluate GHG emissions associated with earthworks, pavement, drainage, structures, road furniture, and land use change in the project by summing the emissions generated by material, equipment, and transport in each activity. The tool generates a pie chart to show the distribution of project emissions according to the type of work component and GHG generators.

Based on the project data input and the calculation result, ROADEO can identify relevant technical options to limit GHG emissions and generate reports that provide useful mitigation ideas for designers and planners. Some examples of the recommendations provided by the tool include: manage overloading, use high modulus asphalt, and optimize alignment to minimize structures.

Carbon Tool

Carbon Tool is an Excel-based tool developed by Highways England to track data on GHG emissions in its supply chain. The tool was first published in 2015 and had its latest update in 2016. Contractors using this tool are required to complete and submit the spreadsheet on a quarterly or monthly basis. The required user inputs for the tool include data on material usage for construction, transportation from the construction site, business and employee transport, fuel, electricity, water, and waste. The tool contains an extensive database of material emission factors from the Bath Inventory of Carbon and Energy (ICE), and energy and waste factors from Defra 2014 and the Waste Resources Action Programme (WRAP). After the data inputs are provided by a contractor, the tool automatically generates the CO_2 emissions, and the result is subsequently tracked by Highways England.

GasCAP

The Greenhouse-Gas Assessment Spreadsheet for CAPital Projects (GasCAP) is an Excel-based model developed by the Alan M. Voorhees Transportation Centre in 2014 for the New Jersey Department of Transportation. The current available version is its Beta Version 2.0 and its interface resembles the MTO's internal tool. The tool has been designed to estimate life-cycle GHG emissions including CO_2, CH_4, N_2O, and upstream SF_6 for different components of construction and maintenance activities for transportation projects. It consists of modules that cover different materials and recyclables, project staging decisions, construction equipment used on a project site, lighting and life-cycle maintenance required over the lifetime of the project.

In comparison to the other tools reviewed in this study, GasCAP allows for providing more detailed user input. For example, for the material input, intricate details such as heating temperature, percentage moisture, and percentage of cutback can be specified. An interesting feature of GasCAP is its traffic disruption module. It contains a model that allows details relevant to a work zone such as single lane base capacity, ramps or access point per mile, and road grade to be used to calculate the traffic disruption procedure totals. The tool is useful for conducting a more detailed emissions analysis following a planning-level analysis, once engineering documents, material quantities, and construction plans are established.

PE-2

The Project Emission Estimator (PE-2) is a web-based life cycle assessment tool developed for the Michigan Department of Transportation (MDOT) to identify the contributions to GHG from development and maintenance of transportation infrastructure. The study, done by Michigan Technological University in 2011, developed a comprehensive inventory of materials and equipment by collecting and organizing data from 14 pavement construction and maintenance projects. This allows the tool to generate GHG emission reports suitable for MDOT's specific needs based on materials used, equipment used, and project summaries.

Athena LCA

Athena Pavement LCA (version 3.2.01) is a web-based life cycle analysis tool developed by the Athena Sustainable Material Institute (2018) for estimating the life cycle impacts of materials manufacturing, roadway construction and maintenance in Canada and selected states in the USA. The tool contains a large equipment and material database representing the national or industry average and allows the user to specify unique pavement systems including hot mix asphalt, warm mix asphalt, and user-specified concrete mix design. Some required inputs include the pavement type, lanes and lifts, roadway design details, rehabilitation schedule, and traffic. The tool provides flexibility with regards to additional data inputs related to construction equipment, material transportation, and operating energy consumption. Data inputs associated with these technicalities can be selected from the database or customized.

The tool is designed to generate environmental impact reports for global warming potential, human health respiratory effects potential, ozone depletion acidification potential and eutrophication potential for the entire life cycle of the pavement project except for the demolition and disposal phases. It also provides the consumptions of fuel, material, and energy, as well as the related emissions to air, water, and land over the life cycle of the roadway. The results are grouped by the activity stages so that the users can easily compare multiple designs

2.1.2 Emission Quantification Tools for Transportation, Traffic, and Trees

MOVES

The Motor Vehicle Emission Simulator (MOVES) is software developed by the US EPA to model mobile source emissions at the national, county and project level. The simulator is capable of estimating emissions from various combinations of vehicle types and fuel technologies and can be used for state implementation plan (SIP) conformity analysis. The emission types covered include running exhaust, start exhaust, extended idling, tire ware, etc. The air emissions quantified include total gaseous hydrocarbons, methane, nitrous oxide, criteria pollutants, VOCs, and various toxics. The CO_2e emissions modeled by the tool include running exhaust, start exhaust, extended idle exhaust and auxiliary power exhaust, and the CO_2e is calculated based on the emissions and global warming potentials of CO_2, CH_4, and N_2O. Note that the CO_2 emissions from MOVES are modeled based on energy consumption (CO_2 = total energy × oxidation fraction × carbon content ×44/12), so that CO_2 produced from emitted CO and HC are accounted for in addition to the tailpipe emissions (Bai et al., 2008)

The UW team has separately adapted MOVES with Ontario-specific data for most on-road vehicles with the purpose of analyzing the atmospheric impacts of truck freight under a wide range of user-defined conditions (U. Mukherjee et al., 2020; W. Wang et al., 2020). The data gathering process for developing a MOVES model usually requires extensive research and detailed information on a host of factors, including the fuel supply and fuel formulation, local temperature and relative humidity, vehicle/source type fraction for vehicle miles traveled (VMT), and the driving schedule. The model itself is too data and resource intensive to form a part of the tracking template. This study, however, applies the collected data and calculates Ontario-specific emission rates. The emission rates are then used to estimate emission savings due to construction practices that mitigate user delays.

CMAQ Emissions Calculator Toolkit

The CMAQ Emissions Calculator Toolkit is a software developed by the FHWA as a technical support resource for projects under the Congestion Mitigation and Air Quality Improvement Program (CMAQ). The toolkit is designed for assisting departments of transportation across the US, metropolitan planning organizations, and project sponsors in estimating air quality benefits and justifying projects for CMAQ requirements. Greenhouse gas estimations are also covered in some of the tools where applicable.

The toolkit includes a total of ten Excel-based calculation tools that cover traffic related air quality improvement projects including managed lane facilities, dust mitigation, carpooling and vanpooling etc. Some modules within the toolkit, including modules for Diesel Idle Reduction Technology, Advanced Diesel Truck/Engine Technologies, and Congestion Reduction and Traffic Flow Improvement (roundabout) are especially helpful for MTO’s mitigation measurements’ quantification. The emission rates in the tool are based on the US national-scale emissions generated by MOVES2014a. The detailed documentation about tool methodology, MOVES documentation, training webinars for modules are made available on the CMAQ program website. By adapting some of the modules in the CMAQ toolkit, a reasonable estimation can be obtained for MTO’s use, particularly at the project scale.

GREET

The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) (2019) Model is an energy use and emission simulation tool developed by the Argonne National Laboratory. The GREET Model is designed to estimate energy and environmental impacts of various vehicle technologies and fuel combinations from a full lifecycle perspective. The large database for pathways and processes, emissions, and default specifications contained in the tool enables the user to estimate well to product (upstream energy consumption) and well to wheel emissions. For well to wheel emissions specifically, emissions from producing the fuel and operations are covered. The tool also allows the user to modify the database, particularly, essential elements about resources and emissions, technology, process, pathway, mix, and vehicles.

The Alternative Fuel Life-Cycle Environmental and Economic Transportation Tool (AFLEET) (Burnham, 2019) is a spreadsheet tool developed to evaluate the environmental and economic cost of alternative fuel vehicles and technologies. The tool uses data on GHG and tailpipe air pollutant emission rates from GREET and MOVES. The heavy-duty vehicle emission calculator (HDVEC) is a tool developed from AFLEET, and contains components for estimating GHG emissions from commercially available medium and heavy duty vehicles using alternative fuels. HDVEC helps decision makers in comparing vehicle technologies for achieving emission reduction targets. It is particularly suitable for evaluating impacts on emissions from engine repower, clean vehicle replacement, and early retirement of scrapped vehicles.

GHGenius

GHGenius (*GHGenius 5.0d*, 2019) is an Excel-based model developed and maintained by S&T Squared Consultants. The model is based on the partially Canadianized fuel cycle model developed by Dr. Mark Delucchi, as a part of the work for the Lifecycle Emission Model (LEM). The latest version of GHGenius is capable of providing detailed output for criteria pollutants (CO, NO_X, NMOCs, SO_2, PM), GHG emissions (CO_2, CH_4, N_2O, CFC-12, HFC-134a), energy use, and economic assessment of the life cycle cost of greenhouse gas reductions from alternative fuel vehicles. The analysis can be performed from the past (1995) to the future (up to 2050).

The full life cycle, from raw material acquisition to end-use is considered in the model. Some fuel segments included are vehicle operations, fuel dispensing at the retail level, fuel storage and distributions, fuel productions, feedstock transport, feedstock production and recovery, fertilizer manufacturer, and materials used in the vehicles. The fuel segments are then categorized into three stages – fuel production, operation, and vehicle material and assembly. Life cycle assessment for around two hundred fuel pathways and vehicle combinations (See Table C-1 and Table C-2 in Appendix C) are performed for these three stages, respectively.

GHGenius is capable of providing location specific analysis for Canada (east, central, or west), the US, and other countries or regions. For Canada, many processes can be modelled by province. The emission inventory data for power and raw material production come from sources such as reports by Statistics Canada, Natural Resources Canada, Environment and Climate Change Canada, National Energy Board, Canadian Association of Petroleum Producers, and Canadian Gas Association. For non-energy related processes, US EPA AP-42, Mobile6.2C, and relative emission factors obtained from US EPA analysis and available literature are applied.

CUFR Tree Carbon Calculator

The CUFR Tree Carbon Calculator (CTCC) is a spreadsheet tool that quantifies the carbon dioxide sequestration and the building energy impact of an individual tree. The tool was designed by the USDA Forest Service in partnership with the California Department of Forestry and Fire Protection, and since then incorporated into i-Tree and ecoSmart Landscapes. The tool is designed to take tree size or age as input, and calculate the amount of carbon sequestered and the building energy impact based on the users' selection of the US climate zone, tree species code, tree azimuth, distance class, and building conditions. By varying the age of the tree in the input, the tool is able to calculate GHG benefits of the existing trees as well as the forecasted future benefits.

2.2 Scope of Emission Mitigation Quantification

This section presents a detailed literature review of current practices in agency wide GHG reduction quantification and the general practices among current available tools and literatures. Tools and articles have been summarized to provide an overview and further discussion of the comprehensiveness, scale, and baseline of existing work. Highway- and roadway-related GHG emission results from a few other jurisdictions have also been presented. The study finds that most tools and articles focus on project level estimation and are not suitable for directly producing department level quantification.

2.2.1 Emission Mitigation Estimation Tools

One of the general findings from the review of existing tools is that they are designed for quantifying GHG emissions of pavement projects from a life cycle perspective, and therefore do not explicitly include mitigation measures. As shown in Table 2-1, apart from the MTO internal tool, only two out of nine tools have included mitigation tabs with baseline input options. This trend could be attributed to the lack of the current reporting requirements for mitigation at both the jurisdiction and project level. The current active pavement emission inventory programs are implemented either through transportation agencies collecting information from contractors (e.g. Highways England) or as a reporting requirement for an individual project's sustainable rating program (e.g. using PaLATE 2.2 for Greenroads). Both practices can generate estimates of project-wide emissions through project planning level or actual construction data.

Table 2-1 also shows the lack of agency-wide emission quantification tools. Jurisdiction-wide calculation tools, as listed in the table, tend to incorporate agency data including specification lists and aggregated item quantities. Compared to project-based quantification tools, agency tools do not usually take in extensive design details, and instead contain typical design assumptions and assume that different types of road projects will have a similar design. As each project will unavoidably differ from the typical design, summing up the emission from projects gives more accurate results. Agencies such as Highway England and Sacramento Metropolitan require contractors to report project or quarterly emissions. In comparison, currently there are no reporting requirements in Ontario for GHG emissions occurring during the highway life cycle at any scale. As a result, at this time, this study focusses on following the more common approach of developing a tracking template that requires lower cost, less time and coordination, and less extensive project data collection while incorporating locally relevant assumptions. This involves both taking advantage of the extensive readily available project-level details collected by MTO, and supplementing them as needed with locally relevant default data and designs.

Table 2-1: Scopes of the Current Roadway Related GHG Quantification Tool

Tools	Author & Year	Scale	Baseline	GHG	GHG Mitigation Measures Included																
					In-situ Rehabilitation			Recycled Pavement Material			WMA	Transportation	Alternative Energy	Work Zone	Anti-Idling	Electricity		Trees	Albedo	Roughness/ IRI	Carbo-nation
					CIR	HIR	FDR	RAP	RCM	Alternative Material						Lights	Signals				
MTO Internal Tool	Abass, 2018	Agency	Status Quo	CO_2	●	●	●	◉	●		●	◎		◉	◎	●	●	●		◎	
GreenDOT	ICF International, 2010	Project & Agency	Status Quo	CO_2				●	●	●	●	◎	●	◉	●	●	●				
Carbon Tool	Highways England, 2015	Agency collecting through Projects	NA	CO_2e				◉		●		◎				●					
Road Construction Emission Model	Sacramento Metropolitan, 2020)	Agency collecting through Projects	NA	CO_2, CH_4, N_2O, CO_2e								●	`								

Tools	Author & Year	Scale	Baseline	GHG	GHG Mitigation Measures Included																
					In-situ Rehabilitation			Recycled Pavement Material			WMA	Transportation	Alternative Energy	Work Zone	Anti-Idling	Electricity		Trees	Albedo	Roughness/ IRI	Carbo-nation
					CIR	HIR	FDR	RAP	RCM	Alternative Material						Lights	Signals				
PaLATE 2.0	Horvath et al, 2007	Project	NA	CO_2	●	●	●	●	●	●		◎	●								
ROADEO	The World Bank, 2011	Project Qualitative	NA	CO_2e				○	○	○	○	○		○	○	○				○	
PE-2 (Michigan DOT)	Mukherjee & Cass, 2012	Project Benchmark	NA	CO_2e				●		●		◎		◉							
FHWA Infrastructure Carbon Estimator	Gallivan et al, 2014	Project Ballpark	Status Quo	CO_2e	◉		◉	◉	◉	◉	◉		◉	◉						●	
Athena Pavement LCA Tool	Athena Sustainable Material Institute	Project	NA	CO_2e	●	●				●	●	◎								●	

Tools	Author & Year	Scale	Baseline	GHG	GHG Mitigation Measures Included																
					In-situ Rehabilitation			Recycled Pavement Material			WMA	Transportation	Alternative Energy	Work Zone	Anti-Idling	Electricity		Trees	Albedo	Roughness/ IRI	Carbonation
					CIR	HIR	FDR	RAP	RCM	Alternative Material						Lights	Signals				
GASCAP (NJ DOT)	Noland & Hanson, 2014	Project	NA	CO_2, CH_4, N_2O, CO_2e				●	●	●	●	●	◎	●		●	●				

●	Quantify Mitigation Explicitly in Detail
◉	Quantify Mitigation through Rough Estimation
◎	Have Capacity to Quantify (Model Proposed are Useful)

The review also finds that most tools are suitable for calculating material related emissions, which include reclaimed asphalt pavement (RAP), recycled concrete material (RCM), warm mix asphalt (WMA) and various substitution materials for aggregate, binder, and cement. The emissions occurring during the material transportation phase are also accounted for in most tools. However, as mentioned, most tools are not designed for mitigation quantification, so estimating emission reductions require running the model twice with project and baseline data separately. Traffic emissions introduced by work zones are often considered as well, though most tools except for GasCAP provide only a rough estimation. On the contrary, in-situ recycling including cold in-place recycling, hot in-place recycling, and full-depth reclamation, which represent activities Ontario is actively engaged in, are not well documented. Among the tools that do cover in-situ activities, there is no established baseline scenario, except in the MTO’s internal tool. Trees, roughness, and carbonation, which are often considered in the literature, are rarely included in existing tools.

These gaps may explain why there are few examples of department-level application of these tools for GHG mitigation tracking. Of all the tools, it seems that GreenDOT is best suited for the purpose of agency-wide tracking because it has an intuitive design, calculates mitigation directly, and is relatively detailed and comprehensive. Despite this, limited examples can be found for its application in quantifying agency wide highway emission reductions. The reported department wide applications of GreenDOT include calculating mitigation by NYSDOT’S “ecoluminance” approach and Illinois’s retroreflective overhead signs replacement (Frank Gallivan et al., 2010); both of which fall into the category of electricity usage in roadways. Project level application of the Athena LCA and PaLATE can be found in multiple journal articles and technical reports including Alkins et al. (2008), Batouli et al.(2017), and Ahammed et al.(2016).

2.2.2 Journal Articles and Technical Reports

This section reviews the technical literature including documents discussing quantification of GHG emission mitigation from highway and roadway infrastructure. All relevant and recent documents including peer-reviewed journal articles, technical reports, and theses have been reviewed. Among the 24 relevant documents reviewed in this study, most cover recycled materials including recycled asphalt pavement (RAP) and recycled concrete material (RCM). Warm Mix Asphalt (WMA) is covered in most tools. In comparison to quantification tools, journals and reports generally provide more detailed accounts of energy for material extraction and processing. For example, quantification of RAP in the literature often takes specific details regarding the percentage of binder replacement and moisture content into consideration. For WMA, details on the additive that allows the lower processing temperature are typically included the study. Table 2-2 lists the literature’s scope of coverage, scale of quantification (project or jurisdiction level), mitigation baseline, and the literature category. While information on most agency-wide quantifications are found in technical reports which rely on general data, such as

Intergovernmental Panel on Climate Change (IPCC) emission factors, academic journals rely on smaller case studies involving real world data on emitting activities. Note that, among the articles listed, some only provide the framework and calculation method with no detailed results, which is the case for most agency wide/network level work.

Table 2-2: Scopes of the GHG Mitigation Related Journal Articles and Technical Reports

Author & Year	Scale	Type	Mitigation Baseline	GHG Mitigation Measures Included																
				In-situ Rehabilitation				Recycled Pavement Material			WMA	Transport	Alternative Fuel	Work Zone	Lights	Trees	Albedo	IRI	Carbonation	Long Lasting
				CIR	CIREAM	HIR	FDR	RAP	RCM	Substitutes										
California Department of Transportation & ICF International, 2013	Transportation Department	Government Report	Status Quo	•						•	•	•	•		•					
(Marhaba et al., 2014)	Transportation Department (NJDOT)	Technical Report	Status Quo					•		•	•		•							
(Foth & Berthelot, 2013)	City of Edmonton & Project	Conference	Status Quo (Traditional)	•			•	•												
(T. Wang et al., 2013)	California Network Level	Research Report	Do Nothing and Mill & Overlay					•				•	•					•		
(California Air Pollution Control Officers Association, 2010)	Project & Plan	Report-Government Decision Support	Status Quo									•	•		•	•				

Author & Year	Scale	Type	Mitigation Baseline	GHG Mitigation Measures Included																
				In-situ Rehabilitation				Recycled Pavement Material			WMA	Transport	Alternative Fuel	Work Zone	Lights	Trees	Albedo	IRI	Carbonation	Long Lasting
				CIR	CIREAM	HIR	FDR	RAP	RCM	Substitutes										
(N. J. Santero et al., 2011a)	Typical Road, Lit Review	Technical Report	NA						•	•				•			•	•		
Mukherjee & Cass, 2012	Project	Technical Report	NA					•	•	•		•		•						
(Alkins et al., 2008)	Typical Project	Journal	Status Quo (Mill & HMA)	•	•															
(Turk et al., 2016)	Project	Journal	Status Quo (Traditional)	•			•	•				•								
(Santos, Bryce, et al., 2014)	Project	Journal	Traditional Reconstruction and corrective Maintenance	•			•					•	•	•				•		
(Liu et al., 2014)	Project	Journal	NA					•	•		•	•		•		•	•		•	
(Santos, Ferreira, et al., 2014)	Not Specified	Journal	NA									•		•				•		
(Cooper et al., 2012)	Typical Project	Journal	NA					•	•	•	•							•		

Author & Year	Scale	Type	Mitigation Baseline	GHG Mitigation Measures Included																
				In-situ Rehabilitation				Recycled Pavement Material			WMA	Transport	Alternative Fuel	Work Zone	Lights	Trees	Albedo	IRI	Carbonation	Long Lasting
				CIR	CIREAM	HIR	FDR	RAP	RCM	Substitutes										
(Chen et al., 2015)	Typical Project	Journal	20 vs 40 year					•	•									•		•
(Yu & Lu, 2012)	Project	Journal	NA					•	•			•		•			•	•	•	
(Chehovits & Galehouse, 2010)	NA	Conference	NA	•		•		•			•	•								
(Thenoux et al., 2007)	Project	Journal	Overlay and Reconstruction		•							•								
(Giani et al., 2015)	Typical Project	Journal	NA	•				•			•		•							
(N. J. Santero et al., 2011b)	NA	Technical Report-Lit Review	NA					•		•				•			•	•		
(Frank Gallivan et al., 2010)	Project & Agency	Technical Report	Status Quo					•	•	•	•	•	•	•	•					
(Trupia, 2018)	Project	Thesis	NA									•		•			•	•		

2.2.3 Highway GHG Quantification at Jurisdiction Level

The literature on GHG emission quantification for highway infrastructure consists primarily of case studies of selected projects. Conversely, jurisdiction level reports mainly: (1) offer recommendations for GHG reductions without any quantification; or (2) solely focus on reducing emissions from on-road vehicles by calculating the effect of reducing transportation activity, improving system efficiency and energy efficiency, factors which a transportation agency has little control over (e.g. Highways Agency, (2013), Alberta Infrastructure and Transportation (Lukomskyj, 2003)). As a result, limited information is available stating the level of GHG emissions for which transportation agencies are responsible and the extent of possible mitigation results. Among the six quantification efforts at the jurisdiction level reviewed in this study, only one (Caltrans report) directly addresses agency wide GHG mitigation with emission factors accounting for reductions. The CMAQ Program, despite providing great resources for on-road mitigation calculations, focuses primarily on air pollutants instead of GHGs. This limits the results that are applicable to be reviewed and presented in this study. Table 2-3 summarizes the jurisdiction level results and the methods used for emissions and emission reductions quantification.

Table 2-3: GHG Quantification and Mitigation Results for Road Activities at Jurisdiction Level

Jurisdiction	Source	Calculation Method	Results
California Department of Transportation	Caltrans Activities to Address Climate Change – Reducing GHG Emissions and Adapting to Impacts (California Department of Transportation & ICF International, 2013)	Based on the product of an activity level and the per unit emission reduction from the alternatives; Uses design, cost data from California counties, and other literature and studies.	Achieves total average annual GHG reduction of 161 kt of CO_2e; GHG reduction from materials, operation strategies, and administration strategies are 108.71, 41, 11.4 kt , respectively.
United States	Towards Sustainable Pavement Systems, (Van Dam et al., 2015)	Based on construction expenditure of the construction work done in 2012, and uses the EIO-LCA Calculator.	Estimates 75 Mt CO_2e emissions (5 percent of US transportation GHG total)
India	Methodology for Estimating Carbon Footprint of Road Project Case Study: India, 2010 (Asian Development Bank, 2010)	Process based; Find GHG emission per km for 4 types of road design and extrapolates to the entire road network.	Estimates 10.98 Mt of CO_2e for a 2008 project, and a 268.17 Mt carbon footprint for all ADB funded projects for their design life.

Jurisdiction	Source	Calculation Method	Results
British Columbia	Reducing GHG Emissions in the BC Road Building and Maintenance Industry, 2011 (British Columbia Ministry of Transportation and Infrastructure, 2011)	Not presented.	Estimates 37 kt of CO_2e emissions from 17 projects in BC. Contribution from construction, rehabilitation and maintenance phases are 160, 110, 100 kt, respectively.
Rijkswaterstaat (Dutch Ministry of Infrastructure and Water Management	Green Public Procurement The Rijkswaterstaat Approach (van Geldermalsen, 2015)	Calculating and monetizing environmental impact/design using DuboCalc. Quantifying CO_2 from company's process and activities using CO_2 performance ladder	Estimate a total yearly carbon footprint of 818 kt CO_2, including asphalt, road base material, concrete construction, etc. Emissions are 20% less in comparison to 1990 levels due to green procurement.
Highways England	Highways England Carbon Tool Guidance (Highways England, 2015)	Collect and calculate carbon emissions from supply chain construction and maintenance contractors using Carbon Tool.	NA
United States	Congestion Mitigation and Air Quality Improvement (CMAQ) Program (Federal Highway Administration (FHWA) Office of Natural Environment, 2020)	CMAQ Emissions Calculator Toolkit is provided. 2-year and 4-year cumulative emission reductions (mostly air pollutants) are reported by State DOT; The total emission reductions are equal to the sum of daily kilogram of emission reductions.	NA (The first Mid Performance Period Progress Report CMAQ Performance Plan due on Oct 1, 2020).

Four of the six reports specifically quantify GHG emissions using the product of activity levels and emission factors. The report collects activity information from local offices, typical projects, as well as contractors. A life cycle perspective is usually adopted in quantification processes. However, emissions from upstream energy sources and end of life recycling are often omitted. The Towards Sustainable Pavement report uses the EIO-LCA method to quantify emissions based on economic activity, which traces all inputs to the sector and provides a quick general estimation when expenditure data is available. However, while this approach is suitable for overall GHG emission (i.e. a baseline total emission) quantification from an economic sector, its system boundary is the economy, so it cannot be easily applied to estimating emissions at the agency-level or from mitigation activities.

Reported annual GHG emissions from pavements at the jurisdiction level range from 37,000 tonnes (in British Columbia, Canada) to 75 million tons (in the United States). These emissions are not comparable partly because the listed jurisdictions have different governance structures for pavement management and have varying numbers of projects. Within the same area, a road could be the responsibility of a city, region, or a province, making it harder to hold a single jurisdiction or agency responsible for all road activities. In addition, among the reports reviewed, each jurisdiction or agency includes different activities in its quantification. For example, Caltrans includes its office building energy saving and workplace commute programs as efforts to reduce emissions. In the quantification for the projects in India, on-road emissions are included, which greatly increases the GHG emissions calculated. While these elements do not fall under the MTO's purview, the MTO has additional needs for quantification of savings such as sequestration by trees and congestion mitigation.

2.3 Overview of Mitigation Quantification Methods

In general, a majority of the GHG tools quantify mitigation by totaling GHG emissions, and then comparing the difference in emissions between alternatives (and baselines). Common methods for quantifying GHG emissions include emission factors, monitoring, and direct measurement, mass balance, and engineering estimates. The most common method adopted for GHG estimation purposes is to use emission factors. They are used in CAPCOA, BC Best Practices Methodology for Quantifying Greenhouse Gas Emissions, and in the majority of the GHG quantification tools including PaLATE 2.0 and the MTO's Emission Reduction tool.

Most pavement related GHG emission quantifications cover, to some extent, measures in materials, construction, and transportation. Since 2009, an increasing number of pavement LCA studies have expanded their scope to include categories such as traffic delay and carbonation (N. J. Santero & Horvath, 2009). Trees and lighting with more efficient fixtures, though not typically considered as a part of the pavement LCA, are commonly employed by transportation agencies and offer meaningful GHG reductions (California Air Pollution Control Officers Association, 2010; Frank Gallivan et al., 2010). An overview of quantification methods for each mitigation category is discussed below.

2.3.1 Materials

Material extraction and production generates large amounts of GHG emissions. In comparison to using a 100% traditional new asphalt or concrete material, emissions can be reduced by limiting the quantity of raw materials used, using material substitutions such as Supplementary Cementing Materials (SCMs) and glass cutlet, and by reducing the energy consumed during processing. Material recycling is one of the most common measures to reduce GHG emissions in highway infrastructure, and Ontario has an active pavement recycling program that is strongly promoted and monitored (Alkins et al., 2008).

Emission factors for representative materials such as cement, asphalt binder, and aggregates can be obtained from various published life-cycle inventories and studies. Material emission factors generally relate to the amount of emissions generated per unit of material used. They are most consistently provided for CO_2, with many also accounting for methane (CH_4) and nitrous oxide (N_2O) which are emitted in relatively small amounts compared to CO_2 during many combustion processes, including, e.g., cement manufacturing. On-Site Processing/Construction Equipment

GHG emissions from on-site processing come from the combustion of fossil fuels by construction equipment. Construction equipment including pavers, rollers, and millers contribute a relatively small percentage of the total GHG emissions.

Current practices in quantifying construction equipment emissions largely depend on the methodology and emission factors provided by the US EPA's NONROAD (U.S EPA, 2008) software and the California Air Resource Board's OFFROAD (2009) model (Ahn & Lee, 2012). In these models, the amount of emissions from each equipment is based on the specification of the equipment, and the operating hours are determined in the operation plan. When the operation plan is not available, the hours are estimated based on the amount of material requiring processing and the productivity of the equipment. The CO_2 emission factor for a piece of construction equipment depends on its brake specific fuel consumption and the load factor specifications developed to indicate the average proportion of the rated power used, which varies by equipment.

Alternatively, a fuel-based method can also be used. The variables in fuel-based consumption are weight, quantity, and the density of fuel. GHG emissions can be obtained using the quantity of the fuel type in kL, the energy content factor for a fuel in GJ/kL, and the GHG emission factor for the fuel in kg of CO_2e/GJ. Previous studies have compared construction related emissions calculated by the two methods. Frey et al. (2010) conducted a field study and compared these estimations with testing data. The results show that the fuel-based emission rates are less sensitive to engine size and load in comparison to the time-based emission rates. A similar conclusion is drawn by (Lewis et al., 2009), suggesting that a fuel-based factor is more suitable for CO_2 emissions while time-based rates are better suited for non-CO_2 emission quantifications. As a result, fuel-based emission rates are preferred when fuel consumption data is available. However, this relies on reliable fuel consumption data. Without that, fuel consumption rates are difficult to estimate, as they often vary by the type of equipment and its condition (e.g., year, engine power), operating conditions (e.g., job site condition, altitude), equipment maintenance (e.g., routine maintenance, tire/track condition), and equipment operations (e.g., idling and control, operator skills). Portable Emission Measurement Systems are thus often required for measuring emissions in the field.

In some life cycle analyses, the impact of construction machinery manufacturing is also included. The calculations here are carried out by first multiplying equipment production emissions to the number of hours the equipment is used and then dividing the product by the total predicted equipment service life. These calculations are likely to be omitted in this study as the GHG emissions from machine manufacturing are expected to be low in comparison to other sources, and this even attribution approach does not account for potentially differing emission profiles as the equipment ages. Emissions associated with manufacturing the construction equipment are expected be important under two conditions: (1) if low-emission construction equipment were adopted (e.g., as more electric options become available following the development of products like the electric excavator Norwegian Pon Cat 323F) and (2) there is reason to believe that their construction is significantly different in emission intensity from traditional equipment. If diesel powered equipment were to be converted to electric, (as was the case for the aforementioned Pon Cat 323F), emissions associated with the conversion and battery production may offset some of the emission savings. As the use of alternative fuel in construction equipment is less common and the emissions for each model vary, emissions from the use of such equipment are currently excluded from the template.

2.3.2 Transportation

GHG emissions from on-road mobile sources are attributable to the burning of fossil fuels. The transportation required in a pavement project usually involves the movement of material between material extraction sites, production facilities, project sites, and landfills. Transportation GHG emissions are affected by the transportation mode, fuel used, the material that needs to be transported, and the transportation distance. As a result, using alternative fuels, increasing fuel efficiency, and reducing the need for travel are the main principles of GHG mitigation. Some effective GHG mitigation measures for transportation include using rail for long distance transportation, switching to cleaner fuel for trucks, in situ recycling, and using rocks within the right of way.

Emissions of GHGs from transportation depend on a variety of conditions, including driver activities (speed, braking, idling), vehicle characteristics (age, technology), fuel properties, road conditions, and weather. Some of the more sophisticated mobile emission models, such as MOVES, attempt to account for these various factors, especially when considering the impact of an on-road fleet is crucial. For the purposes of tracking GHG mitigation efforts by a transportation ministry, this level of analysis would normally not be used.

Outside of a full mobile emission simulator, there exist two options that are commonly used for calculating transportation emissions. The first option is an activity-based approach which applies to the situation where the energy or fuel consumption data is not readily available. The appropriate CO_2e emission factor for the transportation mode (in kg CO_2/tonne-km) can be selected, and the CO_2 emissions can be evaluated with the material quantity and the distance transported. Some of the important parameters in determining the emission factors for an activity-based approach are load factor, the share of empty running or deadheading, and the energy efficiency of the vehicle. When data are limited, it is also possible to estimate the total travel distance by finding out the number of trucks required assuming full load and that the truck only carries the load one way. An approximate GHG emission estimation can then be obtained by multiplying the fuel consumption rate (L/km), and the GHG emission factor (in kg CO_2/tonne).

The second main method involves using fuel based emissions factors. This method can be more accurate if fuel consumption and fuel properties are well known. It requires no assumptions about empty running or loading rates. Fuel-based emission factors for CO_2, CH_4 and N_2O for mobile combustion are available in the 2019 Canadian National Inventory Report of greenhouse gas emissions in grams/liter fuel.

2.3.3 Traffic Delay

Traffic delay can be a significant GHG contributor if a pavement section has high traffic, relatively low capacity, no detours, and a peak hour lane closure (N. J. Santero et al., 2011a). According to the Federal Highway Administration Work Zone Management Program in the US, work zones are estimated to constitute about 10% of overall congestion which translates into an estimated annual fuel loss of over 310 million gallons in 2014. As a result, reducing traffic delay caused by construction and maintenance is a crucial part of GHG mitigation. Measures to mitigate the GHG impact of the traffic effect can be grouped into congestion mitigation strategies, speed management techniques, and traffic flow smoothing techniques (Barth & Boriboonsomsin, 2008). Some effective GHG mitigation measures include rapid construction techniques such as rapid set concrete, construction time reduction including aggressive closures, and smart staging considerations such as roundabouts.

To evaluate the GHG emissions from a specific project, the integration of an emission model and a traffic (work zone) model is usually considered when no field traffic measurement is available. Various models with different accuracies are available for both work zone and vehicle emissions. In other studies for transportation GHG emissions, a combination of models such as QUEWZ-98+MOBILE5a (Benz & Fenno, 2001), KyUCP+MOBILE6 (A. W.-C. Chan, 2007), SUMO+VT-micro (Jamshidnejad et al., 2017), and VISSIM+MOVES (Abou-Senna et al., 2013) have been used. These models range from low cost, and low complexity (for planning) to simulation software that are more resource intensive and more accurate (for design and implementation purposes). For example, an average speed emission model such as EMFAC (Board, 2017) can generate vehicle emission factors by counties based on selected road type, fuel type and temperature for a standardized driving cycle, whereas MOVES (US EPA, 2014) in microsimulation mode requires a large number of inputs including tables for activity distribution, vehicle age distribution, and fuel formulations to generate second-by-second running emission rates for each vehicle type.

The methods for estimating additional GHGs emitted from traffic delay are based on those used for on-road transportation and are generally activity-based or fuel-based. For agency-wide emissions estimation, simpler models are preferred, as their operation requires lower technical skill, capital cost, running time, and data collection. Activity-based emission factors (grams/kg) are generally derived from more sophisticated on-road emissions models, such as MOVES, or the

Comprehensive Modal Emission Model (CMEM). The emission rates derived often vary with the vehicle speed, with the lowest GHG emission rate being at moderate speeds (45-50 mph), and a significantly higher rate at a very low speeds (<12.5 mph). MOVES is used in Canada's own National Inventory Reports of GHG emissions. Fuel-based estimation requires the record of actual fuel consumptions of each vehicles, and these data are currently not collected by MTO.

In additional, RealCost 2.5 (FHWA, 2004), which is the FWHA's pavement design life-cycle cost analysis tool, could be a viable option for quantifying CO_2 emissions due to traffic delay. The software estimates the cost based on the normal number of lanes and traffic volume, speed and composition, life cycle closure, and closure duration. Fuel consumption can be back calculated based on assumed values of time factors, and the CO_2 emissions can be estimated based on the fuel used.

2.3.4 Lights and Signals

Lighting is typically not covered in project based pavement LCA because the energy consumption occurs during the use phase, and is outside of the pavement itself. From an agency's perspective, adopting more efficient lighting fixtures is easy to implement and cost effective. The California Air Pollution Control Officers Association (CAPCOA, 2010)'s fact sheet suggests that a 90% reduction in GHG emissions from lighting can be achieved by adopting LED traffic lights and signals. This is because LEDs consume 90% less power than traditional incandescent lights. However, the potential savings will vary with the GHG intensity of the electricity grid. The MTO's current mitigation activities in lighting include using LED lighting, LED traffic signals, and solar and wind powered counting stations. The smaller wattage of LED lights in comparison to conventional fixtures contribute to emission savings for each light and signal. A 100% emission reduction is estimated for solar and wind powered fixtures as they are assumed to have zero emissions.

2.3.5 Trees

Trees have been planted in many MTO projects. Through trees' carbon sequestration, CO_2 reductions have been achieved. While trees are not commonly covered in highway LCA work, much research has been dedicated to understanding carbon sequestration for numerous tree species. Generally, the weight of carbon in the tree is a function of the tree's diameter and height (which are correlated with the tree's age), moisture, and average carbon content.

The types of trees planted and the age of the trees will result in varying degrees of CO_2 sequestrated. According to the IPCC, annual CO_2 accumulation per tree ranges from 0.0121 (Juniper) mt CO_2/yr to 0.052 mt CO_2/yr (Hardwood Maple). As trees planted by the MTO are usually small, their survival factor also needs to be considered. The US EPA's Voluntary Reporting guideline (DOE, 1998) suggests that by the end of year 20, approximately 46% of standard sized trees (age 0 trees) planted will survive. Combining the survival rate and carbon sequestration (kg CO_2/yr) enables estimating the overall sequestration achieved during the life time of the trees planted by the MTO. The trees also provide shade and serve as windbreaks, which could reduce the electricity consumption of nearby facilities. The Centre for Urban Forestry Research Carbon Calculator (CTCC)(USDA Forest Service et al., n.d.) provides estimates of energy savings in the form of electricity (cooling) and MMBtu (heating) per tree and its carbon dioxide equivalent emissions. The effect of land use of forest and cropland and its influence on biomass has also been considered by Liu et al. (2014).

2.3.6 Carbonation

During the lifetime of concrete products, CO_2 emitted from the limestone during the cement kiln process is re-absorbed into the concrete that is exposed to the air through carbonation (Figure 2-2). Carbonation is not a designed mitigation measure, but this CO_2 sequestration needs to be credited if concrete pavement and cement based materials are to be selected (Yu & Lu, 2012). N. J. Santero & Horvath (2009) estimate that GHG sequestration through carbonation can range from 2.6 Mg/km to 22 Mg/km. To calculate the depth of carbonation with the factor and time, a simplification of Fick's second law of diffusion is usually adopted. Despite carbonation is a carbon sink, it is also a concrete damage that could reduce the service life of concrete products and accelerate the rebar corrosion. Additional GHG emissions may be introduced from the resulting more frequent maintenance and rehabilitation activities.

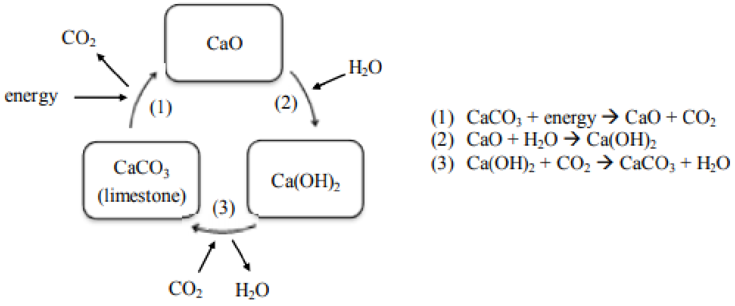


Figure 2-1: Concrete Carbonation Cycle (Santero & Horvath, 2009)

2.3.7 Roughness (IRI)

Pavement roughness increases vehicle fuel usage and decreases free flow speed, both of which increase GHG emissions. Pavement roughness is commonly measured using the International Roughness Index (IRI), which ranges from 1m/km (smoother) to 5m/km (rougher) on highways. According to the Asian Development Bank Report (Rao et al., 2010), when the IRI increases from 2 m/km to 4 m/km, the emissions (CO_2 tons/km/yr) increase by 1.6%. This could have a large GHG impact on high volume roads where the baseline emission is high. By proper timing of maintenance and rehabilitation to keep IRI at an acceptable level, agencies can avoid the additional

GHG emissions emitted. Yu & Lu (2012) have come up with a Fuel Consumption Factor (FCF) to include the IRI impact of vehicle fuel usage for both trucks and passenger cars. In other words, they established a relationship between the values of FCF and IRI. The changes in GHG emissions due to the IRI can be calculated with FCF, AADT, road length, and the fuel emission factor. Researchers including Zaabar & Chatti (2010) have also researched the effects of decreasing a road's IRI on fuel savings. The ratio of percentage fuel savings and decrease in IRI can be used as a simpler alternative for estimating the fuel savings with the change in IRI. A more complex model, MIRIAM (SANDBERG et al., 2011) models the change in vehicle fuel consumption with respect to variables in addition to the IRI, including vehicle speed, the pavement's macrotexture, road curvature, and road slope.

2.4 Summary of Practical and Methodological Gaps

Based on the literature review, some of the practical issues are identified for developing a tracking template that suits MTO's needs. These issues include:

- **Gaps in input data.** As agency wide GHG mitigation is not a reporting requirement, and given the MTO's size, structure, mission, and resources, there are challenges associated with obtaining relevant data. This can be due to decentralized internal knowledge, lack of relevant data collection, and potentially time-consuming efforts for quantification. As a result, various assumptions are required where appropriate to address data gaps and save internal resources.

- **Gaps in comprehensiveness of existing tools.** The different coverage among tools, literature, and reports are not necessarily suitable for understanding existing and emerging activities the MTO uses and hopes to track.

- **Lack of validation data**. There are few comparable reports of agency wide emission savings for comparison; Emissions per functional unit (e.g., per km) are also difficult to compare due to the differences in project type, length, thickness, property of material, etc.

Some methodological gaps this study addresses are:

- **Quantifies mitigation measures.** Provide valid mitigation quantification models that are simple enough to fit in an Excel based spreadsheet tool

- **Broadens scope.** Align with the MTO's current practices while having the option for inputting customized data

- **Incorporates real activity data and practices.** Incorporate MTO's HiCo database as a data source and using the Ontario Design Guide

Chapter 3: Data and Methodology

3.1 Requirements

The performance metrics that make up the requirements of a tracking template focus primarily on its form and function. The ideal process will balance objectives such as accuracy, comprehensiveness, relevance, flexibility, efficiency, clarity, and transparency. The requirements are developed based on best practices in the literature (including data and literature provided by MTO), existing tools (including MTO's calculators), practices from other jurisdictions, regulations and guidelines, and requirements and resource-constraints of the MTO. Section 4.1 assesses the compliance of the template based on the performance metrics listed in the table below.

Table 3-1: Requirements and Objectives in Developing POETT

Performance Metrics	**Description**
Accuracy	Results for GHG emissions and reductions can be validated
Comprehensiveness	Capture existing and future GHG mitigation measures from a life-cycle perspective, if feasible.
Relevance	Use Ontario or Canada specific values; Compatible with the current data collection practice in MTO (HiCo system).
Flexibility	Allow easy updates and minor changes. Provide user-input options to override the default data.
Efficiency	Minimize the amount of data required. The tool should run smoothly.
Clarity	Fully understandable and editable without requiring specialized programming knowledge. Results are easy to interpret.
Transparency	Clearly present the emissions, sources, methods, default values, and possible ranges.

3.2 Selected Activities for Quantification

The MTO has the potential to mitigate greenhouse gas emissions from proposed transportation projects within its jurisdiction. Therefore, the agency has been assessing and implementing various GHG mitigation measures (Ontario Ministry of Transportation, 2020) Estimating the GHG emissions reduced by such measures provides quantitative support for these assessment and implementation activities. This chapter describes the methodology employed by POETT for quantifying the effectiveness of selected GHG mitigation measures.

To maintain the relevance and simplicity of the template, mitigation measurements for quantification was selected based on MTO's data availability, popularity of the mitigation measures, ease of quantification, the extent to which GHG emissions can be reduced by the practice, and it potential for future adoption. Certain effective measures are excluded because their effects are difficult to quantify, including broad administrative measures like "environmental sustainability goal setting" and "performance-based specifications and testing". While GHG reductions are generally ultimately derived from either energy savings or CO_2 sequestration, five general categories were selected to be covered by the tool, which include: materials (in-place recycling and other forms of material substitution), transportation, lights, trees, and traffic.

Table 3-2 presents all five mitigation categories and the detailed mitigation measures chosen to be covered in the tool. Relevant information for calculations that are covered by HiCo or bidding sheets are bolded in the table. This includes the area of in-place recycling activities, area or tonnage of warm mix asphalt used, number of trees planted, and the replacement of signs and signals. It should be noted that the database does not differentiate between full-depth reclamation and full-depth reclamation with expanded asphalt. As a result, the user would be required to specify the percentage of additives in the mix design to reflect the actual practice.

Table 3-2 Mitigation Measures chosen for Quantification

Mitigation Category	**Detailed Mitigation Measures**
Materials	**Cold In-place Recycling (CIR)**
	Full Depth Reclamation (FDR)
	Hot In-place Recycling (HIR)
	Cold In-place Recycling with Expanded Asphalt Material (CIREAM)
	Concrete Non-Standard Special Provisions (NSSP)
	Concrete Supplementary Cementing Materials (SCMs) including Blast Furnace Slag, Steel Slag, Class C Fly Ash, Class F Fly Ash; and Limestone Filler
	Potential Carbonation
	Warm Mix Asphalt (WMA)
	Reclaimed Asphalt Pavement (RAP) with Binder Replacement
	RAP/Reclaimed Concrete Material (RCM) used as Aggregate
	Use of other Aggregate Substitution including Foundry Sand, Blast Furnace Slag, Coal Bottom Ash, and Glass Cutlet
	Use of other Bitumen Substitution including Recycled Tires, Crumb Rubber, and Recycled Asphalt Shingles
Transportation	Distance-based calculation for Alternative Fuel Vehicles including Electric Vehicle, Fuel Cell Vehicle, Hybrid Electric Vehicle, Plug-in Hybrid Electric Vehicle

Mitigation Category	**Detailed Mitigation Measures**
	Hauling Distance Reduction for light duty vehicle and trucks
	Idle Control through Auxiliary Power Unit, Fuel Operated Heater and Engine-Off Mode
	Alternative Transportation Mode (Barge and Rail)
	Fuel based Calculation for Alternative Energy Vehicles
	Diesel Engine Repower (year 1989 to 2018)
Lights	**Use of LED Roadway Lights** to replace HID lights including Pulse Start Metal Halide (PSMV), Metal Halide (MH), High Pressure Sodium Light (HPS), Mercury Vapor Lights (MV)
	Use of LED High Mast Lights to replace Metal Halide (MH)
	Use of LED Signal Head (Type: Standard, Highway, Special, Pedestrian) to replace incandescent signal light
	Wind/Solar Powered Signal Head
Trees	**Coniferous**
	Deciduous
	Shrubs
Traffic	Congestion Mitigation based on Work Zone Closing Time and Duration including: • Precast Concrete Pavement • Rapid Set Concrete (Roads) • Aggressive Closure • 24/7 Construction • Optimize Construction Timing • Get-in Get-out • Accelerated Collision Removal
	Roundabout
	Pavement Roughness Improvement (in terms of decrease in International Roughness Index, IRI)

HiCo does not record the use of items such as concrete SCM and other aggregate and bitumen substitutes as they generally serve as supplements and their price is usually covered in the total cost of the concrete and asphalt material. However, as material substitutions comprise some of the most popular and cost-effective measures for mitigation, and are documented as a current MTO practice, they are included in the material category of the quantification despite the lack of available HiCo data. For materials such as RAP and total concrete, the tool is able to extract and aggregate the quantity values from HiCo. However, the current data collection practice which involves generating a HiCo report for each individual item is prohibitively labor intensive. As a result, the values generally assumed for annual consumption of each material, provided by MTO

(K. Perdue, personal comm., 2020), have been used until the relevant data are more readily available.

Traffic and transportation categories are also covered in the tool because they are commonly used and relatively easy to quantify. The MTO has been actively adopting transportation and traffic mitigation measures through initiatives such as the Electric Vehicle Incentive Program and anti-idling campaign. Measures covered in this report include alternative energy vehicles, alternative vehicles, and diesel engine repower, and congestion mitigation. These measures are frequently covered by the MTO's environmental guide (Ontario Ministry of Transportation, 2020), Ontario's climate change strategy (*Climate Change Strategy*, 2015), and mitigation quantification by other jurisdictions (DOT, 2002; Sovacool et al., 2018).

3.3 Tool Framework

The proposed process organization is shown in Figure 3-1. The figure shows sample mitigation measures, inputs, default values, and emission factors used in the tool. The results of the five mitigation categories are summed to determine the emission reductions achieved by the MTO for the assessed year. GHG emissions and emission savings for activities are quantified through activity data and emission factors. An emission factor represents a relationship between an activity level and the associated emissions, usually derived from a series of measurements under various conditions. The general equation for quantifying the emissions of a GHG using an emission factor is (Equation 3.1):

$$(CO_{2e}) = Activity\ Level\ \times Emission\ Factor \times GWP$$

Equation 3.1

Where:

GWP is the 100-year Global Warming Potential relative to CO_2; POETT considers CO_2, CH_4, and N_2O for GHG emission calculations.

As shown in Figure 3-1, quantity values (including trees planted, lights and pavement raw material used) can be either directly extracted from the HiCo database or input by the user. To convert the quantity values to activity levels that match the available emission factors, default values such as pavement structural number, mix design, and operating hours have been selected to reflect the MTO's general practice. Default emission factors including emission factors for electricity, material extraction and processing, and fuel consumption for transportation have been included in the tool.

The emission reductions can be calculated from equations for carbon sinks (e.g., trees, concrete carbonation), by using emission factors that estimate reductions (e.g., WMA and SCMs), or by subtracting the emissions for mitigated activities (e.g., LED lights) from the baseline emissions (e.g., corresponding HID light), as shown in Equation 3.2.

$$\boldsymbol{E_{Reduction}\ (kg) = E_{Baseline,i} - E_{MS,i}}$$

Equation 3.2

Where:

$E_{Reduction}$ = GHG emission reductions, in kg

$E_{Baseline}$ = GHG emissions under a baseline scenario corresponding to strategy 'i', in kg

E_{MS_i} = GHG emissions for mitigation strategy 'i', as listed in Table 3-1, in kg

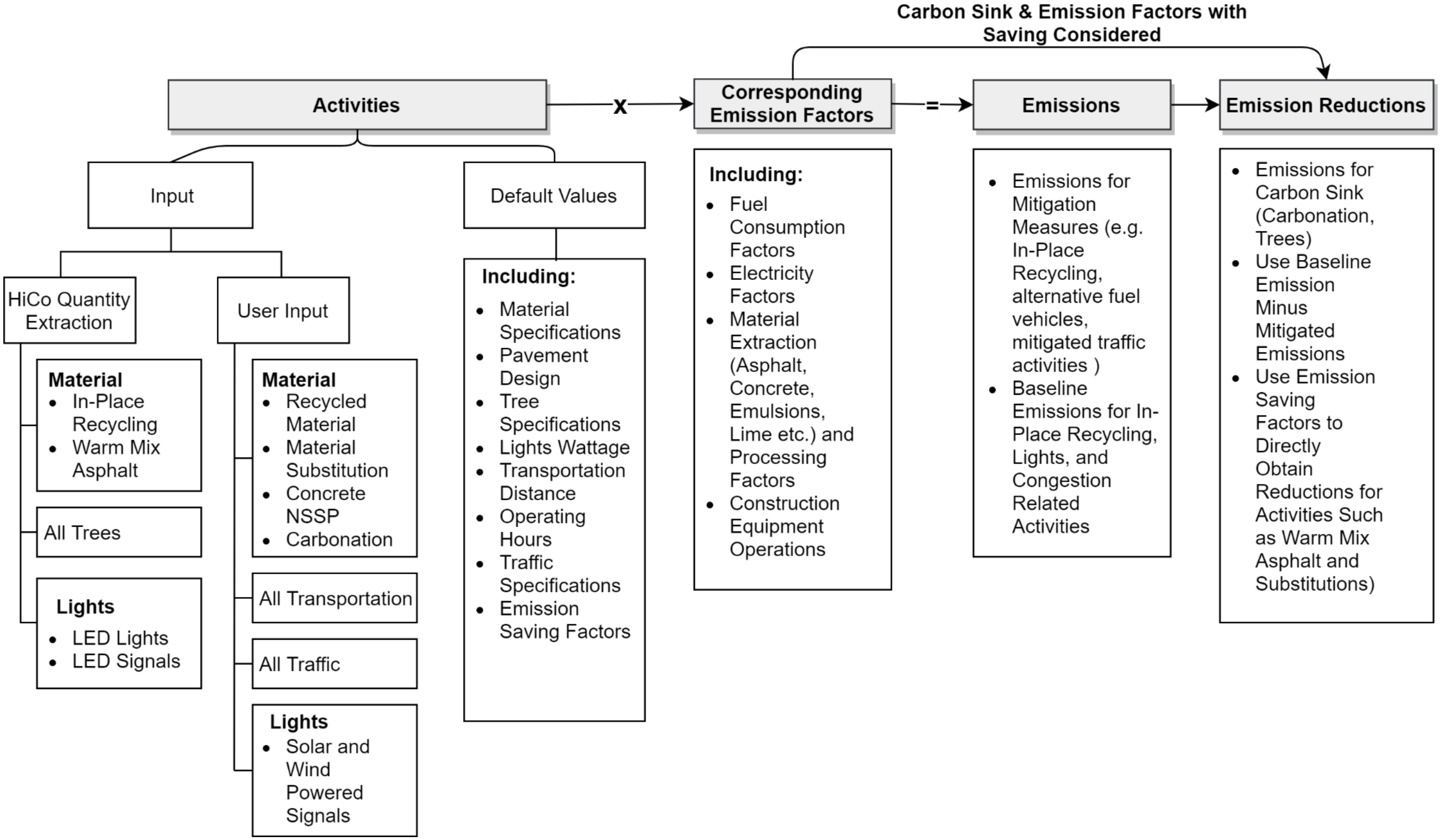


Figure 3-1: Process Organization for Quantifying Annual GHG Mitigation

3.4 System Boundary of the Life Cycle Inventory

Defining system boundaries (stages and processes included) is essential in quantifying GHG emissions from a life cycle perspective. In POETT, both the input-output (EIO-LCA) approach and the process-based approach are applied for the GHG emission inventory. The tool aims to capture all major emission stages and processes while not being data intensive, especially for items that are not currently covered by HiCo. In POETT, emission calculations for In-place recycling, RAP, RCM, alternative fuel vehicles, and coniferous and deciduous trees are covered in detail. For these mitigation measures, the user can view the emissions generated from every process that is included in the system boundary (as shown in Table 3-3).

Table 3-3: System Boundary of the Analysis for Mitigation Measures that are Covered in Detail in POETT from a Life-cycle Perspective

Mitigation Measure	Included in System Boundary	Excluded from System Boundary
In-Place Recycling	• Raw Material Extraction and Material Production (EIO-LCA) • From/To Site Transportation • On-Site Construction Equipment Use	• On-Site Transportation • Equipment and Vehicle Manufacturing • Fuel Production
RAP with or without Binder Replacement, RCM	• Raw Material Extraction and Material Production (EIO-LCA) • Some From/To Site Transportation • Some On-Site Construction Equipment Use	• On-Site Transportation • Equipment and Vehicle Manufacturing • Fuel Production • Transportation and Processing Activity Occur Both in Baseline and Mitigated Scenarios
Alternative Fuel Vehicle and Vehicle Distance Reduction	• Vehicle Operation* • Fuel Production • Vehicle Material & Assembly	
Coniferous, Deciduous	• CO_2 Sequestered by Trees • CO_2 Released through Tree Decomposition	• Emissions Involving Tree Plantings, Maintenance, and Disposal • Possible Emissions Reductions from Nearby Building Heating and Cooling

* By default, the well to wheel emissions, which include all upstream stages of the alternative fuel vehicles are calculated. The user has the option to only include operational emissions.

Activities including concrete carbonation, coniferous trees, deciduous trees, shrubs, and lights and signals have a continuous impact on GHG reduction during their lifetime or operational period. For these activities, POETT allows the user to specify the analysis period, as shown in Table 3-4. The calculations of the listed activities focus on the operational emissions, and processes such as manufacturing and installation of the LED lights and disposal of the used lights are omitted.

Table 3-4:Mitigation Activities that have Multi-year Impacts and Their Period of Analysis

Mitigation Measure	Emission Process Covered	Period of Analysis
Concrete Carbonation	CO_2 Absorbed by Concrete Material for a Specified Period of Time	1-100 year
Coniferous, Deciduous	CO_2 Sequestered by Trees and CO_2 Released through Tree Decomposition	1-50 year, integer only
Shrubs	CO_2 Sequestered Based on the Area that Shrubs Occupy	1-50 year, integer only
LED Lights and Signals	Electricity Consumption in Operation	1-10 years

Detailed life cycle results by stage are not provided for measures that are not covered in Table 3-3 and Table 3-4. Instead, these measures rely on reduction factors that may include multiple stages, but do not distinguish between them explicitly. For material-related measures, GHG reductions are sometimes calculated with general reduction factors, which are obtained from tools and literature and cover emission reductions from energy saving in material production, processing, and disposal. For transportation and traffic-related measures, running emission reductions are often the major consideration, except for the emission reductions for idle control technologies, which are based on the idling rate and idling hours. Further details are provided in Section 3.10.

3.5 Annual Emission Quantification

The primary aim of the tool is to track the quantity of GHG emissions mitigated annually. As such, the tool calculates annual emissions and emission reductions from a life-cycle perspective to highlight the overall climate change mitigation benefit of each activity. For the purposes of annual reporting, the emission reductions of activities that could span multiple years are credited as a single year emission savings. Through this, the full life-cycle benefit of the reduction is assigned to the year in which the activity was initiated. For example, despite the approximately 15 year lifetime of a cold in-place recycling project, the reduction from its material extraction and processing, transportation, construction and end-of-life recycling is entirely credited to the year when the rehabilitation first started. This way, it is easier to interpret the annual mitigation as the result of measures initiated that year. As every project has a different duration, this accounting method may cause some GHG reductions to be attributed to a year in which the material is not necessarily used. The alternative would be to track reductions over the years in which they are expected to occur. This would provide a time series of reductions that more accurately reflects the actual reductions as they occur. In this case, however, emissions mitigated in a given year would primarily reflect the effects of projects initiated in past years. Through discussion with MTO team members, the former approach was adopted. This approach links reductions to their project initiation dates, which matches well with the current data collection process.

This approach of assigning full life-cycle emission reductions to the year of project initiation applies to most activities covered in the tool. For material-related activities, all emission reductions have been credited to the year in which the contract tender is posted. This can be identified from the project contract number. Similarly, for lights, signals, trees, and concrete carbonation, which all have multi-year GHG reductions, the tool credits the multi-year emission reductions to the contract year. Fifty years, five years, five years, and thirty years have been selected as the default life span of the trees (coniferous, deciduous, shrubs), lights, signals, and concrete pavement material, respectively. For example, when planting 100 1.5m height coniferous trees in 2019, and assuming a 50-year analysis period, the total CO_2 sequestered by the trees between 2019 and 2049 (with survival rate adjustment) is credited to the year 2019. Similarly, the LED lights planned for use between 2020 to 2025 have all their electricity savings awarded to 2020. This form of assignment is considered because the information provided by the HiCo database only includes the number of lights, signals, and trees added within a year without counting the existing fixtures and trees. To instead account for actual reductions in a given year, surveying data such as existing LED numbers, number of trees and their conditions should be used. The users have the flexibility to specify any analysis period, or input ‘one year’ to determine the GHG reductions for a given year without considering the overall life-cycle reductions.

For mitigation activities covered in the transportation category, the annual estimates are obtained from using default activity values such as yearly vehicle miles travelled, annual fuel consumption, hours of operation per year, AADT, and annual average operating hours in Ontario.

For traffic-related mitigation activities, the tool does not directly provide an annual estimation. Instead, project-based calculations which calculate emission savings from individual roundabout and congestion mitigation projects are performed. For these modules, detailed project-specific inputs are required. This is because each traffic project has different road design, traffic accommodation, and mitigation scenarios, which will lead to large variations in emission reductions among each roundabout built or road closure project. For annual emissions, roundabout and surface roughness improvement both use 365 days of emission savings whereas the emission savings of congestion mitigation depends on the input project duration.

3.6 Tool Design

The tool aims to (1) comprehensively and clearly capture the GHG reduction efforts and results within the Ministry, (2) provide details of reduction contributions and comparisons of each mitigation activity from a life-cycle perspective, (3) allow the MTO climate change personnel to use minimum input and generate emission reduction reports in a quick and transparent manner, and (4) capture GHG emissions and emission reductions for individual project or activity, when necessary data are available. Below is a short discussion of the tool interface and its design. The user manual is included as the Appendix B of this document.

Figure 3-2. shows the tabs included in the tool. In addition to the introduction tab, there are eight tabs, which include:

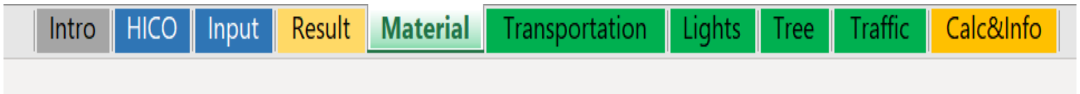


Figure 3-2: Tabs Presented in The Calculation Tool

1. HICO
2. Input
3. Result
4. Material
5. Transportation
6. Lights
7. Trees
8. Traffic

Most of the information can be inputted, extracted, or altered through HiCo and the Input sheet (see Figure 3-1). The emission reduction results for each mitigation activity can be viewed in the 'Result' tab. By limiting the number of tabs that the user needs to work with, user errors such as accidently changing or deleting the default data can be reduced. A short description of each tab in the tool is presented below.

__HiCo Worksheet__

The HiCo Worksheet is designed for importing and aggregating data from MTO HiCo reports. It can combine all the HiCo reports uploaded, and automatically extract data and calculate the total quantity of the material of interest in the selected year. The HiCo tab also allows the user to input material quantities and override the HiCo extracted data, as well as provides space for the user to implement project-based estimation. As discussed, HiCo data is only available for the majority of in-situ recycling, WMA, LED lights and signals, and trees. As a result, POETT requires additional user input.

Input Worksheet

The Input worksheet guides the user to fill in the required information for quantification and make changes to the default data. The input information is categorized into material, transportation, lights, trees, and traffic, which correspond to the name of each green calculation tab. The required input is marked in green, while the default and dropdowns are marked in blue and yellow, respectively. The user can change the default value from the Input tab or restore the tool's default data by pressing the 'set to default' button. Input requirements for each category vary. For example, calculating CO_2 sequestered by trees requires minimal input - the user only needs to select among a few drop downs; while for traffic-related estimation, detailed input including AADT, speed limit, and truck percentage, to name a few, are necessary for a relatively reliable result. For traffic related mitigation activities, a pivot table has been used to record emission reductions for all projects. After inputting individual project information, the user needs to hit 'add projects' to record the calculated results.

Result Worksheet

The Result tab presents the GHG mitigation calculation results after the user completes the HiCo and Input tab. This tab presents the annual GHG reduction from the MTO in tonnes, and places the category and specific measure with the highest reduction at the top. The Results tab also shows: the emission savings by each category (material, transportation, lights, trees or traffic); the percent reduction contributed by each category; and the impact of other possible savings. This tab helps the user to understand the GHG reductions achievable through taking specific measures for the year, and the potential reductions and contributions that can be achieved from each mitigation strategy.

Individual Calculation Sheets

Sheets four through eight (Material, Transportation, Lights, Tree, and Traffic) contains more calculation details. Each tab provides calculations for one or more emission reduction strategies. These tabs are available for users to understand the calculation steps, input project level data, change assumptions, and view sources of the quantity data, emission factors, and equations when needed.

For now, the tool only presents annual reductions for one year. To compare reductions across multiple years, another template needs to be filled and HiCo data extraction needs to be performed for the selected year. It is worth noting that the GHG reductions in a given year will vary depending on the available mitigation opportunities. Emission savings largely depend on the project needs and the economy, which vary annually.

Many mitigation activities involve multiple project phases. For example, RAP reduces GHGs from binder and aggregate extraction and the reduced trips for material disposal. Currently, GHG reductions for each project phase are not available because HiCo does not differentiate by phase.

3.7 Data Collection and Extraction

The accuracy of the tracking template's output will depend in part on a rich foundation of relevant and recent data. Activity data are either obtained from quantities in HiCo or default values from reports, dataset, and standards. When collecting default values for activities, the location information was evaluated to ensure it is relevant to Ontario. Default activity data such as annual driving distance of vehicles, growth conditions of trees, typical wattage of the signals, and IRI for each road section were collected for Ontario. They were collected from sources including Ontario vehicle registration, Natural Resources Canada reports, and OPSS standards. When up-to-date Canada relevant data was not readily available, values from various sources were collected and the median value was used to represent common practices. While the data provided were carefully evaluated to provide the overall picture for Ontario, user specified data (e.g., material density, layer thickness, actual traffic) is always preferred when performing a project-based estimation.

Factors such as recency, geographic relevance, and rating were taken into consideration for the selection of the emission factors. Preference was given to emission factors based on up-to-date Canadian process activity data. US emission factor data was also assumed to be relevant to Ontario's analysis where needed. In some cases, emission factors vary greatly across sources (e.g., bitumen and cement), therefore the median of all collected data was used.

For HiCo provided quantities, POETT processes and aggregates information from the imported HiCo quantity sheet. The HiCo tab of the tool presents a list of included mitigation activities. The imported sheet has been first formatted to store information under the header 'Title', 'Unit', and 'Quantity' for each HiCo item or activity. With Excel macros enabled, POETT can extract the values and units of the listed mitigation items by identifying keyword lists and comparing the item names with the imported sheet. If multiple entries exist in the uploaded sheet that correspond to the mitigation activity listed, the sum of the quantity of the items is presented. For example, if the datasheet contains three CIREAM projects of amounts 40,432 m^2, 159,593 m^2, and 89,032 m^2, respectively, the tool will automatically fill 289,057 m^2 as the HiCo quantity. POETT then processes the extracted HiCo data to match the units of the emission factors. For example, HiCo provides the area of the WMA pavement in 'values' and the lift thickness in 'title' (e.g., Superpave 12.5 - Warm Mix - 40 mm Lift Thickness, in m^2). The tool is set to extract the 40 mm thickness, and multiply with the area provided, and automatically generate the total mass of the WMA based on the default density.

A formatted HiCo master list, when not directly available, can be generated from the MTO HiCo report or tender items list. Generating a master list allows for an easier extraction of values by discarding unnecessary information and improving the tool's speed. Two macro workbooks are included to generate formatted sheets with selected information. Each HiCo report contains the history of one tender item including its unit, contract number, corresponding region, and item cost. To obtain a comprehensive list of mitigation activities, the reports related to individual mitigation activities need to be generated and downloaded. For example, with coniferous trees, four reports including 'coniferous 500 mm height', 'coniferous 1 m height', 'coniferous 1.5 m height', and 'coniferous 2 m height' are downloaded to one folder. The tool can read the folder that contains the HiCo reports and combine all useful information into a pre-made template for the main tool to extract and aggregate.

Instead of using HiCo, the second option is to obtain values from the tender items downloaded from the MTO Registry, Appraisal and Qualification System (RAQS) website (*Contract Bulletin*, 2020). A tender item list contains all items and activities included in one project regardless of whether any mitigation effort is made. All project tender documents for the year need to be downloaded to one folder for the tool to generate a list that fits the existing template. Both options allow the tool to read the contract year so that multi-year estimations could be reported and compared. This also creates the opportunity for understanding emission reductions by region and highway sections.

3.8 Data Values

Table 3-3 shows the default data and the data sources for calculating greenhouse gas emission reductions. A longer list of detailed default data such as construction equipment specifications, alternative energy vehicle emission rates, road IRI, etc., are included in Appendix E.

Table 3-5: Default Values for Calculations in POETT

Category	Item	Value	Unit	Hyperlink	Range	Citation
Material Density	WMA	2420	kg/m^3	Wisconsin DOT Report	2420-2650	(Schmitt et al., 2009)
	Superpave	2420	kg/m^3	PaLATE 2.2, NRCan Report, 2005,	2420-2650	(Canadian Industry Program for Energy Conservation, 2005)
	RAP	2250	kg/m^3	FHWA Report, 2012 (Within Range)	1490-2300	(Federal Highway Administration Research and Technology, 2012)
	Concrete	2439	kg/m^3	Washington DOT Example	2231-2577	(Washington State Department of Transportation, n.d.)
Material Structural Coefficient	Virgin Asphalt	0.42	NA	Pavement Asset Design and Management Guide, 2013	0.4-0.44	(Tighe, 2013)
	Existing Hot Mix Asphalt	0.38	NA	MTO Presentation, Toronto Pavement Design and Rehabilitation Guideline	0.14-0.42	(City of Toronto Transportation Service Division, 2019)
	FDR with Stabilizing	0.25	NA	Alberta Transportation Design Bulletin, 2017, Toronto Pavement Design and Rehabilitation Guideline	0.2-0.25	(City of Toronto Transportation Service Division, 2019), (Alberta Ministry of Transportation, Surface Engineering, 2017)
	FDR only (Pulverization)	0.14	NA	Alberta Transportation Design Bulletin, 2017	0.1-0.14	(Alberta Ministry of Transportation, Surface Engineering, 2017)
	CIR/CIREAM Layer	0.3	NA	Alberta Transportation Design Bulletin, 2017, Davision & Croteau, 2003;Pavement Asset	0.2-0.44	(Alberta Ministry of Transportation, Surface

Category	Item	Value	Unit	Hyperlink	Range	Citation
				Design and Management Guide, 2013		Engineering, 2017), (Davidson et al., 2013), (Tighe, 2013)
	Granular Base	0.12	NA	MTO Presentation; Pavement Asset Design and Management Guide, 2013	0.12-0.14	(Tighe, 2013)
	Subbase	0.115	NA	Pavement Asset Design and Management Guide, 2013	0.09-0.14	(TIGHE, 2013)
	HIR	0.3	NA	Kandhal & Mallick, 1998 (FHWA Report)	NA	(Kandhal & Mallick, 1998)
Material Upstream Emission Factors	Aggregate	0.011	tonne $CO_{2,e}$/tonne material	Median of PaLATE 2.0, ROADEO, Loijos, Chehovits & Galehouse, Adapted PaLATE, PaLATE2.2,, PE2, UK Highway England Carbon Tool, GreenDOT, Chai et al	0.00453-0.014	(Horvath, 2007), (A. Mukherjee, 2013)
	Bitumen	0.48	tonne $CO_{2,e}$/tonne material	Median of PaLATE 2.0, ROADEO, asPECT, , Chehovits & Galehouse, Adapted PaLATE, PaLATE2.2, PE2,GreenDOT	0.285-1.237	(University of Washington, 2011)
	Cement	0.927	tonne CO_2e/tonne material	Median of PaLATE 2.0, Loijos, ROADEO, Jamishidi & Hamzah, asPECT, Chehovits & Galehouse, Adapted PaLATE, PaLATE2.2, PE2, UK Highway England Carbon Tool, GreenDOT	0.29-1.1	(Horvath, 2007), (Jamshidi et al., 2013), (A. Mukherjee, 2013), (N. Santero et al., 2013),(Loijos, 2011), (Highways England, 2015) (University of Washington, 2011) (Chehovits & Galehouse, 2010)
	Concrete	0.15212	tonne CO_2e /tonne material	Median of PaLATE 2.0, ROADEO, Jamishidi & Hamzah, Highway England Carbon Tool,	0.041-0.21	(Horvath, 2007), (Jamshidi et al., 2013), (Deng, 2010) (Highways England, 2015)

Category	Item	Value	Unit	Hyperlink	Range	Citation
	Emulsion	0.221	tonne CO_2e /tonne material	Median of PaLATE 2.0, ROADEO, asPECT	0.19-1.17	(Horvath, 2007), (Deng, 2010) (Highways England, 2015)
Aggregate Substitution	Foundry Sand	0.011	kg CO_2e reduced/tonne material	Gallivan et al., 2010 (GreenDOT)		(Gallivan et al., 2010)
	Blast Furnace Slag	0.011	kg CO_2e reduced/tonne material	Gallivan et al., 2010 (GreenDOT)		(Gallivan et al., 2010)
	Coal Bottom Ash	0.011	kg CO_2e reduced/tonne material	Gallivan et al., 2010 (GreenDOT)		(Gallivan et al., 2010)
	Glass Cutlet	0.000772861	kg CO_2e reduced/tonne material	Gallivan et al., 2010 (GreenDOT)		(Gallivan et al., 2010)
SCMs	Blast Furnace Slag	0.35	tonne calcined CO_2 /tonne material	Barnett & Torres, 2010 (EPA Report)		(Barnett & Torres, 2010)
	Steel Slag	0.51	tonne calcined CO_2 /tonne material	Barnett & Torres, 2010 (EPA Report)		(Barnett & Torres, 2010)
	Class C Fly Ash	0.2	tonne calcined CO_2 /tonne material	Barnett & Torres, 2010 (EPA Report)		(Barnett & Torres, 2010)
	Class F Fly Ash	0.02	tonne calcined CO_2 /tonne material	Barnett & Torres, 2010 (EPA Report)		(Barnett & Torres, 2010)

Category	Item	Value	Unit	Hyperlink	Range	Citation
Limestone	Limestone Filler	0.6535125	tonne CO_2/tonne Limestone	GreenDOT		(Gallivan et al., 2010)
Bitumen Substitution	Recycled Tires/Crumb Rubber	0.0337	kg CO_2e Reduced/ tonne material	GreenDOT	0.337-0.5	(Gallivan et al., 2010)
	Recycled Asphalt Shingles	0.1	kg CO_2e Reduced/ tonne material	EPA WARM Model		(US Environmental Protection Agency, 2015)
Material Processing	Hot Mix Plant	0.0185	tonne CO_2e /tonne material	PaLATE, AP-42	0.0165-0.0185	(Horvath, 2007), (US Environmental Protection Agency, 2004)
	WMA	4.8	kg CO_2e reduction/tonne	MTO Report Politano, 2012	4.1-5.5	(Politano, 2012)
	RAP and Aggregate Drying	1.41	tonne CO_2/tonne HMA	Calculate from NYSDOT Report with Canada Fuel Composition, Median of the multiple RAP%	0.58-1.93	(Frederick & Tario, 2009), (Canadian Industry Program for Energy Conservation, 2005)
Material Transportation EF	Truck	68.46	g CO_2/tonne-km	Cefic 2011 (ECTA Guide)	39.7-151.1, depending on load and % deadhead	(Cefic, 2011)
	Rail	21	kg CO_2 /1000 RTK	Cefic 2011 (ECTA Guide)	7.3-26.3	(Cefic, 2011)
	Barge	31.25	kg CO_2 /1000 RTK	kg CO_2 /1000 RTK	31-32.5	(Cefic, 2011)
	Class I Freight	14.07	kg CO_2 /1000 RTK	Railway Association of Canada Report		(Railway Association of Canada, 2015)

Category	Item	Value	Unit	Hyperlink	Range	Citation
	Regional and Short Line Freight	16.75	kg CO_2 /1000 RTK	Railway Association of Canada Report		(Railway Association of Canada, 2015)
	Liquid Bulk Vessels	20.35	kg CO_2 /1000 RTK	Global Logistics Emission Council Report		(STC-Nestra B.V., 2018)
	Container Vessels	21.667	kg CO_2 /1000 RTK	Global Logistics Emission Council Report		(STC-Nestra B.V., 2018)
Construction Equipment	CO_2 EF (hp<100)	0.586	kg CO_2 /hp-hr	EPA NONROAD Model		(U.S EPA, 2008)
	CO_2 EF (hp>=100)	0.527	kg CO_2 /hp-hr	EPA NONROAD Model		(U.S EPA, 2008)
	Load Factor			Athena Pavement LCA and EPA NONROAD Model	0.42-0.85	(Athena Sustainable Materials Institute, 2018), (U.S EPA, 2008)
	Equipment Fuel Consumption, hp, Productivity	See Table E-3		Athena Pavement LCA, PaLATE2.2, Adapted PaLATE		(Athena Sustainable Materials Institute, 2018), (University of Washington, 2011), (Horvath, 2007)
Regular and Alternative Energy/Technology Vehicle	CO_2, CH_4, N_2O, and CO_2e Emission Rates for Vehicle Type and Fuel Combinations	See Table E-9	g/km	GHGenius 5.0d	139.79-1997.83 for HDV and 57.58-207.95 for LDV	(*GHGenius 5.0d*, 2019)
	VKT for Light Duty Vehicle	16200	km	Transportation in Canada Report (Table RO4)		(Transport Canada, 2020)
	VKT for Trucks for Hire	70400	km	Transportation in Canada Report (Table RO11) – for hire	70400-146000	(Natural Resources Canada, 2009), (Transport Canada, n.d.)

Category	Item	Value	Unit	Hyperlink	Range	Citation
	Number of Light Duty Vehicle	8357600		Statistics Canada (Ontario 2018)		(Government of Canada, 2019)
	Number of Heavy-Duty Vehicle (Short Haul)	113743		Statistics Canada (Ontario 2018) and Vehicle Distribution from Wilson Wang's thesis		(Government of Canada, 2019), (W. Wang et al., 2020)
	Number of Heavy-Duty Vehicle (Long Haul)	18209		Statistics Canada and Vehicle Distribution from Wilson Wang's thesis		(Government of Canada, 2019), (W. Wang et al., 2020)
	Road/Off Road Emission Rate (Fuel Based)	See Table E-10	g/L fuel	NIR 2020 Emission Factor for Mobile Combustion (Table A6-13)	1508-21599	(Environment and Climate Change Canada, 2020)
	Diesel Engine Repower Emission Rate	See sample in Table E-12	CO_2e kg/mile	CMAQ Toolkit $CO_{2,e}$ emissions rates are derived from US National Scale Run for all 2019-2030 for all years, months, and hours, Rates for 2019 $CO_{2,e}$ that replace the vehicle from 1989-2019 was used	0.843-1.824	(Federal Highway Administration (FHWA) Office of Natural Environment, 2020)
Truck Idle Control Technology	Extended Idle	7151	g/hr	Sonntag & Choi, 2017 (EPA MOVES Presentation), AFLEET, EPA Phase 2 Standard	5114-7478	(Wysor et al., 2016) (Sonntag & Choi, 2017.), (Agronne National Laboratory, 2019), (United States Environmental (Protection Agency, 2016, p. 2)
	Auxiliary Power Unit	3510	g/hr	Sonntag & Choi, 2017 (EPA MOVES Presentation), AFLEET, EPA Phase 2 Standard	1924-3510	
	Fuel Operated Heater	577	g/hr	AFLEET MODEL calculated with Canada Fuel CO_2 Emission	346-577	

Category	**Item**	**Value**	**Unit**	**Hyperlink**	**Range**	**Citation**
Lights	Electricity (Ontario)	40	g/kwh	National NIR 2017		(Environment and Climate Change Canada, 2017)
	LED and Corresponding HID	See Table E-4		Interpolate from Industry Fact Sheets: Galco Industry, Cooper Lighting, MidAmerican Energy Company, ecopower, MyLED		(Electronics, n.d.), (Wolf, 2015)
Signals	Signal Load Factors	See Table E-5		GreenDOT	0.05-0.45	(Gallivan et al., 2010)
	Power of the Signals	See Table E-6	Watts	Original OPSS 2461 calculated with OTM Book 12 Signal Type	95-123.7	(*OPSS 2461 Signal Heads*, 2007), (*Ontario Traffic Manual - Book 12 - Traffic Signals*, 2012, p. 12)
Trees	Survival Factor	See Table E-8		US Department of Agriculture Report, with linear interpolation	0.2-0.75	(McPherson, 1999), (DOE, 1998)
	Shrub CO2 Sequestered Rate	0.81	Mg/ha-year	Justine et al. - Supporting Information Table S5	0.2-2.29	(Justine et al., 2017)
	Constant for Tree Growth Curve (dbh) Calculation	See Table E-9	inch	Carbon Dioxide Reduction: Through Urban Forestry Appendix D in North Growth Zone		(McPherson, 1999)
	Biomass Allometric Equation		kg	Carbon Dioxide Reduction: Through Urban Forestry Appendix D in North Growth Zone		(McPherson, 1999)

Category	**Item**	**Value**	**Unit**	**Hyperlink**	**Range**	**Citation**
Congestion Mitigation	Speed-based Aggregated Emission Rate	See Table E-10	kg/km	EPA MOVES 2014b with Ontario Specific Data Wilson Wang's thesis	0.848-4.895	(US EPA, 2014), (W. Wang et al., 2020)
Road Improvement	Sample IRI for Ontario Road in 2017	See Table E-13	m/km	Ontario Transportation Dataset – Pavement Condition for Provincial Highway		(Ontario's Open Data, n.d.)

3.9 Process Flow of the Calculation

Figure 3-3 presents the general process for the quantification using the data discussed and highlights the calculation process and data type. As shown, default values including specifications and emission factors can be applied to one or more mitigation activities, especially for the material and transportation category.

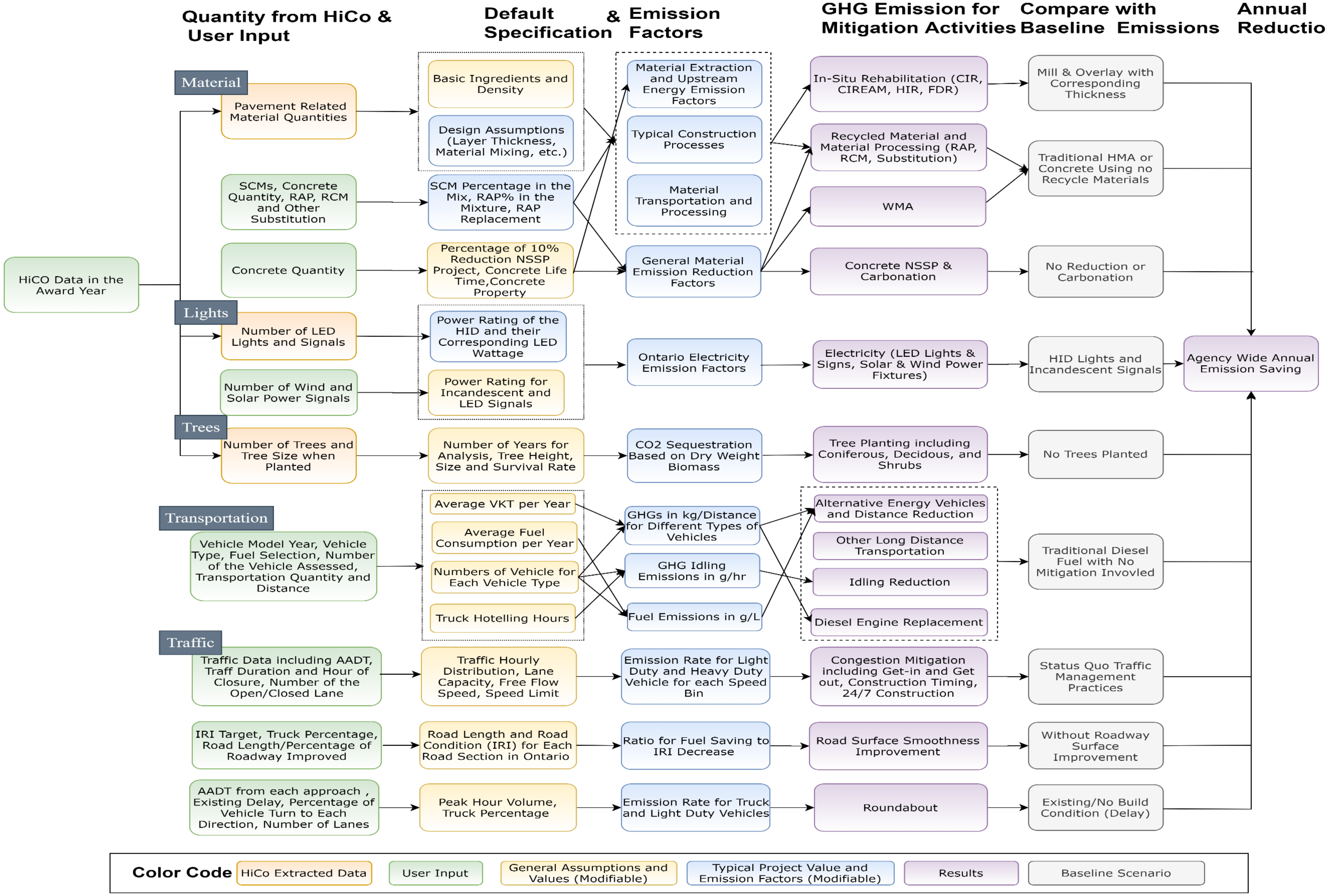


Figure 3-3: Detailed Data Used and Calculation Processes for each Mitigation Activity

3.10 Detailed Methods and Assumptions

This section describes the equations used within POETT to estimate greenhouse gas emission reductions for emission categories and mitigation strategies. Underlying assumptions to reduce the complexity in the adopted methodology and data availability issues for the tool have also been described here. It is important to note that these assumptions can be modified at the discretion of the user by providing project-specific data. The values of parametric inputs to equations described in the following sections are shown in the Section 3.8 (Table 3-5) and the Appendix E of this document.

A few strategies, including concrete carbonation, IRI, and diesel engine repower, though calculated in the tool, do not directly count towards the total GHG reductions. For the first two activities, this is primarily owing to gaps in data or methods that hinder accuracy, and obscure the level of adoption of these activities. Concrete carbonation does offset some of the GHG emissions with concrete use, and, while not a mitigation activity, could arguably be credited to MTO as a carbon sink (Rehan & Nehdi, 2005). However, the carbonation rate depends on the concrete dimensions, which vary considerably by application (e.g., barriers or pavement) and are not tracked in HiCo. As such, this value is provided only as high-level estimate and not automatically included in mitigated emissions. IRI, similarly, is not included because the method adopted (detailed in this chapter) is purposefully simplified to limit data requirements, thereby yielding a high-level estimate. Lastly, emission reductions owing to diesel engine repower are not included in the total reductions by default as it is assumed that these reductions would mainly be credited to contractors; however, MTO may choose to include it, e.g., for any relevant vehicles under their purview. For these reasons, reductions by concrete carbonation, IRI, and diesel engine repower are all considered as additional savings and are calculated separately. The results of these three strategies are also compared with the total reductions achieved by the other strategies.

3.10.1 In-Situ Recycling

When estimating GHG emissions from a life cycle perspective, POETT accounts for emissions from in-situ recycling activity including (1) raw material extraction and processing (2) material transportation (which include trips from source to plant, plant to site, and site to landfill), and (3) on-site construction equipment. An estimation of the thickness of the recycled and additional overlay layer is required to ensure a sound selection of the baseline and mitigation scenario. Here, the AASHTO 1993 method is applied. The recycling measures, outlined in this method, must achieve the same structural number as its baseline mill & overlay by adjusting their thickness for the recycling layer and the overlay. The thicknesses of the layers can be obtained using Equation 3.3.

$$D_j\ (mm) = \frac{SN - \sum_k a_k D_k M_k}{a_j}\ for\ j = 1, and\ k = 2, 3$$

$$D_k (mm) = \frac{SN - \sum_j a_j D_j}{a_k M_k}\ for\ j = 1, and\ k = 2, 3$$

Equation 3.3

Where:

a = a layer coefficient that represents the relative strength of the material

D = actual thickness of the layer, in mm

M = drainage coefficient for the base course

The layer thicknesses estimated for the baseline and mitigation scenarios can then be used to determine the material mass of each raw material used (in tonnes) and any associated waste for each layer via Equation 3.4. The equation below also requires values for the area (in square meters) over which the in-place recycling is performed (provided by HiCo), the density for each basic ingredient in the surface course (with defaults derived from technical reports), and the percentage of emulsion and other additives (provided by the user). The weight of each raw material may vary depending on the mix design.

$$Material\ Quantity_i\ (tonne) = A_i \times D_i \times \rho_i \times Weight\ Percentage\ _i \times 10^{-6}$$

Equation 3.4

Where:

$Material\ Quantity_i$ = mass of the basic ingredients (e.g., aggregate, asphalt binder) in the layer, in tonne

A_i = Area over which in-place recycling activities were performed, provided by HiCo database or user input, in m^2

D_i = thickness of the layer, in mm

ρ_i = Density of each basic ingredient in the surface course, in kg/m^3

$Weight\ Percentage\ _i$ = percentage of the mixture by weight in asphalt concrete mixture

The total CO_2e emitted from extracting and processing all raw materials ($\boldsymbol{E_{Material\ Processing}}$) can then be calculated by applying their respective emission factors ($\boldsymbol{EF_i}$) as shown in Equation 3.5. The GHG reduction for a given raw material category can then be calculated by subtracting emissions for in-place recycling from the baseline emissions. It is expected that GHG emissions from in-place recycling are lower because of the savings from reduced use of raw materials generally outweighs the additional emulsion and chemical use.

$$E_{Material\ Processing}(kg\ CO_2e) = \sum_i Material\ Quantity_i \times EF_i$$

Equation 3.5

Where:
EF_i = raw material production and processing CO_2e emission factor for material i, in kg/tonne

GHG emissions from transportation ($E_{Material\ Transportation}$) for in-situ recycling include the transport of a certain material quantity for a specified distance using trucks, rail, or barge. The GHG reduction in this case is attributed to less material being transported. A collection of emission factors (in g CO_2/tonne-km) that are varying with deadhead percentage and load quantity have been selected for trucks, while a constant number has been selected for rail and barge, respectively. Given the distance between each location (e.g., plant to site, site to landfill), GHG emissions for transporting aggregate, bitumen, HMA, emulsions, chemicals, and waste can be estimated with Equation 3.6.

$$E_{Material\ Transportation}\ (kg\ CO_2e) = \sum (Material\ Quantity_i \times D_i \times EF_{i,j,k}\ \times 10^{-3})$$

Equation 3.6

Where:

$Material\ Quantity_i$ = Quantity of Material i (including basic ingredient, asphalt mixture, and waste) transported, in tonne

D_i = Distance material i was transported, in km

$EF_{i,j,k}$ = Emission factor for transport mode i corresponds to payload tonnes j and percentage deadhead k, in g CO_2/tonne-km

Equipment covered by the construction section includes asphalt pavers, compactors, rollers, in-place recyclers, etc. Each equipment has unique values of horsepower, productivity, and load factors. The CO_2 emission factors, in this case, are based on the brake-specific fuel consumption value, which is related to the rated horsepower. Equation 3.7 is adapted from the EPA NONROAD (U.S EPA, 2008) and used for quantifying construction emissions.

$$E_{Construction}\,(kg\ CO_2) = \sum \frac{Material\ Quantity_i}{Productivity_j} \times Power_j \times LF_j \times EF_j$$

Equation 3.7

Where:

$Material\ Quantity_i$ = Quantity of Material (e.g., hot mix asphalt, recycle material, etc.), in tonne, m^2, or m

$Productivity_j$ = Productivity of the construction equipment j, in corresponding material quantity process per hour

$Power_j$ = Average power of the construction equipment j, in hp

LF_j = Load Factor (fraction of available power) of the construction equipment j

EF_j = Emission factor for construction equipment j, in kg CO_2/hp-hr

Assumptions for the quantification boundary and default values have been made to maintain the simplicity of the template. All emissions, including raw material extraction, have been credited to a project contract year. POETT focuses on factors that are known to have a relatively large impact on GHG emission reductions. Water use, for example, though required in every pavement project, is excluded from POETT because it does not emit much GHGs nor does it differ significantly between mitigation activities.

Concerning the properties of raw materials, unless otherwise specified, virgin aggregate and bitumen are used for both the mill and overlay baseline and the overlay layer on top of the in-place recycled material for mitigation measures. A variety of additives are used to improve the structural stability of the recycled layer (e.g., various kind of chemicals, cement). Lacking specifics about the additives applied, a constant value is selected for the default density and the emission factor.

With default assumptions, the thickness used for recycling is assumed to be equal to the mill/pulverizing thickness. In this case, there is no waste occurring in the process. As a result, no material is sent to the landfill for in-situ recycling, while all the milled material from mill & overlay goes to landfill. These assumptions can be changed by the user based on the actual practices in the project. It should be noted that the HiCo dataset shows only one option for FDR, namely 'In-Place Full Depth Reclamation'. This implies that the database does not specify if mixes contain emulsion/foamed asphalt (EAS). As a result, the user should specify the emulsion content in the mix design, or a 0% value will be assumed.

For the transportation of materials, unless otherwise specified, all trucks are assumed to share the same loading capacity and deadhead percentage. A fixed emission factor has been applied to all trucks, rails, and barges, respectively. Variations in emission factors due to road, temperature and humidity conditions, and vehicle characteristics are not included. For each type of material (including additives), the same value of source to destination distance is assumed, despite the possibility of obtaining virgin material from different locations in the same project. By default, 30 km is assumed for one-way truck transport and 300 km is assumed for one-way rail and barge transport.

For construction equipment, one set of specifications is applied for each type of equipment. In practice, multiple different units with the same function could be used on site. As a result, with the adapted NONROAD equation, emissions from one equipment to process a certain quantity of material is the same as the emissions from multiple pieces of equipment with the same specifications. Also, for simplicity, one pass for all processes is assumed (e.g., roller only goes through a certain quantity of material once).

3.10.2 Concrete NSSP

For concrete NSSP, a simple 10% concrete GHG emission reduction, which is applicable to all MTO projects, is assumed. For 'enhanced reduction' projects which are currently used for demonstration, the quantity of concrete used or the percentage of projects that achieve a 20% reduction target can be specified by the user. The total emission reductions have been calculated by multiplying the concrete quantity that achieved each reduction target with the respective emission reduction factor as shown in Equation 3.8. The tool also provides estimates of CO_2e reduction for different SCMs/limestone combinations. By inputting the concrete quantity, cement percentage, and mix percentage of SCMs or limestone, the total CO_2e emission reduced by the combination can be estimated. Additionally, the tool will show if the NSSP mix requirement, 10% reduction goal, and 20% reduction goal are met by the combination, respectively.

$$Total\ Emission\ Reduction\ (kg) = Q_{10\%\ R} \times EF_{10\%}\ + Q_{20\%\ R} \times EF_{2o\%}$$

Equation 3.8

Where:

$Q_{10\%\ R}$ = Concrete Quantity that achieves the target of 10% GHG emission reduction, in tonne

$EF_{10\%}$ = Emission factor that represents 10% concrete GHG emission reductions, in kg/tonne

$Q_{20\%\ R}$ = Concrete Quantity that achieves the target of GHG emission reduction, in tonne

$EF_{20\%}$ = Emission factor that represents 20% concrete GHG emission reductions, in kg/tonne

The selected emission factors for concrete account for the detailed processes involved in its production life cycle and assume that the concrete mix is domestically produced. The MTO has consumption data reports on more than 100 concrete related items; however, the agency currently does not have an established way to extract multiple reports other than downloading each of them individually from the HiCo system. Therefore, following a direct consultation with the MTO, a constant concrete consumption quantity of 50,000 m^3 has been assumed.

3.10.3 Concrete Carbonation

To estimate the CO_2 sequestered by the concrete material, this report follows the steps specified by 'Global Warming Potential of the Pavement' (N. J. Santero & Horvath, 2009). The first steps involve calculating the depth (d_c) of the carbonation using Equation 3.9. The user specifies the evaluation time in years (Default value: 30 years).

$$d_c(mm) = k\sqrt{t}$$

Equation 3.9

Where:

d_c = Depth of carbonation, in mm.

k = Rate factor, in mm/year$^{1/2}$; the value can vary from 0.15 to 15 mm/year$^{1/2}$ depending on the concrete strength and exposure type

t = Evaluation period, in years

The mass of CO_2 sequestered through carbonation (kg) can then calculated using Equation 3.10.

$$m_{carb}(\text{tonne}) = d_c \times A \times \rho_c \times m_{\text{cement}}/_{concrete} \times m_{\text{CaO}}/_{cement} \times \frac{M_{CO2}}{M_{CaO}} \times \varepsilon$$

Equation 3.10

Where:

m_{carb} = Mass of CO_2 sequestered through carbonation, in tonne

d_c = Depth of the carbonation, in m

A = Surface area of the pavement, in m^2

ρ_c = Density of the concrete, in tonne/m^3

$m_{\text{cement}}/_{concrete}$ = Mass ratio of cement in concrete

$m_{\text{CaO}}/_{cement}$ = Mass ratio of CaO in cement

M_{CO2}= Molar mass of CO_2 (44 g/mole)

M_{CaO}= Molar mass of cement (56 g/mole)

ε = Binding efficiency of CO_2 to CaO

In addition to assuming a constant consumption volume for concrete, an assumption is required for the general depth or thickness of the concrete. In this report, 225 mm is assumed as the thickness of the concrete pavement. The area of the concrete is then calculated from the ratio of its volume and thickness. This assumption does not consider concrete barriers, poles, culverts, etc. as they vary in size and usually have specific standards for sizing. In the default setting, the mass ratio of cement in concrete is 10%, the mass ratio of CaO in cement is 65 %, and binder efficiency of CO_2 to CaO is 75%.

3.10.4 WMA, Aggregate Substitution, and Bitumen Substitution

In POETT, the GHG emission reductions for WMA, RCM, aggregate and bitumen substitution are all calculated using Equation 3.11, where emission reduction factors are multiplied to the respective quantities of materials used.

$$CO2e\ Reduced_i(kg) = Quantity_i \times E_a \times 1000$$

Equation 3.11

Where:

$Quantity_i$ = Quantity of the material (e.g., WMA, glass cutlet, recycled asphalt shingles, RCM), in tonne/year

E_a = CO_2e avoided for each material in comparison to status quo practices (e.g., HMA, raw binder, raw aggregate), in tonnes CO_2e /tonne material used

The emission reduction factor, 4.8 kg CO_2e /tonne WMA is taken from the MTO report which suggests WMA reduces 4.1-5.5 kg CO_2e/tonne material (Politano, 2012). The tool does not account for the CO_2e emissions attributable to the use of additive, primarily due to: 1) lack of available data accounting for chemical production emissions; and 2) additive content in WMA is relatively small (approximately 0.1%). Therefore, it is assumed to have an insignificant contribution to emissions.

POETT also includes aggregate substitutions including foundry sand, blast furnace slab, coal bottom ash, glass cutlet, and bitumen substitution which includes recycled tires, crumb rubber and recycled asphalt. The emission factors for these reductions are obtained or calculated from emission quantification tools such as GreenDOT (Gallivan et al., 2010) and EPA WARM (US Environmental Protection Agency, 2015). Instead of a more comprehensive life-cycle approach, GHG emissions from only material extraction and processing are considered.

3.10.5 Supplementary Cementing Materials (SCMs)

The emission reduction calculation for SCMs is similar to that of WMA and material substitutions as they are all based on emission factors that directly estimate the emissions reduced. For SCMs, the concrete quantity and the SCMs' mix percentage of the cement is required to conform with Concrete NSSP requirement. Equation 3.12 calculates the emissions reduced. By default, the cement content in the concrete mix is assumed to be at 10% (usually ranges between 10%-15%). POETT also assumes that emission reductions only occur during the material extraction and processing phases. Transportation activities are not examined in emission reduction calculations related to SCMs.

$$CO2e\ Reduced(kg) = Quantity_C \times Percentage\ SCMs\ in\ the\ Cement \times E_a \times 1000$$

Equation 3.12

Where:

$Quantity_C$ = Quantity of the Concrete, in tonne/year

E_a = CO_2 avoided for each SCM, in tonnes calcined CO_2 /tonne material

3.10.6 RAP and RCM (without binder replacement)

RAP and RCM can be treated as aggregate material. In this case, the emission reduction calculation procedure follows that of in-situ recycling as explained earlier. A similar logic to that adopted in Equation 3.3 to Equation 3.7 can be applied for estimating emission reductions for material usage, transportation, and construction of the RAP material. Under the material category, instead of having virgin aggregate, which requires more energy to process and extract, recycled material such as RAP/RCM is used. For emission reductions from material transportation, the tool assumes that the waste materials' trip to landfill and the virgin aggregates' trip from quarry to plant can be avoided; however, an additional trip to bring RAP from the construction site to the plant for processing is added. Crushing and screening are the additional processing steps considered for RAP processing.

3.10.7 RAP with Binder Replacement

To calculate CO_2e emission reductions for RAP with binder replacement, the percentage of binder replacement is first calculated using Equation 3.13, obtained from MTO OPSS 1151 (Special Provision 111F06). The remaining procedures are in general similar to those used for in-place recycling and RAP as aggregate substitution.

$$Binder\ Replacement, \% = \frac{\%Binder\ Content\ of\ RAP\ \times \%RAP\ in\ Mix}{\%Total\ Binder\ Content\ of\ Mix} \times 100\%$$

Equation 3.13

To account for additional emissions from processing RAP, the results from a New York Department of Transportation study (Frederick & Tario, 2009) examining the energy consumption for heating and drying RAP and virgin aggregate, respectively, are applied. The additional energy consumption for processing RAP under 300°F discharge temperature, 60°F ambient temperature, and 1%, moisture content is obtained for every 10% increment RAP percentage. The additional CO_2 emissions for scenarios that were presented in the New York report are then calculated by applying the emission factors (in kg/million BTU) that represent typical Canadian HMA plants' fuel composition. To cover more scenarios with various RAP percentages in the HMA mixture, a linear interpolation is performed using the existing CO_2e emission and reduction results. The general process of quantifying additional CO_2e emissions for drying and heating RAP is represented by Equation 3.14.

$$Additional\ Emissions_{processing,i}(kg) = EF_{energy} \times (E_{RAP} - E_{Aggregate})/10^6$$

Equation 3.14

Where:

EF_{energy} = Composite CO_2e emission factor based on the general fuel use composition in Canadian HMA plant, in kg/MMBTU

$Additional\ Emissions_{processing,i}$ = Additional CO_2e emission from heating and drying RAP in comparison to that from virgin aggregate processing

E_{RAP} = Energy to heat/dry RAP, in BTU/tonne

$E_{Aggregate}$ = Energy to heat/dry virgin aggregate, in BTU/tonne

In addition to the excess heating and drying emissions for RAP, the emission calculations for RAP with binder replacement are similar to the calculations for RAP as an aggregate substitute. The binder quantity saved can be calculated with the binder replacement percentage, and the emission reduction from material extraction can then be estimated by applying the bitumen emission factor to the quantity of binder replaced. For transportation of the materials, in addition to the avoided trips to the landfill and the transportation of raw aggregates to the asphalt plant, the trip involving transporting bitumen to the plant (usually done by rail), is also avoided. The emissions from screening and crushing are accounted for in the construction phase.

In emission reduction calculations for RAP with binder replacement, 100% binder availability is assumed. This implies that all the binder in RAP is available for mix design purposes. The calculation also assumes that all the RAP retrieved by the MTO has a similar property. The user may adjust these default values for project-based calculations if some fraction of these materials is not considered structurally useful.

3.10.8 Distance Based Transportation Related Calculations

The mitigation activities under the transportation category that utilize distance-based metrics to estimate GHG emission reductions include alternative fuel vehicles, alternative transportation modes, diesel engine repower, alternative energy/fuel, and haul truck distance reduction. For each mitigation activity, the emissions can be calculated from the product of vehicle distance driven and the corresponding emission factor in CO_2e emissions per unit of distance (Equation 3.15).

To obtain annual emissions and emission reductions of all or a certain percentage of all Ontario vehicles, the tool uses the number of vehicles from Ontario's vehicle registry and the average vehicle driving distance per year in the province.

$$CO_2e\ Emissions_{j,k,l}\left(\frac{kg}{year}\right) = \frac{\sum EF_{i,j,k,l,m} \times N_{j,k} \times VKT_{j,k} \times GWP_i}{1000}$$

Equation 3.15

Where:

$CO_{2,e}\ Emissions_{j,k,l,m}$ = CO_2e emissions corresponding to vehicle type or mode 'j' (e.g., PHEV, EV, vehicle powered by biomass fuels, rail, barge), fuel type 'k' (e.g., compressed natural gas, corn ethanol E10, electricity), quantification scope 'l' (including well to pump, operational, and well to wheel), and the engine year 'm' (from 1989 to 2019, for diesel engine repower)

$EF_{i,j,k}$ = Emission factor for greenhouse gas 'i' (CO_2, CH_4, N_2O) corresponds to vehicle type 'j' (e.g., and fuel type 'k', and operation mode 'l', in g/km)

N_v = Number of vehicles assessed

VKT = Annual vehicle kilometer travelled, in km/year

GWP_i = Global warming potential of the greenhouse gases

The emission factors primarily vary by the type of vehicle and the fuel used. Alternative fuel vehicles in the tool include internal combustion engine vehicles (ICEV) that use fuels other than traditional gasoline or diesel, electric vehicles, biomass-based vehicles, fuel cell vehicles, and biomass fuel cell vehicles, and plug-in hybrid vehicles. To estimate emission reductions achieved through these vehicles, baselines are established. The baselines in this case include emission factors for light-duty vehicles and trucks using gasoline oil and Petrol diesel with 0.0015% sulfur content, respectively. POETT provides emission factors for CO_2, CH_4, N_2O and CO_2e which vary based on the fuel type and vehicle technology. These emission factors further vary based on the processes it encompasses, namely vehicle operation, fuel production, and vehicle material & assembly.

Emission reductions achieved via the alternative transportation mode mitigation activity involves comparing it with baseline emissions occurring from trucks with a 20-tonne load and 0% deadhead. The alternative transportation mode emissions calculation includes emissions from rail (class 1 freight and regional and short line freight) and barges (liquid bulk vessel and container vessel).

For the diesel engine repower and replacement, the emission rates (in kg/km) for combination long haul, combination short haul, single unit long haul and single unit short haul trucks have been obtained for vehicle engine technologies commonly used between 1989 and 2019. The tool accounts for savings from vehicle running emissions attributable to repowering/replacing the vehicle engine. Emissions associated with vehicle starts and extended idling are not currently covered. Emissions rates for the new engine are based on vehicular standards set for the 2019 vehicle model in MOVES (US EPA, 2014). GHG emissions can be reduced further with new models which are expected to have higher fuel efficiency.

3.10.9 Truck Idling Reduction Technology

Auxiliary power units, fuel operated heaters, and engine-off mode are common technologies and practices for long haul truck idle control. By providing an alternative heat source or engine shut off during idling (i.e., engine-off mode), fuel consumption from operating the main propulsion engine can be significantly reduced or avoided. To estimate the annual GHG emissions from the implementation of idle reduction strategies, the number of vehicles that adopt each available technology and the number of hours that trucks spend on extended idling modes are used as shown in Equation 3.16.

$$CO_2\ Reduction_i(kg) = N \times \left(EF_{extended} - EF_{mitigated,i}\right) \times hour_{hotelling} \times 10^{-3}$$

Equation 3.16

Where:

N = Number of trucks with idle reduction

$EF_{extended}$ = Emission factor for extended idling in trucks, in g/hr

$EF_{mitigated,i}$ = Emission factor for idle reduction practice 'i', where 'i' can be an auxiliary power unit, fuel operated heater, or engine-off mode, in g/hr

$hour_{hotelling}$ = Hotelling hours, in hr/year

Emission rates (in g/hr) for each idling emissions reduction technology is either directly obtained from a presentation prepared by Sonntag & Choi (2017),or calculated from the fuel consumption rate (gallons/hr) using Canadian fuel emission factors (Canadian Industry Program for Energy Conservation, 2005). In cases where data on emission rates from both sources are available, the values from Sonntag & Choi (2017) are preferred.

Often, the number of hotelling hours for trucks are not known. As a result, this value is estimated based on MTO's driver shift schedule, which suggests drivers to take at least 8 hours rest after working for 13 hours (refer to Equation 3.17).

$$hour_{hotelling} = Operating\ hours\ \times \frac{8\ hotelling\ hours}{13\ operating\ hours}$$

Equation 3.17

Data on the operating hours, if not available, is estimated through average truck VKT in Canada divided by an average speed of 90 km/hr. This results in 782 hours/year of operating hours, by default. When data on the number of trucks that adopt idle reduction is not available, the user has an option to enter the estimated percentage of Ontario trucks that adopt the technology as a ballpark estimate.

3.10.10 Fuel-Based Transportation Related Calculations

Fuel based transportation calculations often estimate vehicle GHG emissions more accurately in comparison to activity-based calculations that rely on the vehicle distance driven. Currently, the MTO does not have a program that records the fuel consumed by different vehicle categories. Therefore, for the purposes of POETT, mobile emission factors from the 2019 Canadian National Inventory Report (Environment and Climate Change Canada, 2019) are applied (refer to Equation 3.18). This section provides emission estimates for on-road vehicles such as light duty gasoline trucks under tier 2 emission standards and heavy-duty vehicles with three-way catalyst. Additionally, estimates for off-road equipment, and other transportation modes such as rail, and marine are also covered.

$$CO_2e\ Emission(kg/year) = \sum EF_{Fuel\ i,j} \times N_j \times GWP_i\ /1000$$

Equation 3.18

Where:

$EF_{Fuel\ i,j}$ = Emission factor for greenhouse gas ‘i’ for vehicle type ‘j’ (e.g., Tier 2 gasoline vehicles, LDGT non-catalytic controlled), in g/L

N_j = Number of the vehicles for the assessed vehicle type ‘j’

GWP_i = Global warming potential of the greenhouse gase ‘i’

3.10.11 Coniferous and Deciduous Trees

The total amount of CO_2 sequestered by coniferous and deciduous trees largely depend on their respective sizes, species, and the numbers planted. MTO’s HiCo database provides data on the quantity, height, and caliper of the trees when they are initially planted. To accurately track the sequestered value, detailed size measurements for each tree planted are required through careful surveying and gathering of a large amount of field data. To reduce this burden of required input data, POETT aims to provide a ballpark estimate of sequestration and only requires the user to enter the year of analysis, and select from ‘moderate’, ‘high’ or ‘low’ options for tree age and survival rate. The tool is set to perform CO_2 reduction calculations between year 1 to year 50, allowing the user to change the value and observe the effect on the change in emissions. Details and effects of this approach are discussed in the Chapter 4 of this document. The first step in determining the amount of sequestered emissions involves estimating a tree’s diameter at breast height (dbh). For this, the age of each tree type and size category is required (see Equation 3.19).

B_0, B_1, and B_2 represent constants that are derived from empirical data and correspond to the growth of a specific tree type and size in northern US (McPherson, 1999). The tool is set to perform CO_2 reduction calculations between year 1 and year 50, allowing the user to change the value and observe the effect on emissions. The minimum dbh for all trees is set to be 0.4 inches in the tool.

$$dbh = B_0(1 - e^{(B1+Age)})^{B2}$$

Equation 3.19

Where:

B_0, B_1, B_2 = Constants where each set of values represent a tree type and size (e.g., small deciduous, large coniferous) in northern US

Age = Age of a tree, in years

Using the obtained dbh for each tree type, its dry weight biomass can be calculated using urban general equations as the allometric equations (Equation 3.20) (McPherson, 1999)

$$Broad\ leaf_{biomass} = 0.16155 \times dbh^{2.310647}$$

$$Coniferous_{biomass} = 0.035702 \times dbh^{2.580671}$$

Equation 3.20

Where:

$Broad\ leaf_{biomass}$ = Total dry weight of broad leaf (deciduous) tree, in kg

$Coniferous_{biomass}$ = Total dry weight of coniferous tree, in kg

dbh = Diameter at breast height, in cm

The total CO_2 sequestered and the yearly sequestration rate per tree can be calculated with the tree carbon content and CO_2/C mass ratio, as shown in Equation 3.21. For CO_2 sequestered for all trees planted during the contract year, a linearly interpolated survival rate based on the initial tree size and age of the tree is used to adjust for tree survival. The user can select ‘high’, ‘moderate’, and ‘low’ survival for trees in a dropdown box.

$$Total\ CO2\ Sequestered\ (kg) = W \times CarbonContent \times \frac{M_{co_2}}{M_c} \times Quantity$$

Equation 3.21

Where:

W = dry weight of the trees, in kg

CarbonContent = Carbon content of the tree, generally 50% of the tree's total volume

M_{co_2} = molecular weight of CO_2, 44 g/mole

M_c = molecular weight of C, 12 g/mole

$Quantity$ = number of the specified tree, with the adjustment of survival rate

Trees that fail to survive at the end of the year experience decomposition, which releases some CO_2 back to the atmosphere. The emissions during decomposition are proportional to the carbon stored in the tree. Equation 3.22 is used for calculating this CO_2 release. The net CO_2 reduction can be obtained by subtracting decomposition emissions from the total CO_2 sequestered from the living trees.

$$CO_{2,decomposition} = C_{stored} \times \%root \times \%root\ release \times N$$

Equation 3.22

Where:

$CO_{2,decomposition}$ = CO_2 released through the decomposition of trees that do not survive, in kg

C_{stored} = Carbon stored per tree, in kg

% root = Percentage of tree root that serves as total carbon stored, 18%

N = Number of trees that did not survive

Due to data limitations, the CO_2 reduction calculated by the tool is based on the general description of tree size and survivability of coniferous and deciduous species. This reduces the effort required for finding specific data for input but reduces the accuracy of the estimate. In addition to this, the calculations only account for the direct impact of CO_2e emission reductions by sequestration. Trees can also have shading and climate effects that help nearby buildings or facilities use less electricity for heating and cooling, thus indirectly reducing GHG emissions. These indirect effects are not captured in the tool, as the additional data requirements are prohibitive, including but not limited to tree azimuth, tree dimensions, and building conditions.

3.10.12 Shrubs

CO_2 emissions sequestered by shrubs are estimated based on the sequestration rate in Mg/ha-yr. The number of shrubs planted, available in the HiCo database, has been translated to the area (in hectares) that shrubs with predetermined spacing could occupy. With the estimated area value, the annual carbon sequestered can be calculated and converted to the CO_2 sequestered, as shown in Equation 3.23.

$$CO_2\ Sequestered\ (kg) = \frac{Quantity}{N} R_s \times \frac{M_{co_2}}{M_c}$$

Equation 3.23

Where:

N = The number of shrubs that can be planted per hectare based on the spacing design

R_s = Mean carbon stock for shrub layer, in Mg/ha-yr

By default, the tool assumes that each shrub is planted 5 feet apart. The tool assumes an average CO_2 sequestration rate applicable to shrubs having a 39 year lifespan, following the literature (Justine et al., 2017). In addition, the tool assumes a 100% survival rate for the shrubs and allows the user to choose a life span of up to 50 years for sensitivity analysis purposes.

3.10.13 Lights and Signals

The HiCO system lists four types of traffic signals - standard, highway, special, and pedestrian. Each type of signal consists one to five signal heads. Based on the Ontario Traffic Manual (OTM) Book 12 (2012), a pedestrian signal only has one pedestrian signal head; a standard signal consists of three signal heads containing a 200 mm ball signal of red, amber and green color; a 'Type 8' special standard signal consists of 5 signal heads with a 300 mm red signal, a 200 mm amber, a 200 mm green, a 300 mm amber arrow, and a 300 mm green arrow signal. The tool assumes that the baseline power consumption of an incandescent lamp equals the average of the maximum lamp wattage (argon, krypton), as specified in OPSS 2461((OPSS 2461 Signal Heads, 2007). The wattage depends on the shape and size, but not the color of the light. The wattage of LEDs has also been assumed using the same OPSS 2461 principle, except that the wattage of LED signals varies with color.

Each signal head has a load factor which represents the fraction of time the signal head is in use in a traffic signal cycle. Generally, POETT assumes the load factors for red, green, and yellow ball lights to be 0.45, 0.45 and 0.1, respectively. All arrows are assumed to have a load factor of 0.05. When needed, the load factors are adjusted so they sum to one. The wattage of each signal type can be calculated through Equation 3.24. The total wattage of a type of signal equals to the sum of the power rating of each individual bulb in a signal head multiplied by its corresponding load factor.

$$W_{signal,k} = \sum \sum W_{i,j} \times LF_i$$

Equation 3.24

Where:

$W_{signal,k}$ = Wattage of MTO signal type 'k' (including standard, highway, special, pedestrian), in watts

$W_{i,j}$ = Wattage of each traffic signal head 'i' (e.g., red ball 300 mm traffic signal head, 300 mm Red Arrow) of bulb type 'j' (incandescent, and LED) in watts

LF_i = Load factor of each traffic signal head 'i' for each signal type

For special signal types, the OTM Book 12 (2012) presents 15 different configurations. The signal wattage of the 15 arrangements for incandescent and LED lights have been calculated, and the average value of the wattage is used as a general representation.

Compared to incandescent or HID, LED lights and signals reduce CO_2e because they are more energy efficient and consume far less electricity. The CO_2e savings can be calculated using Equation 3.25. For LED lights, the tool considers four types of traditional roadway high intensity discharge lamps (HIDs), including Pulse Start Metal Halides (PSMH), Metal Halides (MH), High Pressure Sodium Lights (HPS), and Mercury Vapor Lights (MV), and one general high mast light as the baseline. The rated wattage of a HID and the equivalent LED wattage for each type of light is compiled based on data collected from specification sheets of four light manufacturers. For any LED or HID input, the corresponding result will be linearly interpolated. Note that the emission factor for wind and solar powered signal heads is assumed to be 0.

$$Emission\ Savings\ (kg/year) \\ = Q \times \left(W_{baseline,i} - W_{mitigated,i}\right) \times EF_{electricity} \times t \times lifespan \times 365 \times 10^{-6}$$

Equation 3.25

Where:

Q = Quantity of LED lights or signals,

$W_{baseline}$ = Wattage of the status quo lighting option 'i'; including existing HID lights (e.g., HPS, MH) and incandescent powered signals, in watts

$W_{mitigated}$ = Wattage of the mitigated practice ‘i’ (including LED lights and signals, and wind or solar powered signals), in watts

$EF_{electricity}$ = CO_2e emission factor for electricity in Ontario, in g/KWh

t = Hours of operation of LED lights, LED signals, and wind or solar powered signals, in hours/day

Lifespan = lifespan of the fixtures, in years

The tool collects common data on wattage of HIDs and LEDs to perform a linear interpolation between wattage rating points so that the corresponding wattage of LED or HID can be generated from any user’s input wattage. Maximum and minimum values for wattage input have therefore been set based on the available data. In POETT, the minimum allowable wattage for PSMH, MH, HPS is 70 W, respectively and 75 W for MV. The maximum allowable wattage for PSMH, MH, HPS, and MV is 400 W, 2000 W, 1000 W, 1000 W, respectively. In the default tool setting, the daily operation hours are set at 12 hours for lights and 24 hours for signals.

When the electricity consumption data for the signals is known, Equation 3.26 provides more accurate emission estimates.

$$Emission\ Saving\left(\frac{kg}{year}\right) = (EC_b - EC_m) \times EF_{\ electricity}/1000$$

Equation 3.26

Where:

EC_b = baseline electricity consumption of the year for lights and signals, in KWh

EC_m = mitigated electricity consumption baseline of the year for lights and signals, in KWh

$EF_{electricity}$ = CO_2e emission factor for Ontario, in g/KWh

3.10.14 Congestion Mitigation in Work Zone

Additional GHG emissions caused by lane closure activities are estimated as the difference between the emissions generated due to the work zone and the emissions in free flow conditions for the same road section. Congestion mitigation activities such as 24/7 construction, and get-in get-out help reduce the work zone impact by shortening the construction time and avoiding peak hour construction. The work zone, in POETT, consists of three distinct components: the free flow section, the queue, and work zone, as shown in Figure 3-4. Detours are not considered.

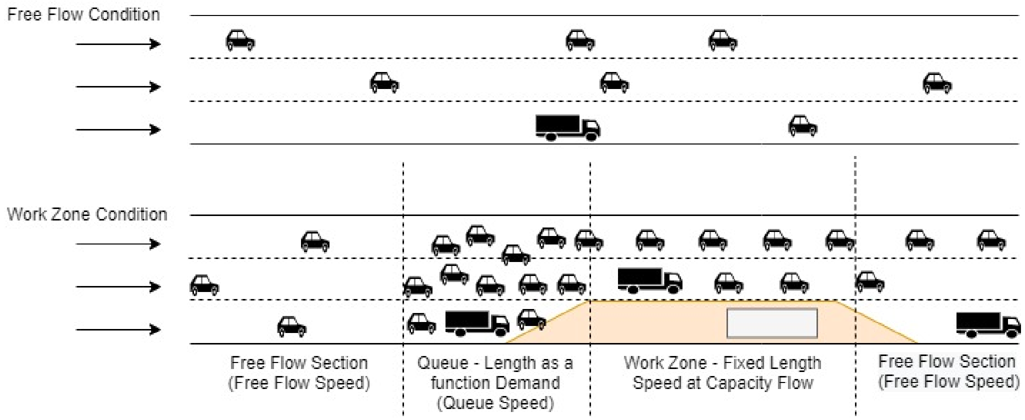


Figure 3-4: The components of work zone delay calculation and the respective traffic conditions. Length shown is not to scale. The queuing zone occurs before the lane closure

GHG emissions from all vehicles driving on each road section are calculated using selected emission factors that are multiplied with the number of vehicles and the average vehicle trip length (Equation 3.27).

$$E_{CO2} = VKT_{wz} \times EF_{wz} + VKT_{queue} \times EF_{queue} - VKT_{base} \times EF_{base}$$

Equation 3.27

Where:

E_{CO2}= Additional CO_2 emissions generated by on-road vehicles due to lane closures (in kg)

VKT = The total kilometer traveled by vehicles in each section; in this case, the work zone length (in km) is fixed whereas the value for queue length depends on demand, capacity, and the condition of queue dissipation. For a fair comparison, the base length is the sum of work zone length and queue length for the time interval; VKT_{wz} , VKT_{queue}, VKT_{base} are the product of the respective section length and the numbers of vehicles in the section.

EF = Emission factor (in kg/km-vehicle) generated for each time of concern, vehicle type, fuel type, and vehicle speed bin. The emission factor itself is also a function of various factors such as vehicle activity distribution, average speed distribution, and alternative vehicle and fuels technology (AVFT).

As shown in Equation 3.27, the quantification of GHGs require the knowledge of emission factors that correspond to the vehicle driving speed and the work zone condition, which include but are not limited to section length, the number of vehicle in each section, and the vehicle speed.

The Ontario-specific emission rates, in kg/km-vehicle, are generated from EPA MOVES (US EPA, 2014; W. Wang et al., 2020). To be consistent with the UW database, a run specification is set up for generating on-road vehicle emission rates of CO_2, CH_4, N_2O for April 5th, 2012 from 8 am to 9 am for an urban restricted access road (W. Wang et al., 2020). MOVES (US EPA, 2014) vehicle types selected in the run specifications are passenger cars (21), passenger trucks (31), light-duty commercial trucks (32), single unit short-haul/long-haul trucks (51 & 52), combination short-haul/long-haul trucks (61 & 62). Given the dominant fuel consumption patterns, gasoline was considered for light-duty vehicles (21, 31, 32), and diesel for all medium and heavy-duty vehicles (51, 52, 61, 62).

To be more compatible with the traffic models, which only specify truck percentage instead of detailed vehicle types, emission rates for each vehicle class are computed. Only medium and heavy-duty vehicles are considered as trucks in this study because their length and weight distinguish them in the traffic model, plus their emissions are considerably larger than light duty vehicles. The emission rates are aggregated to reflect the vehicle source type distribution based on Ontario vehicle registration by vehicle type (Government of Canada, 2019).

The rate per distance output is used for generating the emission rate lookup table. MOVES (2010) outputs provide GHG running exhaust rates corresponding to every combination of vehicle type, fuel type, average speed bin, and time of the day. The exhaust rates are then organized into a total of 16 average speed bins by vehicle type. For the extreme slowest and fastest speed bins, 1 and 16, an average speed of 2.5 mph and 75 mph is assumed, respectively. For speed bins 2 to 15, the average of the upper and lower bound is used. Because MOVES only provides rates by average speed bin (with 5 mph increment for most bins), linear interpolation within each speed bin is performed to get intermediate speeds in the rate lookup table. A 0.5 mph increment is selected to balance the accuracy and the table size. For a LDV with speed of 11.5 mph, for example, $EF_{LDV,11.5}=EF_{LDV,10} + (11.5-10) \times (EF_{LDV,15} - EF_{LDV,1O}) / (15-10)$. This yields emission rates for light-duty vehicles and trucks that are available for speed from 2.5 to 75 mph with 0.5 mph increments. When incorporating the emission factors in the traffic model, they are adjusted based on the user provided truck percent in the traffic. The emission factors that correspond to a certain speed and vehicle type are organized in a look up table and presented in Table E-8 in Appendix E.

Vehicle kilometres traveled (VKT) are determined by the vehicles on the road section and the length of the section. The work zone length is a fixed number determined by construction needs. In POETT, the length of the work zone is the sum of the length of the transition area, longitudinal buffer area, work area, and part of the termination area. VKT_{wz} calculation is shown in Equation 3.28.

$$VKT_{wz} = min\ (Demand, Capacity_{wz}) \times l_{wz}$$

Equation 3.28

Where:

l_{wz} = Length of the work zone, in km

$Capacity_{wz}$ = Capacity of the work zone calculated based on Highway Capacity Manual (HCM)(2010) equation in vehicle/hour

The number of queued vehicles is calculated based on the traffic demand and road capacity of the hour of interest and the number of queued vehicles from the previous hour. Queue length is a function of traffic demand, road capacity, and average vehicle length. In this study, MoDOT Work Zone Impact analysis spreadsheet (Missouri-Columbia, 2016), a tool used by Missouri Department of Transportation based on HCM 2010 is adapted. The work zone capacity is adjusted based on the travel lane width, work location, truck percentage, and number of lanes open using methods in HCM.

The queue length is estimated from the average vehicle length (adjusted by truck percentage), and number of queued vehicles (demand minus capacity), divided by the total number of open lanes. VKT_{queue} is calculated in Equation 3.29.

$$VKT_{queue} = \text{number of queued vehicles } \times l_{queue}$$

Equation 3.29

Where:

l_{queue} = Queue length, in km

For the free flow traffic, conditions with no lane closure are examined for the total length of the queue and the work zone. The distance traveled by the vehicles equals to the work zone length when no queue is formed. The baseline VKT (VKT_{base}) is calculated using Equation 3.30.

$$VKT_{base} = Demand \times l_{wz} + \text{queued vehicles } \times l_{queue}$$

Equation 3.30

Where:

l_{wz} = Work zone length in km

l_{queue} = Queue length in km

Greenshields macroscopic stream model (Greenshields, 1960) is assumed to be applicable for calculating the traffic speed. With the Greenshields Model, a linear relationship between speed and density is established. The speed corresponding to the maximum flow rate equals to half of the free speed. Equation 3.31 to Equation 3.33 are applied in calculating the speed for baseline, queue, and work zone (capacity flow), respectively. The Greenshields model is selected over graphs in the highway capacity manual (HCM) (Council, 2000) because HCM does not provide a flow speed relationship that can be easily derived at level of service (LOS) F, where GHG emissions get affected the most,

$$S_{base} = \frac{S_f \pm \sqrt{S_f - 4S_f V/D_j}}{2}$$

Equation 3.31

$$S_{queue} = (\frac{S_f}{2})(1 - \left(1 - \frac{Capacity_{wz}}{Normal\ Capacity}\right)^{\frac{1}{2}})$$

Equation 3.32

$$S_{wz} = \frac{S_f}{2}$$

Equation 3.33

Where:

S_{base}, S_{queue}, S_{wz}= Speed for baseline scenario, speed in the queue, and speed in work zone respectively; because a macroscopic model is used, all on road vehicles have a homogenous speed per section (in km/h)

S_f= Free flow speed (km/h) occurs during light traffic conditions

V= Hourly flow rate (Demand) in vph

D_j= Jam density (veh/km) occurs where density is so large that traffic speed reaches 0

$Capacity_{wz}$ = Work zone capacity (vph) calculated with HCM 2010

The tool assumes deterministic arrivals and departures for vehicles. A more random arrival pattern (e.g., Poisson) can better reflect real-world travel conditions and will affect the computed value for delay. However, assuming a deterministic arrival makes it possible to plot the queue, and helps to visualize the emissions with respect to queuing activities.

The current model does not consider detours. Detours usually mitigate queueing but increase the VKT. Despite being an interesting aspect to examine, it has been deemed out of scope for POETT. For simplicity, calculations do not differentiate among measures other than the closing duration and the closing time and do not set differences in weekday or weekend demands.

3.10.15 Pavement Condition

Driving on smoother pavement can reduce fuel consumption. Field study results for IRI and fuel consumption are collected and a relative relationship of the changes in IRI and corresponding fuel savings (the Ratio of % Fuel Saving to IRI Decrease, R) is calculated for truck and light duty vehicles, respectively. The median values of the ratio (4.07% for passenger cars and 4.55% for trucks) obtained from Muench et al. (2015) is used for this estimation.

Ontario 2017 Survey, which specifies the road section name, length, and IRI, is used as the baseline condition. A percentage of IRI change can be obtained from the user specified IRI target and the baseline IRI from the survey. Note that when the baseline road is in good condition (small difference between the target and baseline IRI), there is little to no fuel saving. For each section, the emission savings can be calculated through the number of each type of vehicle on the section, road length, fuel emission factors, percentage IRI change (comparing baseline to the IRI target), and the ratios obtained as previously explained, as shown in Equation 3.34.

$$
\begin{aligned}
&Emission\ Changes\ \left(\frac{kg}{year}\right) \\
&\quad = L \times AADT \times \left(\frac{|IRI_e - IRI_I|}{IRI_e}\right) \times \%Truck \times EF_T \times R_T \times 365 \\
&\quad + L \times AADT \times \left(\frac{|IRI_e - IRI_I|}{IRI_e}\right) \times (1 - \%Truck) \times EF_P \times R_P \times 365
\end{aligned}
$$

Equation 3.34

Where:

L = Length of the selected road section, in km

AADT = Annual average daily traffic of the selected road

IRI_e = International roughness index based on the existing pavement condition, in m/km

IRI_i = International roughness index based on the improved pavement condition, in m/km

EF_T = CO2e emission factor for trucks, in kg/hkm

EF_p = CO_2e emission factor for passenger vehicles, in kg/hkm

R_T = Ratio of % truck fuel savings to decrease in road IRI

R_p = Ratio of % passenger car fuel savings to decrease in road IRI

For a more general estimation that is not road-specific, the user can approximate the emission reductions achieved from improving a certain percentage of all Ontario roads with an overall IRI target. The results give the total emission savings based on the percentage of average Ontario road AADT and IRI conditions.

For simplicity, the vehicular operating emission factor is assumed to not vary by speed in this calculation. An emission factor value at 40 mph (64 km/h) generated from MOVES using Ontario specific input is selected to represent the general driving scenario of all highways (W. Wang et al., 2020). The tool also assumes that there is no difference between asphalt and concrete pavement in the IRI-fuel consumption relationship if their measured IRI shows the same value.

3.10.16 Roundabout

The tool adapts the CMAQ Roundabout module designed by FHWA (2020). It generally follows the steps highlighted by the Highway Capacity Manual (Council, 2000) for calculating average control delay at a roundabout, which includes calculating the conflicting flow, adjustment for heavy-duty vehicles, and calculating the volume to capacity ratio. For each approach, a delay reduction can be calculated by comparing the delay in a roundabout to the delay caused by an existing practice or the signalized intersection. The total emission savings can be calculated based on the reduction in delay time, along with the number of through vehicles and idling emission factor (in kg/hr) available from MOVES.

Chapter 4: Results and Discussion

This chapter presents POETT and GHG mitigation results for 2017 based on data provided by MTO. It includes the compliance evaluation against stated requirements, implementation of the tool, the results calculated for selected units and scenarios, and the discussion and comparison of the results. In the first part of this section, POETT's performance against the design requirements is briefly discussed. The remainder of the chapter presents results on GHG emissions and potential reductions for different mitigation measures. The emissions, emission reductions per unit (e.g., per 1-km typical 2 lane pavement, per 1-tonne warm mix asphalt material, etc.), and the overall percentage reductions are presented and compared with tools and literature as shown in Table 4-1, with a focus on in-place recycling. The comparison to some extent serves as validation of POETT and allows us to understand the possible range of results and the effectiveness of each mitigation measure in reducing or avoiding GHG emissions. In addition, sample results from pavement wear (effect of IRI) and intersections (effect of roundabouts) are briefly presented and discussed. Sensitivity analysis is included for in-situ recycling options to analyze the effect on emissions of structural and mix design of the pavement section, and the binder content for general RAP practice. The insights obtained from the section will help the MTO in understanding the largest source of GHG emissions and reductions for the specified unit, and thus better prioritize mitigation measures and track future reductions.

Table 4-1: List of Mitigation Measures and Sources for Result Comparison

Mitigation Measures	**Unit**	**Source for Comparison**
In Place Recycling	1-km typical 2 lane pavement (7000 m^2)	Lower and Higher Value Calculated by POETT, PaLATE 2.0 (Horvath, 2007), PaLATE 2.2 (University of Washington, 2011, p. 2), Adapted PaLATE, Athena (Athena Sustainable Materials Institute, 2018) (Athena is not included in the Final Analysis)
Warm Mix Asphalt	1 tonne	FHWA Infrastructure Carbon Estimator, GreenDOT, Frank et al. (2011), Pouranian & Shishehbor (2019)
Concrete Emission	1 tonne Concrete with 10% Emission Reduction	GreenDOT, PaLATE 2.0, PaLATE 2.2, Highway England Carbon Tool (Highways England, 2015), GasCAP (Noland & Hanson, 2014)
Potential Carbonation	1 tonne Concrete in 50 Year	Extreme and Expected Value from Santero & Hovath (N. J. Santero & Horvath, 2009)
Supplementary Cementing Materials (SCMs) and Limestone	10 tonne concrete with 20% Cement, 10% of Cement being Replaced	GreenDOT, PaLATE 2.2 and GasCAP for all SCMs and Highway England Carbon Tool for some; GreenDOT for Limestone

Mitigation Measures	**Unit**	**Source for Comparison**
Other Aggregate Substitution	1 tonne substituting material	GreenDOT, PaLATE, GasCAP
Other Bitumen Substitution	1 tonne substituting material	GreenDOT, PaLATE, GasCAP
RAP and RCM	1 tonne	PaLATE 2.2 GasCAP, GreenDOT, FHWA Infrastructure Carbon Estimator (F. Gallivan et al., 2014)
Trees	Per tree/year	Adjusted Results Compared to CAOPCA Value (California Air Pollution Control Officers Association, 2010), U.S Department of Energy Worksheet (DOE, 1998), and USDA Paper (Nowak & Crane, 2002)
LED Light	100 Lights, Percentage of GHG reduction is compared	CAPCOA Report (California Air Pollution Control Officers Association, 2010), Caltrans Report (California Department of Transportation & ICF International, 2013), MTO Emission Reduction Calculator (Ahmed, 2018), G & Jaganthan (2019)
Alternative Energy Vehicle and Other Transportation Related Mitigation Measures	Various	General comparison of percentage reduction with GHGenius (*GHGenius 5.0d*, 2019), if available; For transportation-related calculations, POETT added the MTO related default input (e.g., idling hours, number of trucks), and the emission rate is directly taken from official reports such as MOVES, GHGenius and Canadian NIR without alteration. Therefore, no emission rate comparison is needed.
IRI and Roundabout	NA	General Comparison Regarding Ratio for Percentage Fuel Saving and IRI Decrease (Muench et al., 2015)

The second part of this section evaluates the emission savings in Ontario for 2017. The emission reductions are calculated by POETT for items covered in the HiCo system, which includes in-place recycling, warm mix asphalt, trees, and lights. The total GHG reductions for each mitigation activity and each mitigation categories are presented following their percentage contribution to the overall reduction. The emission savings for each mitigation category, including the GHG emissions baseline and emissions by each component are then presented in detail.

4.1 Compliance Evaluation

In Section 3.1, accuracy, comprehensiveness, relevance, efficiency, flexibility, clarity, and transparency were identified as the main requirements for POETT and described the associated performance metrics. To meet these requirements, compliance strategies including using relevant data and designing an Excel template have been adopted, as shown in Table 4-2.

Table 4-2: Compliance Strategies for Meeting Performance Metrics

Performance Metrics	**Description**	**Compliance Strategy**	**Implementation**	**Comments**
Accuracy	Results for GHG emissions and reductions can be validated	Apply validated methods	✓	Standard calculation methods for materials, transportation, and lights. Simplified methods for trees and traffic
		Use data that are relevant to location, time, and the process	✓	When the most relevant data (e.g., industrial average) are not available, median of the available or the most comprehensive dataset is used.
Comprehensiveness	Capture existing and future GHG mitigation measures from a life-cycle perspective, if feasible.	Identify mitigation measures based on MTO's current and planned practices and their alternatives	✓	See Section 3.2 and Figure 3-3
		Include various material substitutes, chemicals, and additives	✓	Currently, one emission factor applies for stabilizers and chemicals, respectively
		Capture all significant sources for GHG reductions within the determined system boundary	✓	See Section 3.2 and Section 3.4
Relevance	Use Ontario or Canada specific values; Compatible with the current data collection practice	Collect default values from sources such as Statistics Canada, Natural Resources Canada, and Canadian NIR reports	✓	Values are Canadian or Ontario based, whenever available
		Use representative road design as default values	✗	Default values need to be collected from additional studies including Ontario contracts and case studies

Performance Metrics	**Description**	**Compliance Strategy**	**Implementation**	**Comments**
	in MTO (HiCo system).	Generate Ontario related vehicle emission rates from US EPA MOVES and GHGenius	✓	See section 3.10.8 and 3.10.14
		Extract item quantity from HiCo and provide annual emission reduction values, as required	✓	Use Macros to extract and aggregate quantities for trees, lights, and materials
Efficiency	Minimize the amount of data required. The tool should run smoothly.	Limit the project-level data by providing Ontario specific default values	✓	Provide default values for road design, car travel miles, idling hours, etc.
		Limit the use of Macros to improve speed	✓	Macros are only used for data aggregation, item addition, and to clear and restore values
Flexibility	Allow easy updates and minor changes. Provide user-input options,	Allow user to easily update values including emission factors and calculation methods that can reflect technology development and new research finding in the template	✓	Use Excel
		Allow users to input values to override the default data, or restore to the default when needed	✓	Set macros that restore default values
Clarity	Fully understandable and editable without requiring specialized programming	Build with Microsoft Excel, which runs on both Windows and macOS and generally does not require additional training	✓	
		Decrease the number of worksheets	✓	Most work can be done with three worksheets: HiCo, input, Results

Performance Metrics	Description	Compliance Strategy	Implementation	Comments
	knowledge. Results are easy to interpret.	Annual emission reductions and the breakdown of the GHG emissions can be easily visualized	✓̲	
		Provide a user manual	✓̲	See Appendix B
Transparency	Clearly present the emissions, sources, methods, and default values	Equations and steps are presented in the tool with comments in Excel	✓̲	
		Methods, emission factors, and the possible range of the values are documented in the report	✓̲	See Chapter 3

✓̲	100% Implemented
✓	Mostly Implemented
✗	Not Included in the Tool

4.2 Unit Emission Results and Comparison

4.2.1 In-Situ Recycling

4.2.1.1 Test Case Conditions

The test case results have been developed using several decisions and assumptions regarding default designs and data. For each in-situ recycling measure, the results are first calculated for 7000 m^2, which is approximately the pavement area for a standard 2 lane, 1 km road with 3.5 m lane width. Several simplifying assumptions are made regarding the pavement structure: (1) the baseline mill & overlay's milled thicknesses are equal to the mill/pulverizing thicknesses for mitigation measures (2) All milled materials are recycled and reused in the pavement, except for FDR and FDR with EAS. Therefore, waste disposal is considered to be 0 for CIR, CIREAM, and HIR (3) the structural integrity has been maintained by adding an additional hot mix asphalt layer on top of the recycled layer, and the thickness of the HMA layer has been determined through the pavement structural number. Detailed layer thicknesses for the testing case are shown in Table 4-3 below. With the assumption that milled thickness in the baseline is equal to the recycled thickness in recycling activities, thickness for baselines are selected based on the common treatment thickness of CIR and CIREAM (75 mm to 100 mm), HIR (less than 50 mm), and FDR and FDR with EAS (full thickness of the pavement plus a predetermined portion of underlying materials). Here, multiples of 25 have been selected for the depth for pavement reclamation. The thickness for mitigated activities is calculated with structural numbers based on the assumptions.

Table 4-3: Layer Thickness of the In-Place Recycling Practices and the Baselines

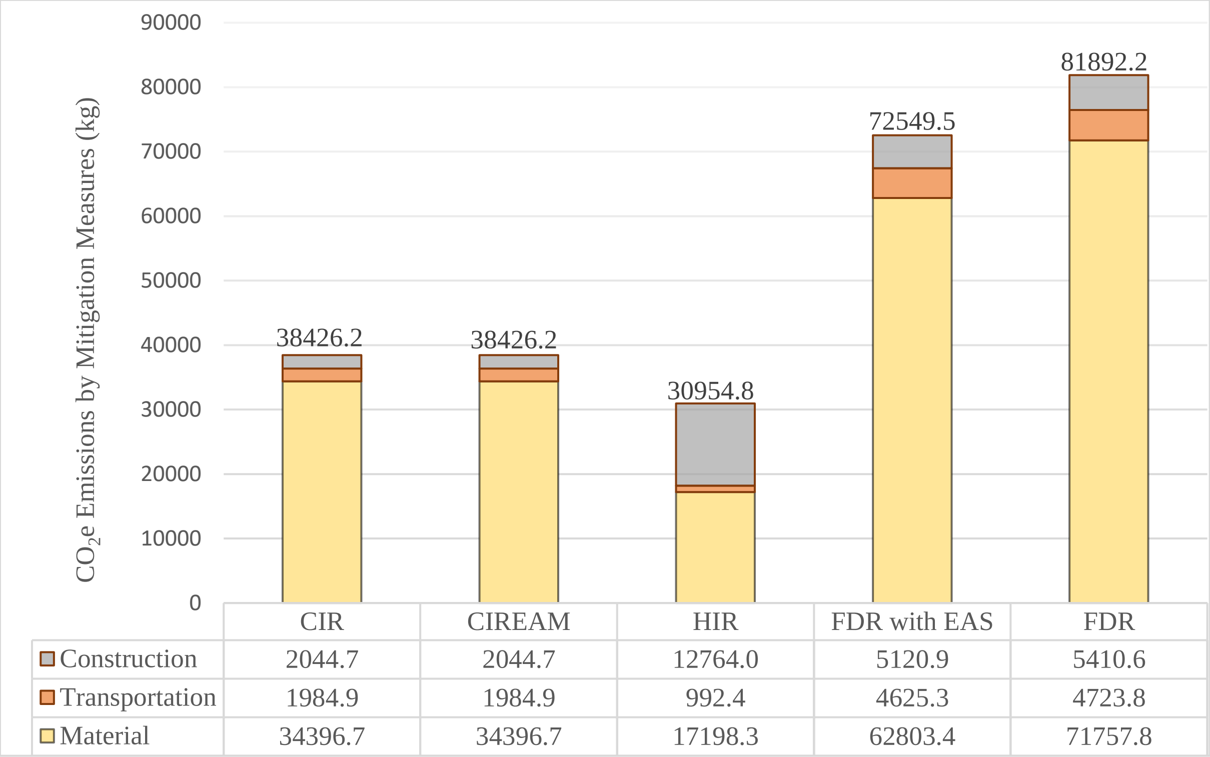
Thickness (mm)	Baseline		Mitigated		
	Mill	Overlay	Mill/Pulverize	Recycle	Calculated HMA Overlay
CIR	100	100	100	100	30
CIREAM	100	100	100	100	30
HIR	50	50	50	50	15
FDR with EAS*	150	120	150	120	60
FDR	150	120	150	120	90

Note: In POETT, only one FDR option is available because HiCo only has one "In-Place Full Depth Reclamation" item without specifying if any stabilizer asphalt is added. The emulsion/expanded asphalt, which can be adjusted through the mix design in the tool, affects the calculated HMA overlay thickness for mitigated scenarios. As long as the emulsion/expanded asphalt content is not 0, POETT uses the EAS's method for the overlay thickness calculation. The calculation for 2017 MTO agency-wide emission savings, presented later, assumes FDR with EAS using 2% expanded asphalt.

For testing purposes, emissions are calculated using the tool's default values. In the default setting, 5% bitumen and 95% aggregate is assumed for all HMA; the emulsion/expanded asphalt content is 2% (including FDR with EAS) except for FDR (without EAS, which is 0%); median values for emission factors are applied. Rail is the mode of transportation used for bitumen. All other materials are transported by trucks, with 20 tonnes per truckload and 15% of deadhead assumed. For construction, all calculations are performed using equipment types and specifications collected from Athena (most) and PaLATE (a few) and loading factors and emission factors are collected from the most recent US Environmental Protection Agency (USEPA) model for non-road mobile emissions (U.S EPA, 2008) (see Table E-3 in Appendix E for details). The equipment included in the test case covers those used in most in-situ recycling processes, including a paver, a recycler, a compactor, and a milling machine, with FDR having an additional breaking machine and HIR having a heating machine. The test case excludes some less significant equipment options that are available in POETT including, e.g., asphalt remixer, crushing and screening, HMA transfer, etc. For a given set of equipment, emissions from construction equipment are generally proportional to the material quantity processed. In reality, equipment vary by project, and the resulting emissions depend on the equipment characteristics including rated power, power source, post-process pollution control, and productivity. Based on the manufacturers' specifications (e.g., from Caterpillar and ROADTEC), similar equipment can vary largely in its horsepower and productivity. While equipment used for CIR and CIREAM can be similar, here the productivity of the milling machine for CIREAM was adjusted to 400hp while leaving the CIR baseline as 363hp. This adjustment, though small, helps the observation of the effect of equipment specifications on GHG emissions and emission reductions.

4.2.1.2 Test Case GHG Emissions Results

Figure 4-1 and Figure 4-2 show the GHG emissions and emission savings for CIR, CIREAM, HIR, FDR with EAS, and FDR, respectively. Material production, including related excavation and processing, contribute most to the emissions, whereas impacts from transportation and construction are relatively small.



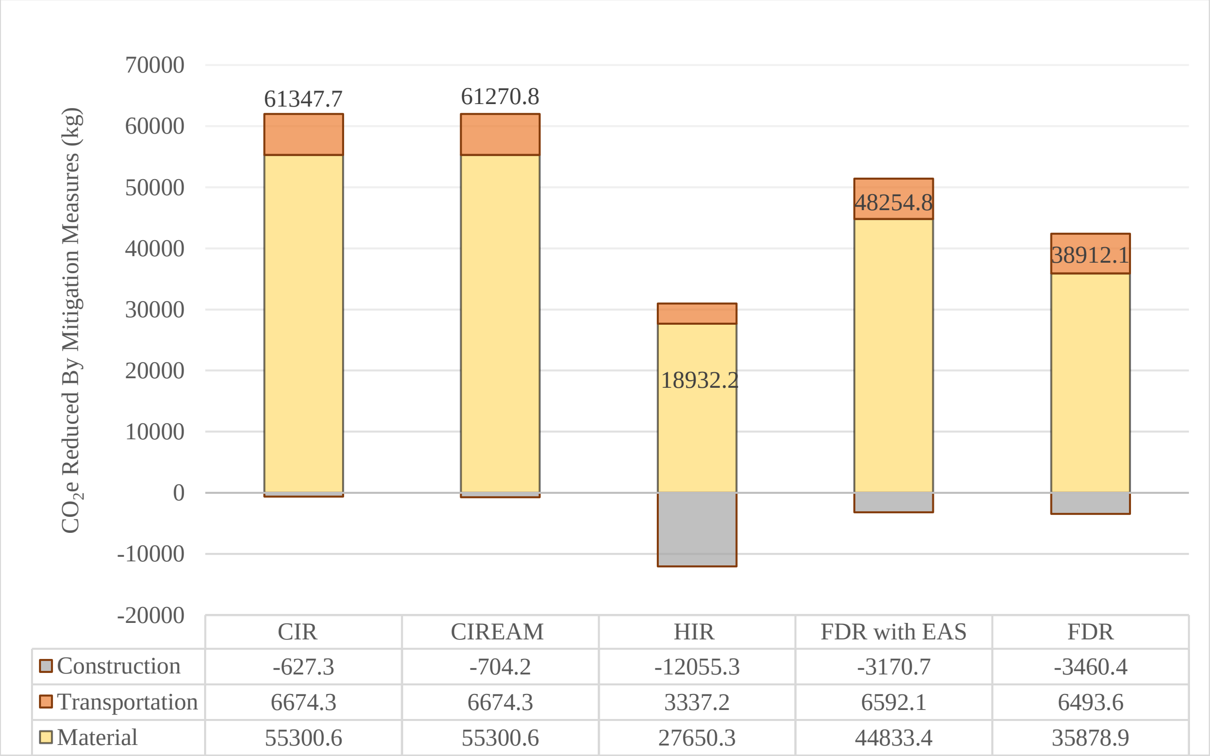
	CIR	CIREAM	HIR	FDR with EAS	FDR
⬜ Construction	2044.7	2044.7	12764.0	5120.9	5410.6
🟧 Transportation	1984.9	1984.9	992.4	4625.3	4723.8
🟨 Material	34396.7	34396.7	17198.3	62803.4	71757.8

Figure 4-1: GHG Emissions from each In-Situ Recycling Options

This finding is in line with numerous other life-cycle analyses of asphalt roadway construction and maintenance (Nasir, 2018); Lee et al.; 2010 Yu & Lu, 2012; Ma et al., 2016). Even for HIR, which has high construction emissions due to the heating required by the asphalt remixer, the material-related GHGs still make up more than 50% of the total emissions. Material and transportation-related emissions are generally proportional to the layer thickness for a given mix design. For construction, negative reductions (i.e., increases) are found for mitigation scenarios. This can be attributed to the additional need for the recycling machine, and the extra thickness of the entire pavement that requires processing.

Generally, the emissions for each mitigation measure are proportional to the thickness of the roadwork, with HIR requiring the least work for relatively shallow surface treatment and FDR requiring more work for reaching the subbase. CIR and CIREAM show similar emission results because the two share similar thicknesses and processing requirements. Compared to FDR, FDR with EAS shows a lower emission. This is because the emulsion added to the recycled material effectively enhances the structure and reduces the additional thickness of the HMA layer.

Among all mitigation activities, the FDR design generates the most emissions while the HIR emits the least. When compared with the baselines, which have equal depth of treatment as the corresponding in-place recycling measure, CIR and CIREAM have the most tonnes of GHG emissions avoided and the HIR shows the lowest reduction. The percentage reductions for CIR, CIREAM, HIR, FDR with EAS, and FDR are 61.5%, 61.5%, 38%, 40%, and 23.6%, respectively.



	CIR	CIREAM	HIR	FDR with EAS	FDR
□ Construction	-627.3	-704.2	-12055.3	-3170.7	-3460.4
□ Transportation	6674.3	6674.3	3337.2	6592.1	6493.6
□ Material	55300.6	55300.6	27650.3	44833.4	35878.9

Figure 4-2: GHG Emission Reductions from each In-Situ Recycling Options

The FDR has low GHG percentage reductions because the recycled materials do not significantly contribute to the structural integrity without the additional emulsion or expanded asphalt, thus it still requires a relatively thick HMA overlay. For a pavement in rural areas with low AADT, a thinner layer is expected, and the emissions for FDR can be low. The structural design for pavement and pavement mitigation activities can have a large impact on the GHG emissions and savings. These will be discussed in the report later.

4.2.1.3 Comparison with Other Tools

This report presents results from five scenarios developed across four tools to compare results for in-situ recycling. Test conditions are run as best as possible using four other tools, including

1. PaLATE 2.0
2. PaLATE 2.2
3. Adapted PaLATE
4. Athena pavement LCA (version 3.2.01)

These tools are chosen as they explicitly consider in-situ recycling from a life cycle perspective. Multiple versions of PaLATE are used, as they are optimized for different purposes, namely comprehensive impacts (2.0), GHGs (2.2), and Ontario (Adapted PaLATE).

To enhance the relevance to Ontario, a fifth comparison scenario is used:

5. Adapted PaLATE with MTO designs

Each tool has specific input requirements. For example, POETT uses recycling area, which is consistent with the HiCo database, while PaLATE 2.0 and PaLATE 2.2 require the material quantity in cubic yards, and Adapted PaLATE requires the layer thickness. As a result, unit conversions have been performed to maintain consistency while comparing the different inputs used among the tools as shown in Table 4-4.

In this comparison, the previously stated assumptions for structural design and mix design are applied. To find the volume (for use in PaLATE) for aggregate, bitumen, and emulsion, the density is 2243 kg/m3 for aggregate and 1050 kg/m3 for bitumen is assumed and a roughly 8.9:1 volume ratio is obtained for aggregate and bitumen to 5% content by weight. The densities assumed above for unit conversion are 2243 kg/m3 and 1050 kg/m3, respectively. Also, in PaLATE 2.2, emulsions are not explicitly considered. To include emissions from emulsions, the additional volume for emulsion is added to bitumen because the materials have similar emission factors. Bitumen and emulsions are assumed to have a material transportation distance of 300 km (186.4 miles) using rail. All other material transportation related activities including waste disposal are assumed to have a distance of 30 km (18.6 miles) with trucks.

Table 4-4: Input Values used by the Selected Tools for Calculating GHG Emissions and Emissions Reductions of In-Place Recycling Activities

Mitigation	**Baseline**	**POETT**	**Assumed Depth/Adapted PaLATE Input**	**PaLATE 2.0**	**PaLATE 2.2**	**Adapted PaLATE (MTO Standard)**	**Athena LCA(version 3.2.01)**
CIR	Mill & Overlay 100 mm, no waste (915.6 yd^3 HMA, 823.1 yd^3 aggregate and 92.5 yd^3 bitumen)	7000 m^2	100 mm CIR 30 mm HMA	915.6 yd^3 CIR 274.7 yd^3 HMA (247 yd^3 Aggregate, 27.7 yd^3 Bitumen), 29.1 yd^3 Emulsion	915.6 yd^3 CIR. 56.8 yd^3 bitumen	CIR 100 mm, HMA 50 mm	100 mm CIR 30 mm HMA (Superpave 12.5 material)
CIREAM	Mill & Overlay 100 mm, no waste (915.6 yd^3 HMA, which include 823.1 yd^{3,} aggregate and 92.5 yd^3 bitumen)	7000 m^2	100 mm CIREAM, 30 mm HMA	915.6 yd^3 CIREAM (with 29.1 yd^3 Emulsion), 274.7 yd^3 HMA Overlay (247 yd3 aggregate and 27.7 yd^3 bitumen	247 yd^3 aggregate, 27.7 yd^3 bitumen, and 29.1 yd^3 emulsion	CIR 100 mm, HMA 50 mm	100 mm CIR, 30 mm HMA
HIR	Mill & Overlay 50 mm , no waste (457.8 yd^3 HMA, which include 411.6 yd^3 aggregate and 46.2 yd^3 bitumen)	7000 m^2	50 mm HIR 15 mm HMA	457.8 yd^3 HIR 137.3 yd^3 HMA (123.4 yd^3 Aggregate, 13.9 yd^3 Bitumen, 14.56 yd^3 Emulsion	123.4 yd^3 aggregate, 13.9 yd^3 bitumen, and 20 yd^3 emulsion	HIR 50 mm, HMA 25 mm	50 mm HIR 15 mm HMA
FDR with EAS	Mill 150 mm, Overlay 120 mm, (275 yd^3 waste and 1099 yd^3 overlay, which include 988 yd^3 aggregate, and 111 yd^3 bitumen)	7000 m^2	Mill 150 mm, recycle 120mm FDR , additional 60 mm HMA as overlay	1098.678 yd^3 FDR 549.3 yd^3 HMA which include 493.8 yd^3 aggregate, 55.5 yd^3 bitumen, 34.9 yd^3 emulsion; 275 yd^3 waste	1373.3 yd^3 FDR, 288 yd^3 aggregate, 32.4 yd^3 bitumen, and 60.3 yd^3 emulsion	FDR 180 mm, HMA 100 mm	150 mm FDR, 60 mm HMA
FDR	Mill 150 mm, Overlay 120 mm, (275 yd^3 waste and 1099 yd^3 overlay, which include 988 yd^3 aggregate, and 111 yd^3 bitumen)	7000 m^2	Mill 150 mm, recycle 120mm FDR, additional 90 mm HMA as overlay	1098.678 yd^3 FDR 824 yd^3 HMA which include 740.8 yd^3 aggregate and 83.2 yd^3 bitumen	740.8 yd^3 aggregate, and 64.7 yd^3 bitumen	FDR 180 mm, HMA 100 mm	150 mm FDR 90 mm HMA

PaLATE 2.0 and PaLATE 2.2 usually provide multiple options for each type of construction equipment and the option for users to override values to reflect project specific use. In this comparison, the default brand/model (first selection option) is used within the tool that has the complete productivity and fuel consumption rate information. For Athena, the options for

equipment are different. Rather than selecting individual types of equipment based on rated horsepower, it “provides a comprehensive list of equipment used for” each specific mitigation activity. Thus, the default suite of all applicable equipment in the category is selected. For POETT, construction equipment mostly obtained from the Athena database was used (see Table E-3). Athena was chosen because it is Canadian and recent (last update in 2020).

While including the essential construction equipment for project completion, it is important to be aware of the fact that each project has distinctive requirements and access to certain equipment, which could lead to drastically different emission results. For example, the productivity of an asphalt remixer ranges from 8.3 tonnes/hr to 208 ton/hr (189 tonnes/hr), generating 0.46 kg to 11.61 kg of GHG emissions from equipment for 1 tonne of material processed. Similarly, for the milling machine, the productivity in Athena is shown to be 40 m^3/hr whereas the productivity in PaLATE ranges from 40 ton/hr to 1100 ton/hr. These differences in equipment specification alone can lead to large emission differences when processing materials in large quantities.

Figure 4-3 and Table 4-4 show the GHG emissions for five mitigation scenarios with the four tools listed above. For adapted PaLATE, the comparison presents both a similar design for the tools’ testing case and the typical thickness provided by MTO from a previous project (Nasir, 2018). The MTO designs are included not to evaluate the tool, but to display emissions using recent MTO conditions so these can be compared to the test conditions. Athena combines material and construction component values and does not calculate results for FDR, which precludes comparison by emission category.

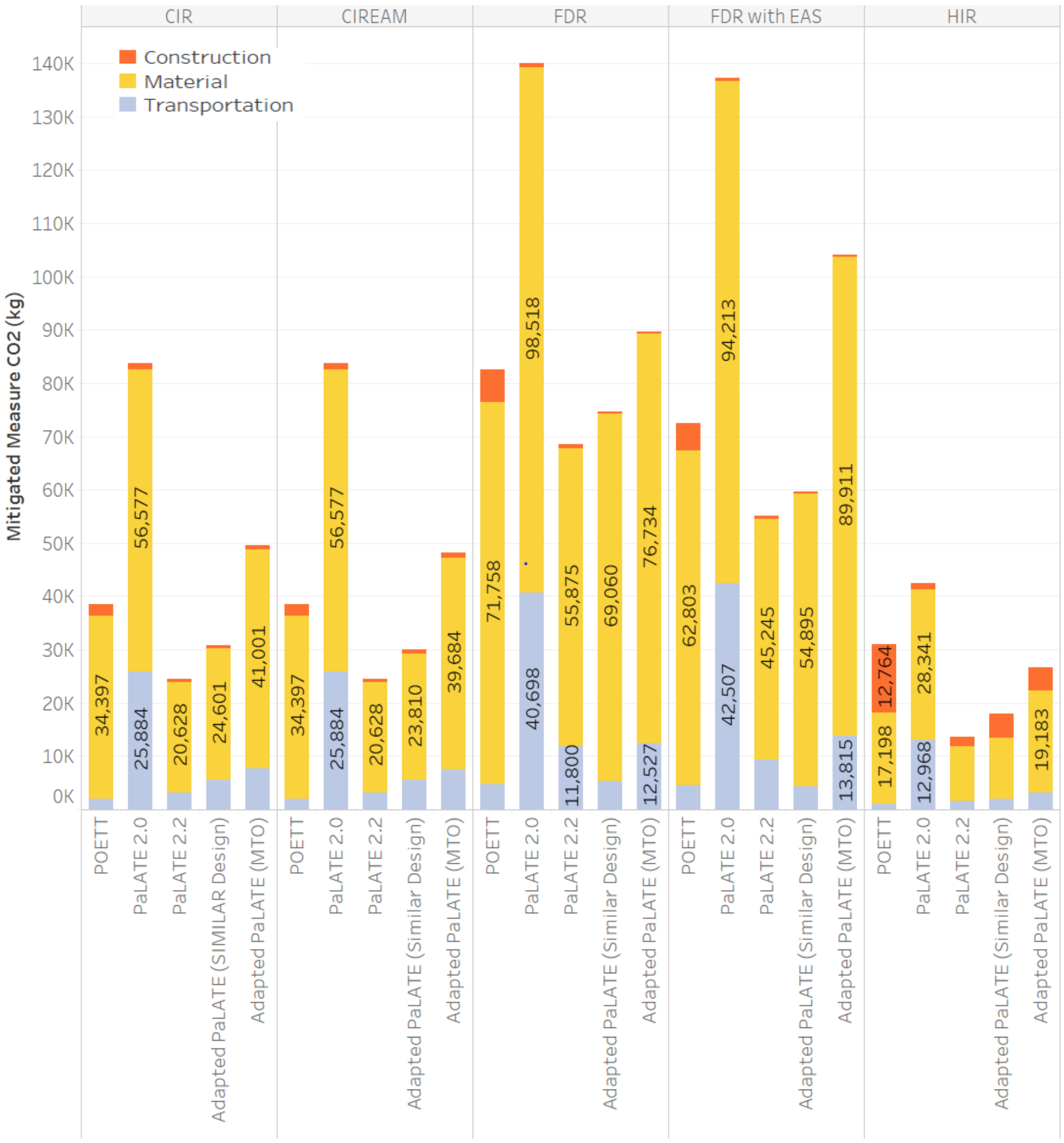


Figure 4-3: GHG Emissions (in kg) from In-Situ Recycling Activities for 7000 m^2 Pavement Calculated by Selected Tools

Athena results are presented separately in Table 4-5. The total emissions from Athena generally fall between the other estimates, except for HIR, for which it gives a much higher value. This may be because Athena calculates HIR emissions with a more comprehensive equipment list that includes equipment with very high emission rates.

Table 4-5: Greenhouse Gas Emissions Results Generated from Athena Pavement LCA

Mitigation Measures	Material & Construction Emission (kg)	Transportation (kg)	Total (kg)
CIR	59640	3355	62995
CIREAM	59640	3355	62995
HIR	94630	2201	96831
FDR with EAS	94230	12970	107200
FDR	-	-	-

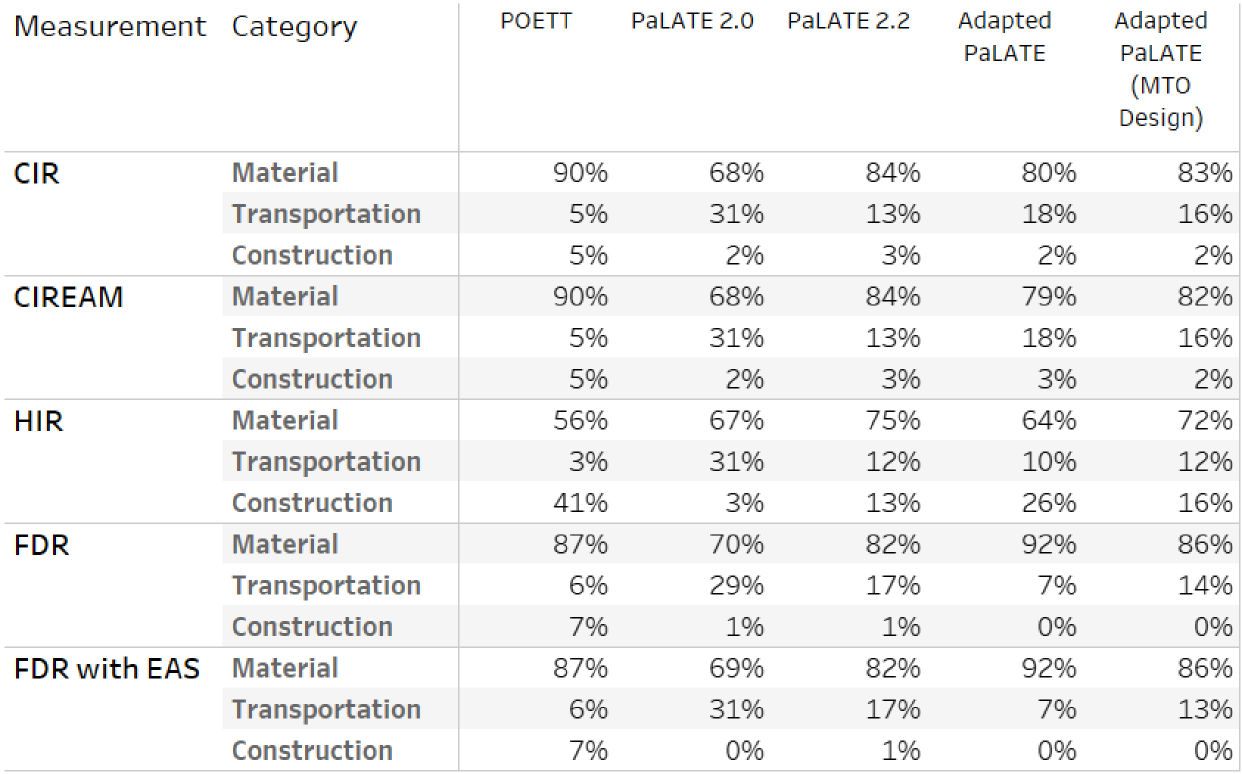
Figure 4-3 shows that all tools generally show a similar pattern of GHG emissions for mitigation activities, and the resulting emission values fall in acceptable ranges. Among the results calculated, FDR shows the highest GHG emissions and HIR shows the lowest emissions (with the exception of Athena). Material emissions are the largest among the components, followed by transportation, and construction in most cases. Among different versions of PaLATE, PaLATE 2.0 consistently shows the largest emission results for all mitigation activities whereas PaLATE 2.2's values are relatively low.

When comparing transportation-related emissions, those of PaLATE 2.0 are the highest. This is because, in the test scenario, rail is used as a transportation mode for bitumen and emulsions. While many tools assume the emission rate per kilometer is lower for rail than trucks, the rail calculation in PaLATE 2.0 has a lower capacity and fuel efficiency (0.42 l/km for truck and 0.7 l/km for rail), leading to much higher emissions. For example, when transporting the same quantity of aggregate for 30 km, GHG emissions using truck and rail are 842 kg and 28,327 kg, respectively, based on PaLATE 2.0. In contrast, POETT has lower transportation-related emissions than the others. This may be due to its differing methodology. Specifically, the emission rates applied are taken from Cefic (2011), which cover different payloads and levels of deadhead (20%, by default). By asking the user to specify "empty run percentage" (fraction of distance travelled while deadheading) and number of truckloads, more accurate results reflecting the specific supply can be obtained. POETT also shows a slightly larger construction emission because Athena's database was applied for equipment related data.

Percentagewise, all tools show that the material component has the largest GHG emissions for all mitigation measures - the values vary from 55.6% for the HIR in POETT to 92.42% with FDR in adapted PaLATE. POETT also shows smaller transportation emission values with the default setting, and relatively larger values for construction emissions. Again, POETT uses equipment specifications from Athena, which have lower productivity for construction equipment in many cases, resulting in higher GHG emissions. Detailed percentages regarding each component's contribution are presented in Table 4-6. This table indicates that material production contributes to approximately 70%-90% of the total emissions, and transportation contributes to around 5%-

20% for most mitigation activities. The percentage contribution does not vary significantly for most activities except for HIR, which shows a higher percentage for construction, and has a lower percentage for material and transportation as a result.

Table 4-6: Percent Contribution of GHG Emissions from each Component (Material, Transportation, Construction) for In-Place Recycling Activities Calculated by the Selected Tools



Measurement	Category	POETT	PaLATE 2.0	PaLATE 2.2	Adapted PaLATE	Adapted PaLATE (MTO Design)
CIR	Material	90%	68%	84%	80%	83%
	Transportation	5%	31%	13%	18%	16%
	Construction	5%	2%	3%	2%	2%
CIREAM	Material	90%	68%	84%	79%	82%
	Transportation	5%	31%	13%	18%	16%
	Construction	5%	2%	3%	3%	2%
HIR	Material	56%	67%	75%	64%	72%
	Transportation	3%	31%	12%	10%	12%
	Construction	41%	3%	13%	26%	16%
FDR	Material	87%	70%	82%	92%	86%
	Transportation	6%	29%	17%	7%	14%
	Construction	7%	1%	1%	0%	0%
FDR with EAS	Material	87%	69%	82%	92%	86%
	Transportation	6%	31%	17%	7%	13%
	Construction	7%	0%	1%	0%	0%

Figure 4-4 presents the emission savings calculated by tools for the same five mitigation measures. The emission savings are obtained by subtracting the mitigated GHG emissions from their mill & overlay equivalents. The baseline emissions are presented in Appendix D.

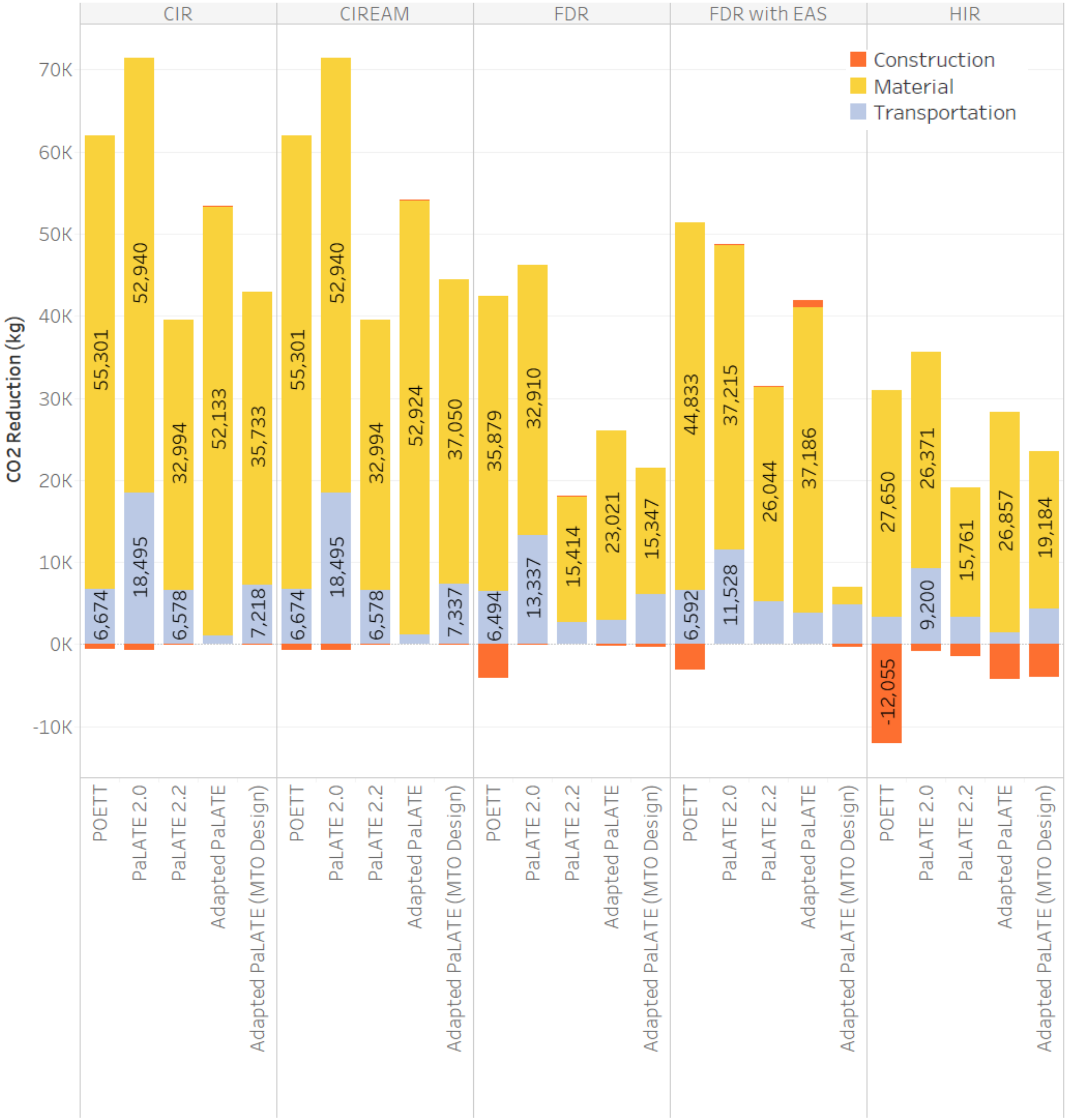


Figure 4-4: GHG Emissions Reductions (in kg) from each In-Situ Recycling Option for 7000 m^2 Pavement Calculated by Selected Tools

Results from Athena are not presented in the figure above because there is no good way to compare its outputs among categories and the emission reduction for FDR is not available, and therefore they have been presented separately in Table 4-7. Athena shows slightly larger reductions for CIR, CIREAM, and FDR with EAS, and negative reduction for HIR. Athena generally produces high baseline emissions, leading to large emission reduction values. The negative results for HIR obtained from Athena might be caused by the high construction equipment emissions from HIR.

Table 4-7: Greenhouse Gas Emission Reduction Results Generated from Athena Pavement LCA

Mitigation Measures	Material & Construction Emission (kg)	Transportation (kg)	Total (kg)
CIR	79760	11765	91525
CIREAM	79760	11765	91525
HIR	-12640	5427	-7213
FDR with EAS	68420	6430	74850
FDR	-	-	-

From Figure 4-4, the pattern of emission reductions follows that from the GHG emissions. Among the PaLATE tools, PaLATE 2.0 shows the greatest reduction while PaLATE 2.2 shows the lowest. Among mitigation activities, CIR and CIREAM have the greatest reductions, ranging from 39,000 kg to 71,000 kg, followed by FDR with EAS, FDR, and then HIR. The fact that HIR has the lowest emissions and the lowest GHG reductions is expected because this recycling measure applies to a thinner layer of pavement surface, reducing both emissions and savings opportunities. The heating process further limits the construction-related emission savings. Compared to CIR and CIREAM, FDR with EAS has a lower GHG reduction. The lower reduction is likely because part of the recycled mix is the subbase material and does not have a high structural coefficient, and therefore still requires a large amount of HMA, in turn producing more GHG emissions.

The material component yields the highest emission reductions, contributing to over 80% of the reductions for most measures, followed by the transportation component, which is around 10%-30%. For construction equipment, most tools show a negative or a low value of reduction because more GHGs are generated by the additional processing required to reuse materials.

The percentage reductions compared to the baseline for each mitigation activity are shown in Table 4-8. Despite the differences in the magnitudes of GHGs emitted and reduced, percentage reductions are more consistent across tools. For all tools, CIR and CIREAM show the highest percentage reductions, whereas FDR shows the lowest (except for Athena, which, as discussed has negative reductions for HIR). The average percentage reductions across all six scenarios (five different tools) for CIR, CIREAM, HIR, FDR with EAS, and FDR are 56.3%, 56.7%, 39.3%, 35.0%, and 32.7%, respectively.

Table 4-8: GHG Percentage Reduction for each In-Place Recycling Measure Comparing to the Baseline

	POETT	PaLATE 2.0	PaLATE2.2	Adapted PaLATE	Adapted PaLATE (MTO Design)	Athena (version 3.2.01)
CIR	61.5%	45.8%	61.7%	63.3%	46.4%	59.23%
CIREAM	61.5%	45.8%	61.7%	64.2%	48.0%	59.23%
HIR	38.0%	45.0%	56.1%	57.3%	42.2%	-8.05%
FDR with EAS	39.9%	26.2%	36.4%	41.3%	6.0%	41.12%
FDR	32.2%	24.8%	20.9%	25.6%	19.0%	-

4.2.1.4 Range of Emissions

To evaluate the possible impact of the default values on emissions and reductions, reasonable ranges for mitigation activities are calculated. The goal is to estimate maximum and minimum values for each mitigation activity and observe their impact on the corresponding emission reduction. The maximum and minimum values of emission factors obtained from the literature have been applied in this study. For example, maximum transportation emissions were obtained with a quantity of 10 tonnes per truckload and trucks were assumed to run empty for 50% of their distance travelled. The corresponding minimum emissions was calculated using fully loaded trucks, i.e., 29 tonnes materials per truckload, and 0% deadhead. The median values shown refer to the previously presented defaults. The values for construction equipment do not change.

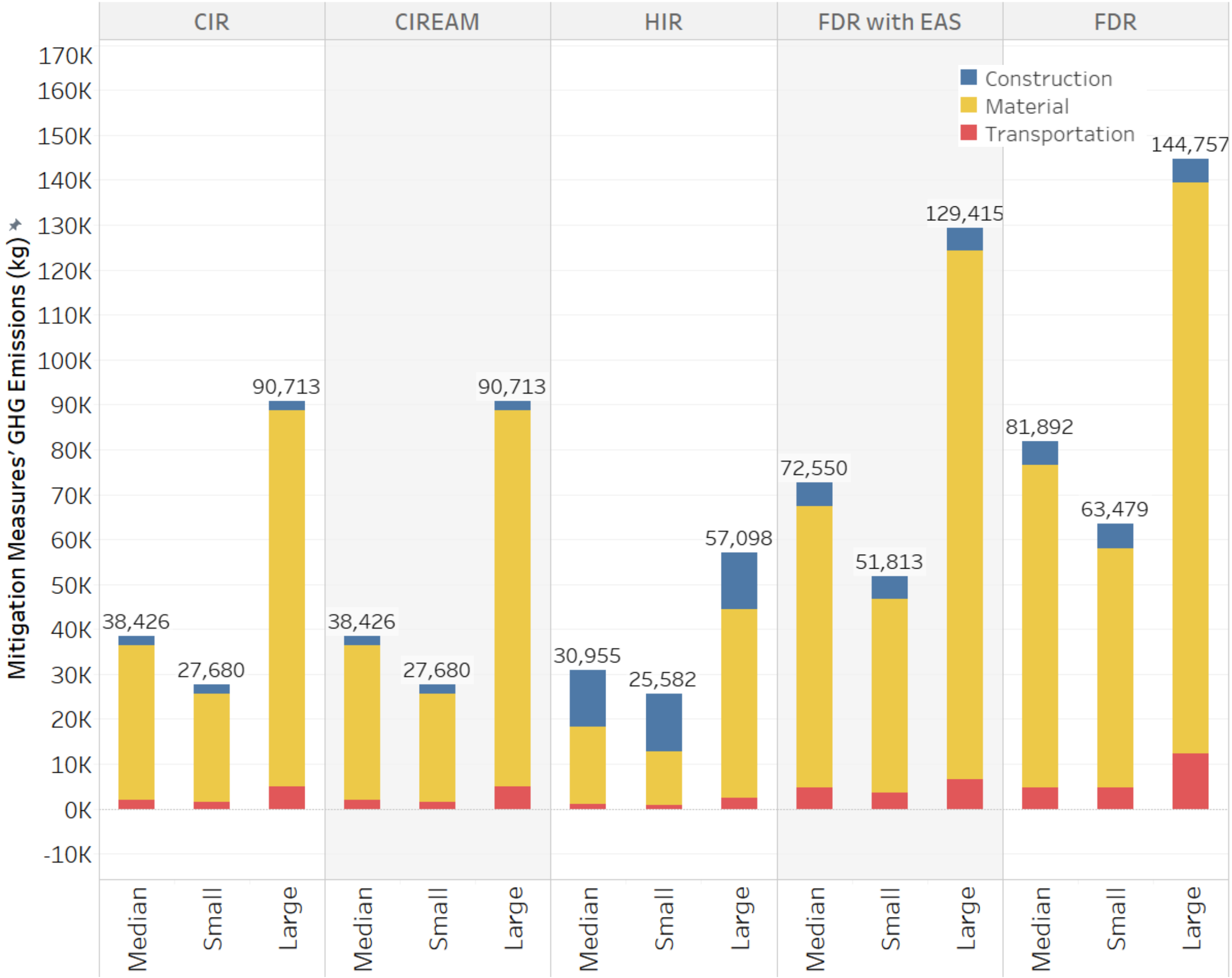
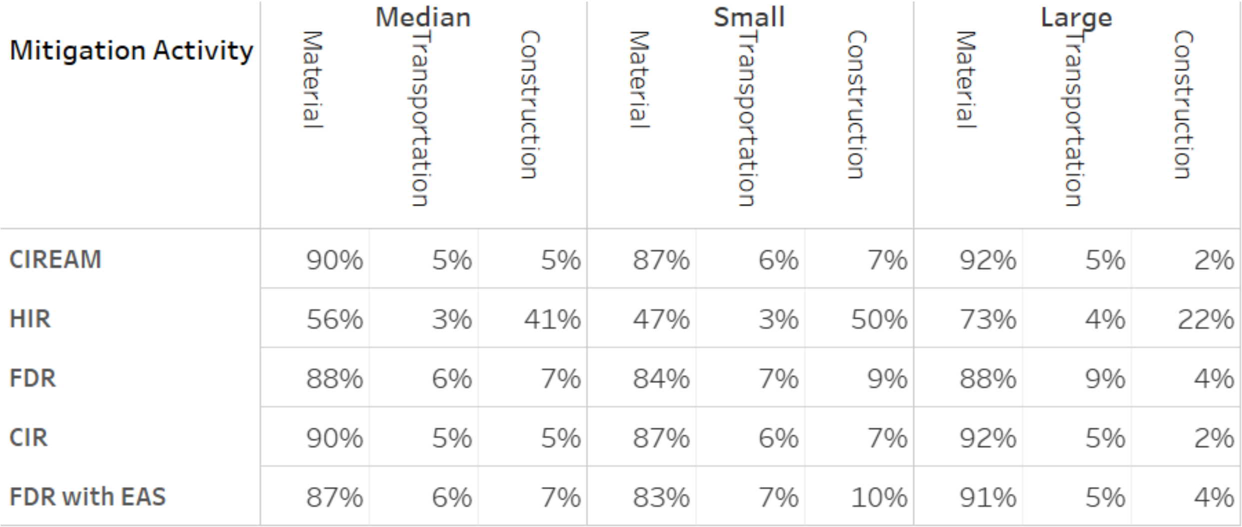


Figure 4-5: Median, Small, and Large Possible Values of GHG Emission (in kg) for each In-Situ Recycling Option Calculated using POETT

Figure 4-5 shows the median, small, and large values of emissions for each mitigation activity calculated using the test conditions in POETT. Minimum emissions are slightly smaller than the median value, while the upper limit is approximately twice the median. This suggests a long tail in the uncertainty and variability of emissions.

On a percentage basis (see Table 4-9), transportation-related emissions are stable across the range. As emissions increase, the share of material-related emissions rise as the share of construction-related emissions drops.

Table 4-9: Percentage Contribution to the Total GHG Emissions from each Component (Material, Transportation, Construction) for the Calculated Median, Small, Large Values of each In-Situ Recycling Option



Mitigation Activity	Median			Small			Large		
	Material	Transportation	Construction	Material	Transportation	Construction	Material	Transportation	Construction
CIREAM	90%	5%	5%	87%	6%	7%	92%	5%	2%
HIR	56%	3%	41%	47%	3%	50%	73%	4%	22%
FDR	88%	6%	7%	84%	7%	9%	88%	9%	4%
CIR	90%	5%	5%	87%	6%	7%	92%	5%	2%
FDR with EAS	87%	6%	7%	83%	7%	10%	91%	5%	4%

As shown in Figure 4-6, for GHG reductions, CIR and CIREAM consistently yield the high reduction potential across the range. For FDR and FDR with EAS, median reductions are relatively low; however, reductions are much higher when larger emission factors are selected. This can lead to the maximum reduction for FDR with EAS to exceed the maximum value for CIR and CIREAM.

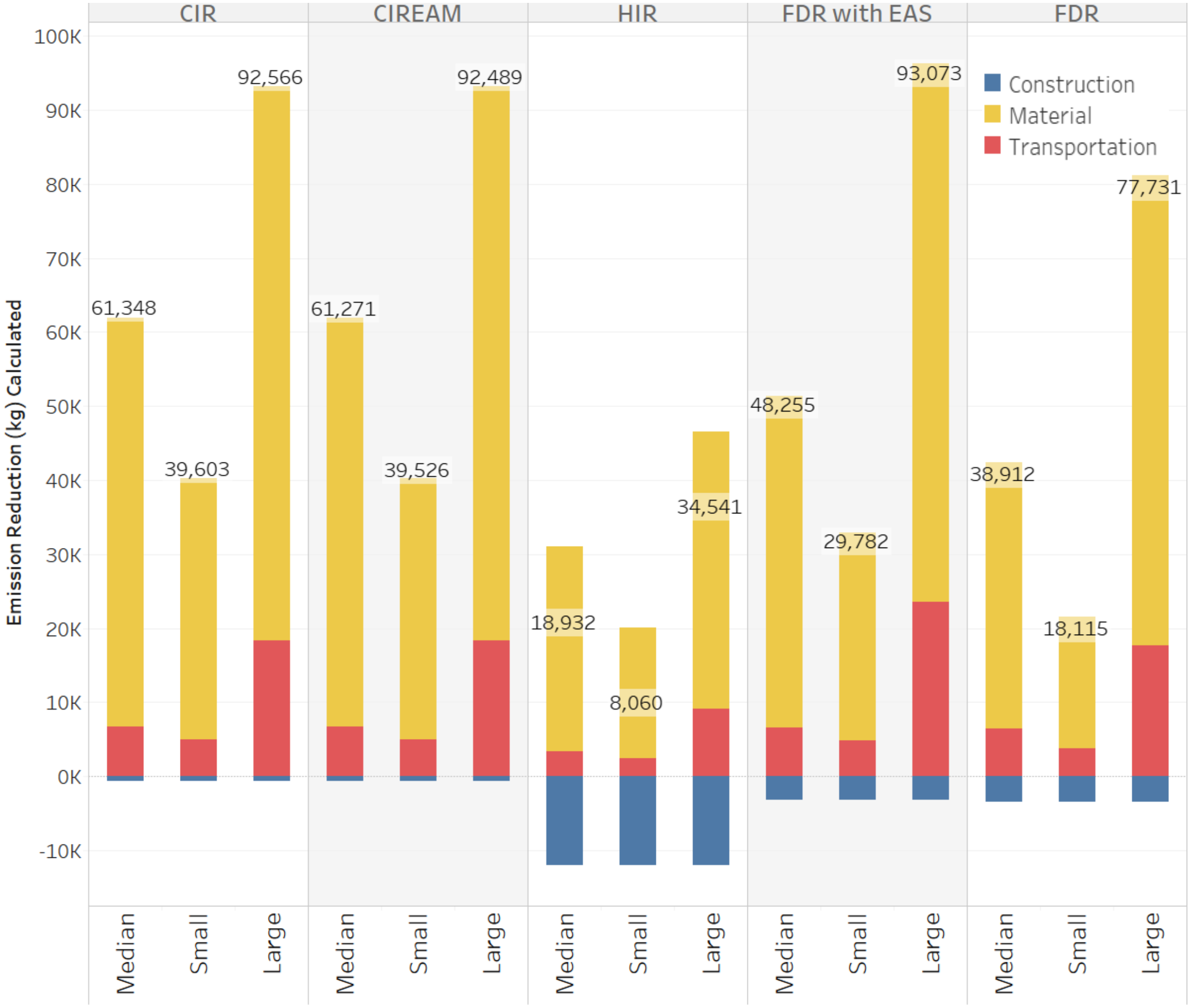
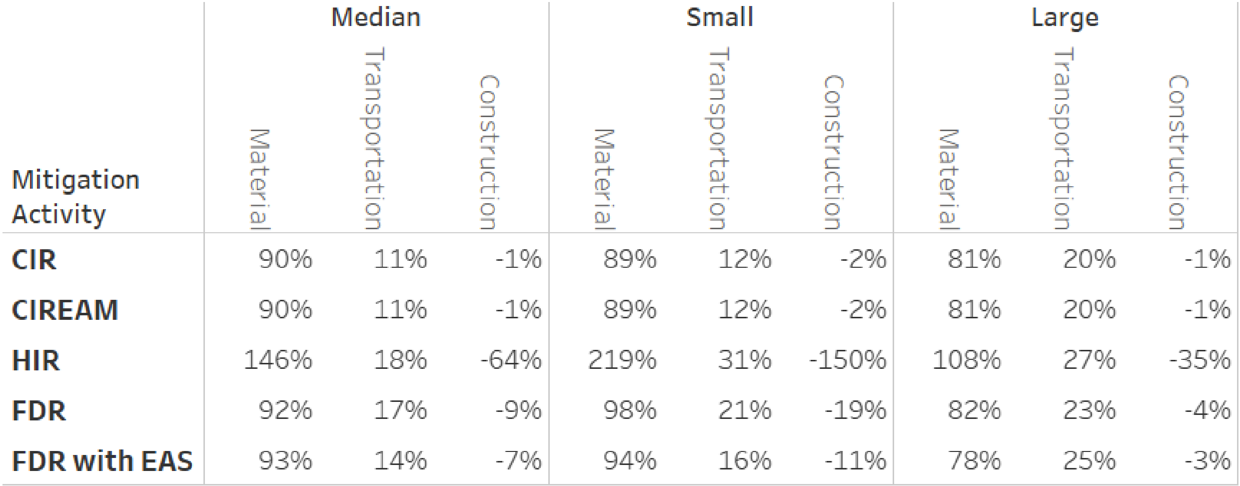


Figure 4-6: Median, Small, and Large Possible Values of GHG Emission Reduction (in kg) for each In-Situ Recycling Option Calculated using POETT

Table 4-10 presents the percentage contributions of material, transportation, and construction component.

Table 4-10: Percentage Contribution to the Total GHG Emission Reductions from each Component (Material, Transportation, Construction) for the Calculated Median, Small, Large Values of each In-Situ Recycling Option



	Median			Small			Large		
Mitigation Activity	Material	Transportation	Construction	Material	Transportation	Construction	Material	Transportation	Construction
CIR	90%	11%	-1%	89%	12%	-2%	81%	20%	-1%
CIREAM	90%	11%	-1%	89%	12%	-2%	81%	20%	-1%
HIR	146%	18%	-64%	219%	31%	-150%	108%	27%	-35%
FDR	92%	17%	-9%	98%	21%	-19%	82%	23%	-4%
FDR with EAS	93%	14%	-7%	94%	16%	-11%	78%	25%	-3%

4.2.1.5 Unit Emission/Reduction

Figure 4-7 and Figure 4-8 show the range for unit GHG emissions and reductions (per m^2). Test conditions are included, along with the four comparison scenarios performed with PaLATE and one with Athena. This helps to show uncertainty and variability across models, model versions and design. The boxes in Figure 4-7 and Figure 4-8 represent the upper and the lower boundary for total GHG emissions and reductions, respectively, developed above using POETT. The orange dot represents the median value, which are the results generated from POETT by default. The other five dots (four dots for FDR) each show the result calculated from the comparison scenarios, respectively. The dots, therefore, reflect differences across model versions and conditions, while the boxes reflect uncertainty in emission factors.

The large range of results can be obtained by POETT suggests that the emission factor uncertainty is significant even when compared across models. Default values fall in the middle of the range for GHG emissions, and at the upper end of the range for reductions. Figure 4-7 and Figure 4-8 also show that, within errors, POETT generally agrees with other models, except for the emission reductions for HIR estimated by Athena.

Figure 4-7: GHG Emission Results for each In-Place Recycling Activity Calculated by Selected Tools

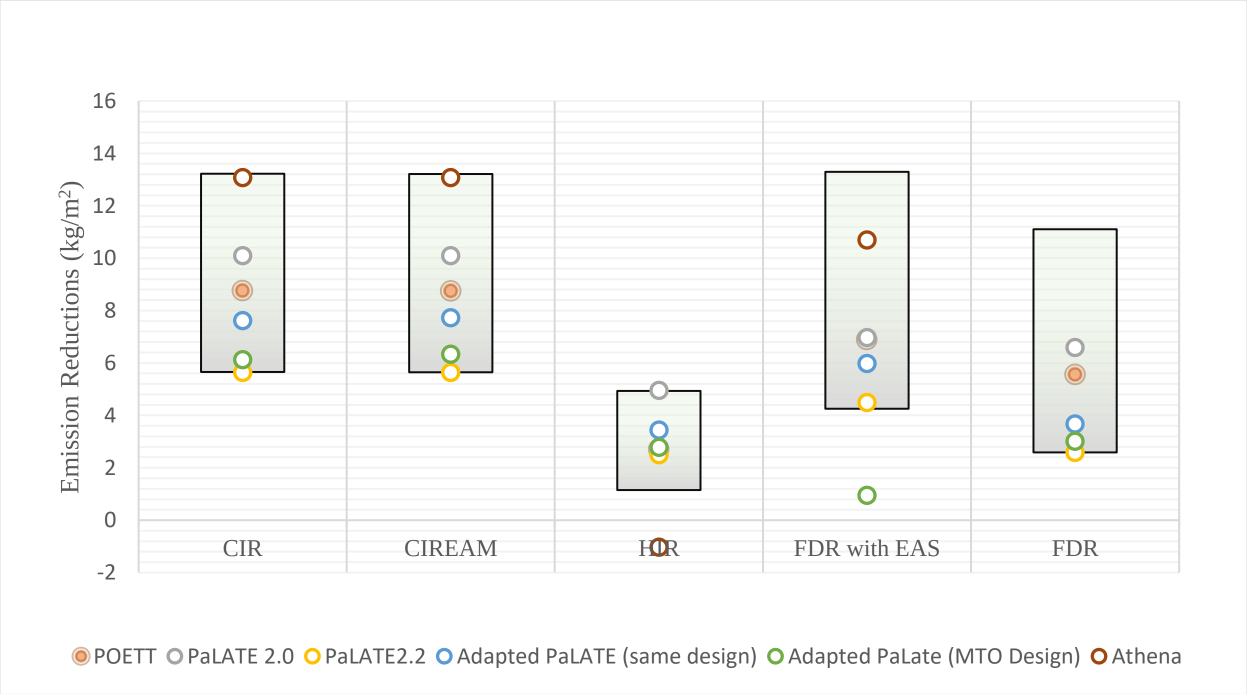


Figure 4-8: GHG Emission Reductions for each In-Place Recycling Activity Calculated by Selected Tools

4.2.1.6 Sensitivity Analysis

Sensitivity analysis allows us to understand the robustness of the emission and emission reduction results with respect to pavement design. For pavement mix design, several factors are evaluated, including emulsion percentage in the recycled mixtures and the bitumen percentage in HMA (including the overlay in both baseline and mitigated scenarios). For pavement structural design, combinations of different baseline mill and overlay thickness are used to assess their impact on GHG emissions and reductions for mitigation activities.

4.2.1.6.1 Mix Design

Figure 4-9 shows the relationship between the recycling measures' unit GHG reduction (kg GHG reduction per m^2) and emulsion content in the recycling mix. The reduction decreases linearly as the emulsion content increases for all mitigation measures. With an additional 0.5 percent emulsion, the GHG emissions for FDR with EAS, CIR, and HIR increase by 0.42, 0.28, and 0.15 kg/m^2, respectively. With the highest percentage emulsion (2.5%), the unit emissions for FDR with EAS, CIR/CIREAM, and HIR are 8.9, 8.5, and 2.6 kg/m^2, respectively.

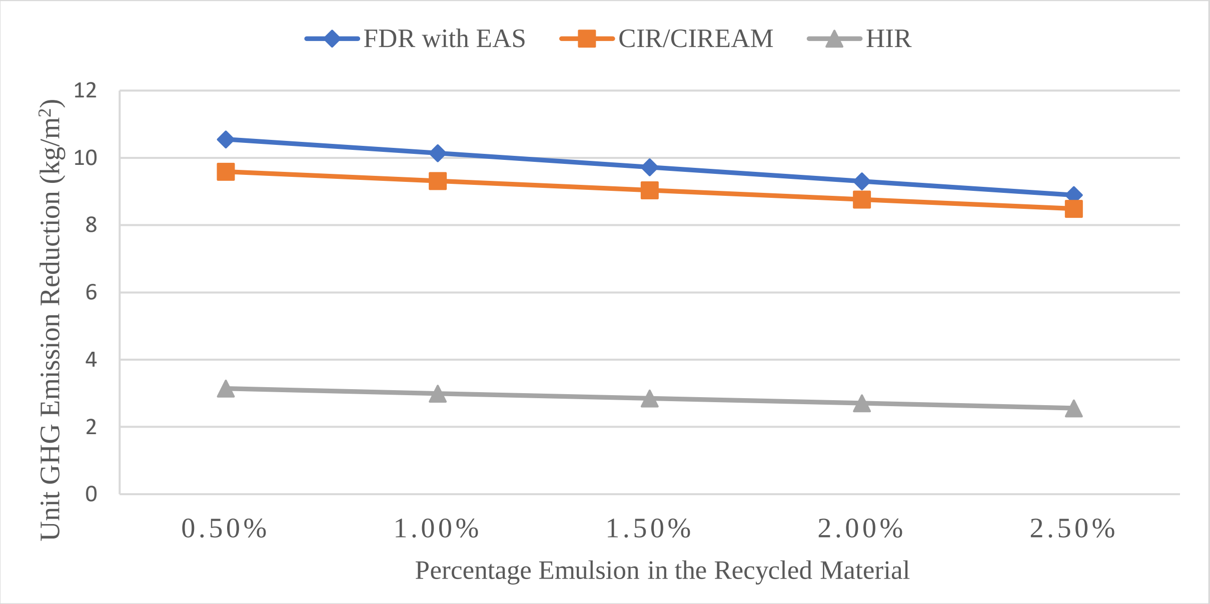


Figure 4-9: GHG Emission Reductions with Respect to the Percentage Emulsion in the Recycled Material for each In-Place Recycling Activity

Figure 4-10 presents the effect of the percent bitumen on GHG reductions. The unit GHG reduction increases linearly with an increase in bitumen percentage required for HMA. As the recycling activity reduces the quantity of HMA required for the project, the bitumen requirement is reduced proportionally, while the mill and overlay always has a higher need for HMA and bitumen. With a higher bitumen content, per unit HMA emissions go up, and, as a result, the savings from mitigation activities become more prominent. With each 0.5% increase in bitumen content in the asphalt, the mitigation measures will reduce a further 0.45, 0.23, 0.4, 0.2 kg GHG/m^2, respectively.

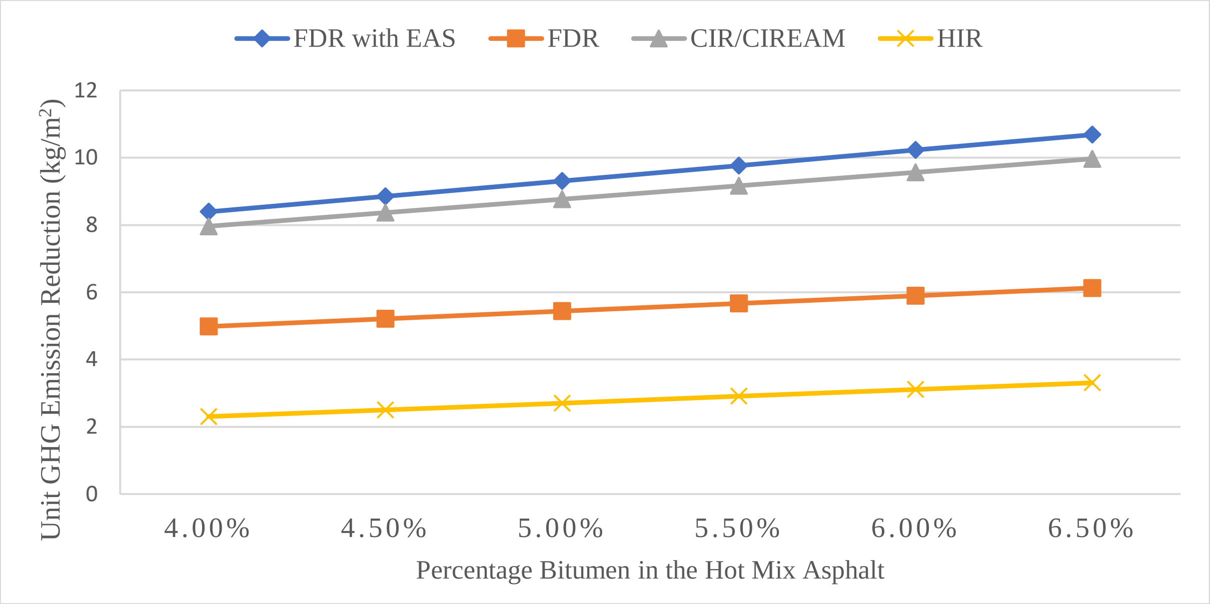


Figure 4-10: GHG Emission Reductions with Respect to Percentage Bitumen in Hot Mix Asphalt for each In-Place Recycling Activity

4.2.1.6.2 Structural Design

To understand how the structural design of the rehabilitation activity affects emissions, this report tests the different mitigation designs with a combination of mill and overlay thicknesses. For this sensitivity analysis, a range of baseline and overlay thicknesses are used as input, and the GHG emissions and reductions for the equivalent mitigation scenarios are determined. For simplicity, it is assumed that the thicknesses for pulverization/recycling are the same as those for milling in M&O; and the additional HMA overlay thicknesses for mitigation measures are calculated using structural numbers. That is to say, in this case, if the baseline M&O operations require milling 100 mm and paving 90 mm HMA, the equivalent mitigation alternative would involve pulverizing and recycling 100 mm pavement material, and adding an additional 20 mm HMA layer for structural integrity. An original pavement thickness of 130 mm is assumed. This value only affects emissions of FDR and FDR with EAS. Given these structural assumptions and the constant number assumed for mix design, it should be noted that the sensitivity analysis conducted does not represent the full possible range of GHG emissions and reductions. Given the variety of potential designs, actual variations may be greater.

Figure 4-11 to Figure 4-14 show the GHG emissions for mitigation activities with the selected mill and overlay thickness baselines. The baseline conditions are presented, with the x-axis showing the milled thickness and each line representing an individual overlay thickness. Only certain overlay thicknesses are shown on the figure for clarity though the sensitivity analysis is performed for overlays for every 10 mm increment. The y-axis represents the unit GHG emissions (kg/m^2) for the equivalent mitigation activities calculated from the corresponding Mill & Overlay baseline.

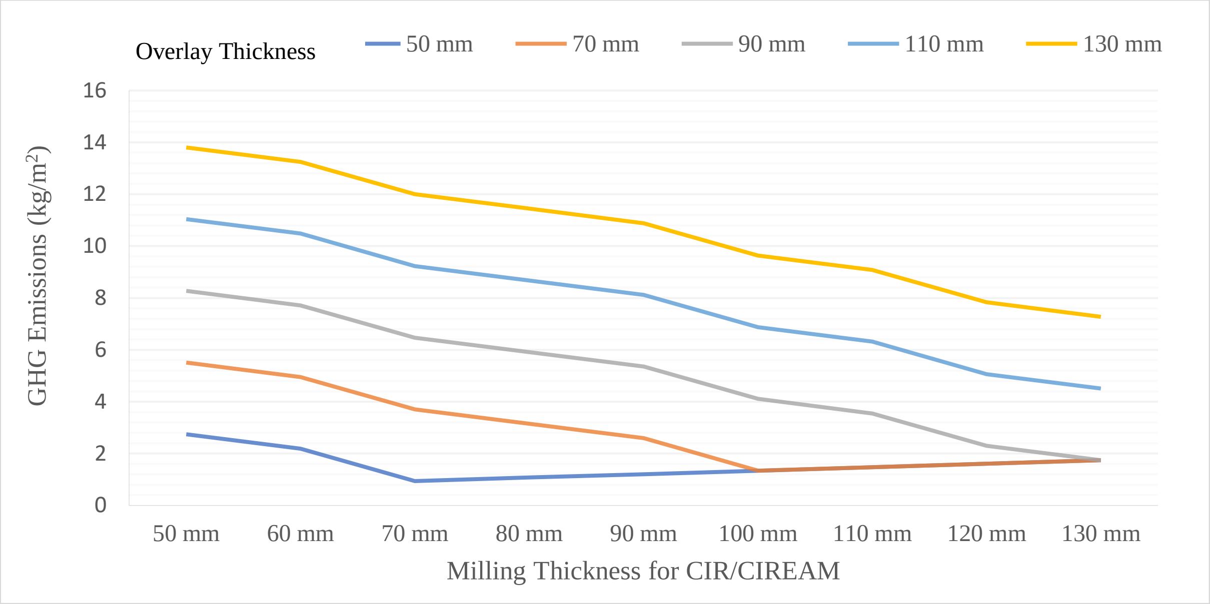


Figure 4-11: GHG Emissions of CIR/CIREAM using the Selected Combinations of Milling Thickness (mm) and Overlay Thickness (mm)

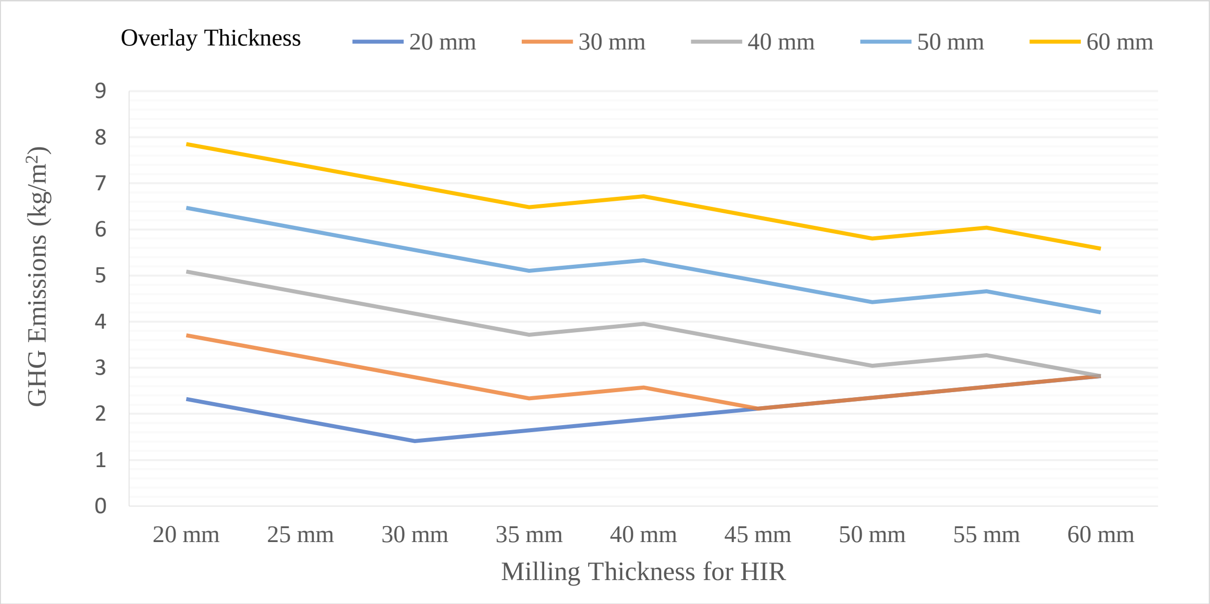


Figure 4-12: GHG Emissions of HIR using Selected Combinations of Milling Thickness (mm) and Overlay Thickness (mm)

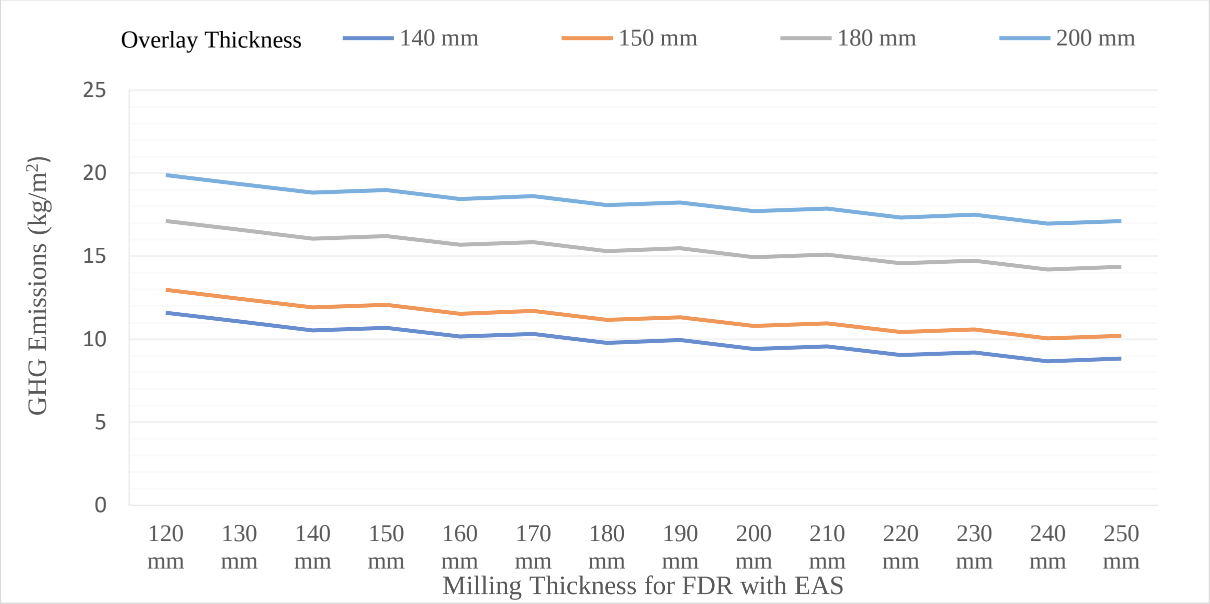


Figure 4-13: GHG Emissions of FDR with EAS using the Selected Combinations of Milling Thickness (mm) and Overlay Thickness (mm)

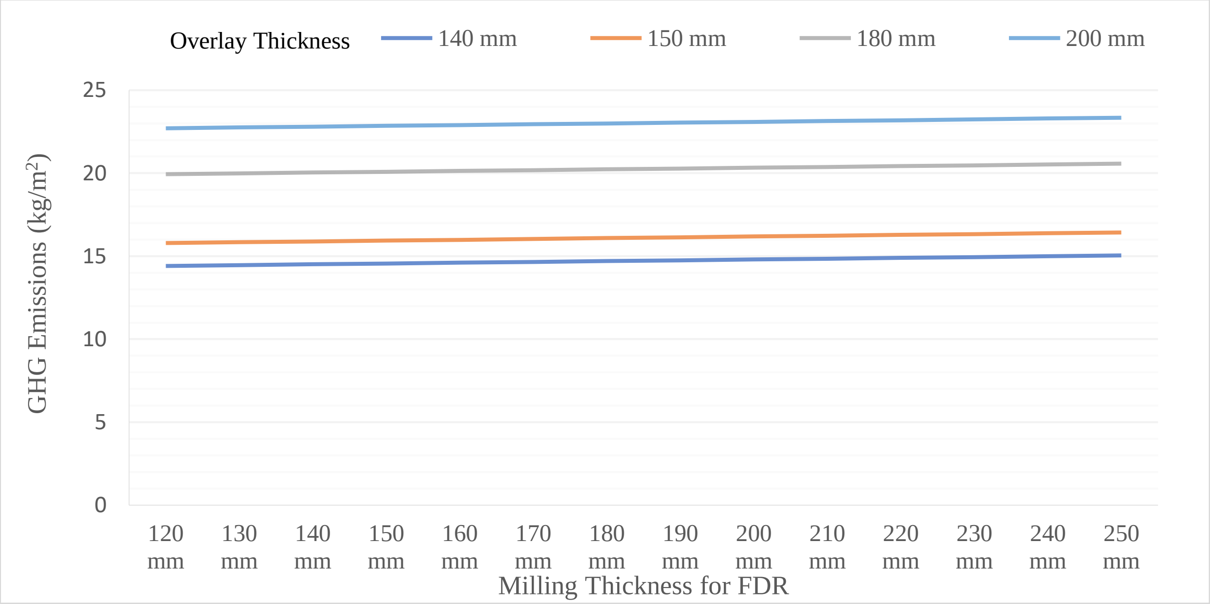


Figure 4-14: GHG Emissions of FDR using the Selected Combinations of Milling Thickness (mm) and Overlay Thickness (mm)

As shown in Figure 4-11 to Figure 4-14 for the same milling thickness (i.e., for a given point on the x-axis), emissions increase with increasing overlay thickness. For a fixed overlay thickness (i.e., for any given line on the figure), when the required milling thickness increases, emissions slowly drop, except for FDR. The decreases in GHG emissions occur because, when adding additional milling thickness, the recycling thickness for the equivalent design alternatives also increases, thus effectively reducing the required HMA layer thickness. In other words, more milling in the baseline means more recycling in the mitigation case, and thus fewer emissions per area. For FDR, because the recycled layer does not contribute to the structure much more than the granular base, the increased recycled thickness cannot reduce much of the additional HMA thickness without enhancement from the expanded asphalt. As a result, little material related GHG reduction is achieved, and the additional transportation and processing slightly increases total emissions, therefore showing an upward trend for GHG emissions.

While the line chart shows a general decreasing trend for the GHG emissions with increasing overlay, there are some irregular intervals where the emission stops decreasing and starts increasing for CIR, CIREAM, and HIR. For example, when the thicknesses of the mill and the overlay are 70 mm and 50 mm, or 100 mm and 70 mm for CIR and CIREAM, the GHG emissions of mitigation activities start to grow with increasing milling thickness. This is because, with these thinner pavements, the recycled material is sufficient and thus will not require an additional layer of HMA. When further increasing recycling thickness (e.g., changing the baseline mill thickness from 70 mm to 80 mm, while keeping overlay at 50 mm), the mitigation measures will have a higher structural number compared to their mill & overlay baseline. With the lowest possible thickness for overlay (0 mm), the material-related emission savings stops even when the recycling quantities increase. The total GHG emissions rise with increasing emulsion demand, larger transportation quantities, and more construction activities.

For each line representing increasing mill thickness with a fixed overlay, emissions fluctuate despite the general downward trend. The overlay thickness calculation is the major component contributing to this variation. When calculating the overlay thickness, the results obtained from the equation are rounded up to the nearest 5 mm to imitate the pavement design process in POETT. Take HIR as an example. With a baseline scenario assuming 50 mm for overlay, the corresponding milling thickness is 40 mm and 35 mm, respectively, and the mitigation measure will have two different thicknesses for recycling. The calculated overlays for mitigations, however, are both 25 mm, with the mill 40 mm scenario having a 22 mm calculated result which has been rounded up. The rounding up leads to higher emulsion emissions for the material, and a slight increase in transportation and construction emissions. The unit emission calculated for recycling 40 mm is 5.3 kg/m^2, which is larger than that of 35 mm (5.1 kg CO_2e/m^2). However, when rounding up to 1 mm instead of 5 mm, the emissions for 40 mm recycling changes to 4.9 kg CO_2e/m^2, thus showing fewer emissions with more recycling activity. If the rounding criteria is changed, the emissions decrement trend will be a smoother line.

The kilogram of emissions per square meter obtained from all baseline combinations tested is presented in Table 4-11 below. For a fixed mill baseline, GHG emissions increase 1.38 kg CO_2e/m^2 per 10 mm increase in overlay thickness.

Table 4-11: Summary of Possible Ranges of GHG Emissions (kg CO_2e/m^2) with Different Pavement structural Design for In-Place Recycling Activities

Mitigation Measures	Unit GHG Emissions (kg/m^2)			
	Min	Max	Median	Average
CIR/CIREAM	0.94	13.80	5.07	5.51
HIR	1.41	7.85	3.73	4.03
FDR with EAS	5.90	19.89	12.76	12.68
FDR	11.65	23.34	17.49	17.49

Figure 4-15 to Figure 4-18 show the GHG emission reductions for mitigation activities. The figures are presented in the same way as the previous sensitivity analysis figure, except that the y-axis has been changed to show the mitigation reduction in kg CO_2e/m^2.

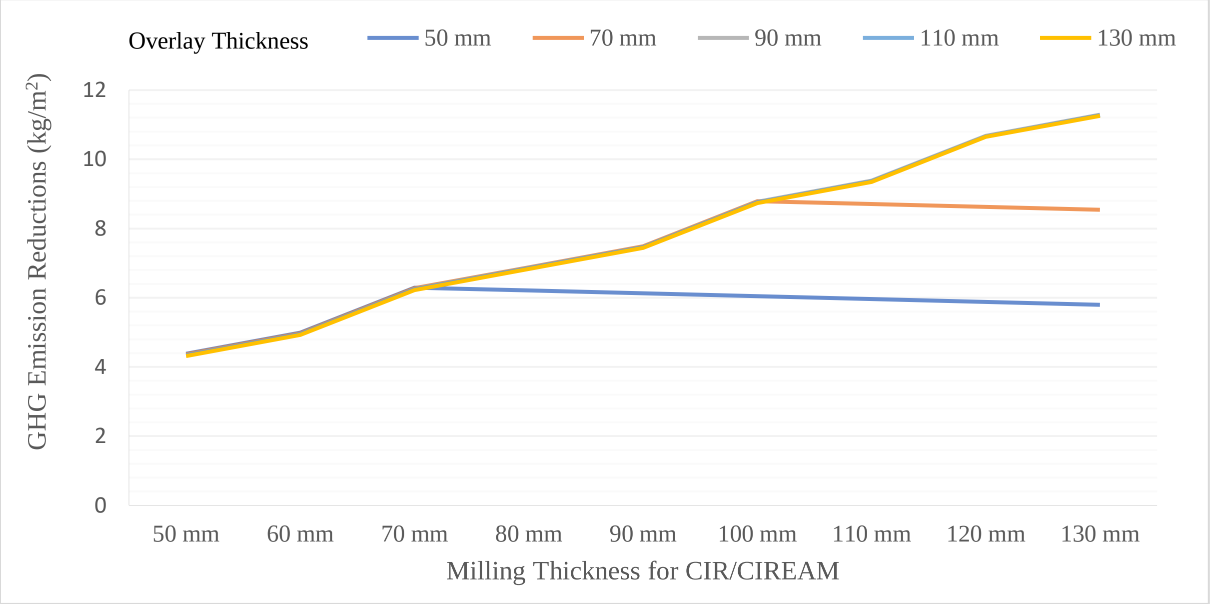


Figure 4-15: GHG Emission Reductions of CIR/CIREAM using the Selected Combinations of Milling Thickness (mm) and Overlay Thickness (mm)

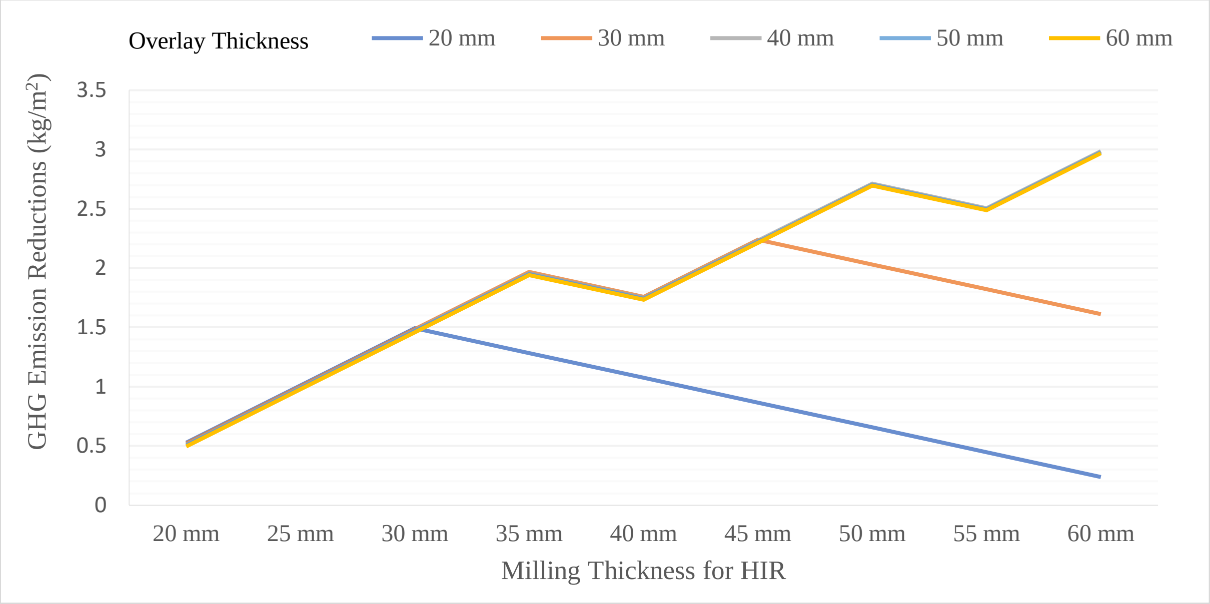


Figure 4-16: GHG Emissions Reductions of HIR with Selected using the Combinations of Milling Thickness (mm) and Overlay Thickness (mm)

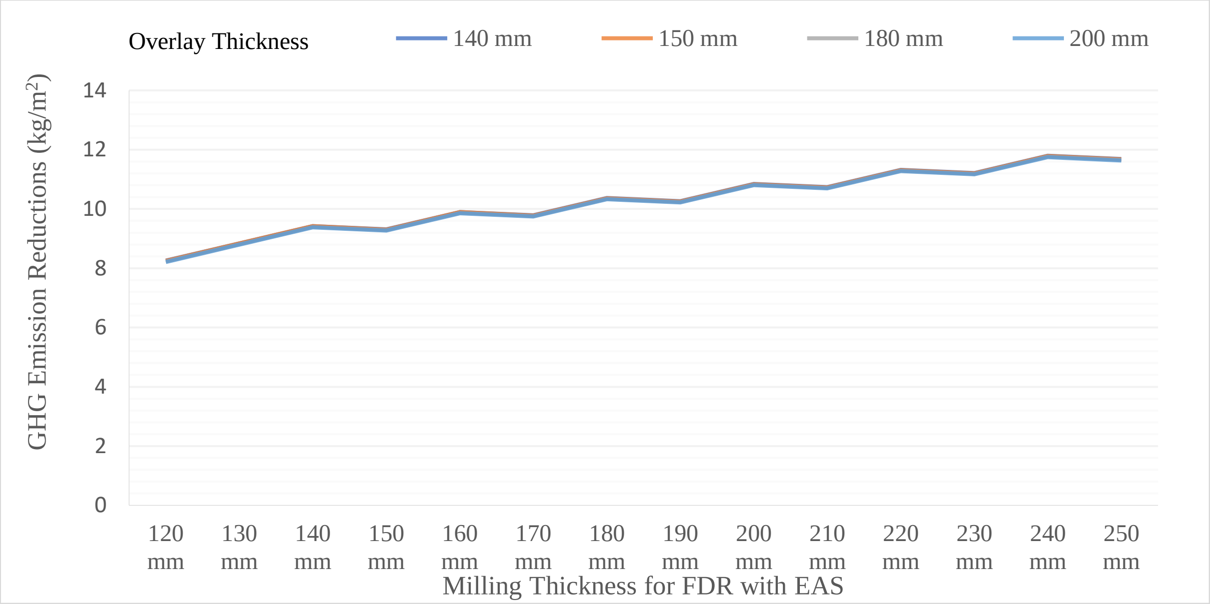


Figure 4-17: GHG Emission Reductions of FDR with EAS using the Selected Combinations of Milling Thickness (mm) and Overlay Thickness (mm)

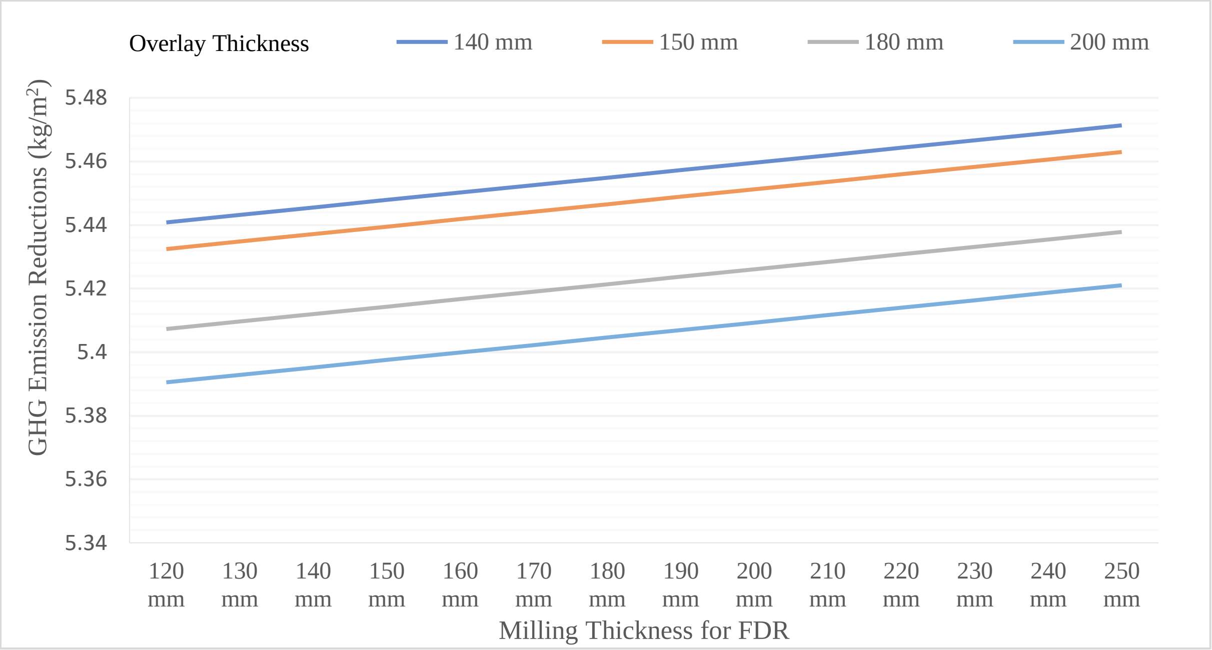


Figure 4-18: GHG Emission Reductions of FDR using the Selected Combinations of Milling Thickness (mm) and Overlay Thickness (mm)

As shown from Figure 4-15 to Figure 4-18, the GHG emission reductions for mitigation activities increase with increasing thickness of the recycled material for CIR/CIREAM, HIR, and FDR with EAS. The emission reductions do not show a significant difference (less than 0.07 kg/m^2) among various overlay thickness values selected for the baseline. For FDR, the reductions almost remain the same across increments in the quantity for recycling. Though the overlay thickness does not have a large impact on the mass of GHG emissions reduced, it slightly changes the transportation and construction emissions with the additional materials. As a result, a thinner overlay shows a slightly higher GHG reduction.

The emissions in Figure 4-15 to Figure 4-18 show a similar pattern to the reductions in Figure 4-11 to Figure 4-14. Specifically, CIR/CIREAM and HIR have some deviations from the general increasing trend. Those deviations represent the point at which no additional overlays are needed with increasing recycled layer thickness (e.g., 100 mm mill and 70 mm thickness for CIR/CIREAM). The step changes in the lines are generally caused by the rounding of the overlay thickness. A smoother line could be obtained if a different rounding setting were applied.

The kilogram emission reductions per square meter obtained from all baseline combinations tested have been presented in Table 4-12.

Table 4-12: Summary of Possible Ranges of GHG Emission Reductions (kg/m^2) with Different Pavement structural Design for In-Place Recycling Activities

Mitigation Measures	Unit GHG Reductions (kg/m^2)			
	Min	Max	Median	Average
CIR/CIREAM	4.31	11.29	6.89	7.32
HIR	0.24	2.99	1.74	1.67
FDR with EAS	8.21	11.81	10.30	10.25
FDR	5.39	5.49	5.44	5.44

Percentage reductions attributable to the structural design are calculated and presented in Figure 4-19 to Figure 4-22. Except for the special cases where the overlay thicknesses are 0, as discussed below, for the same overlay thickness, the percentage reductions increase with mill/recycle thickness for CIR, CIREAM, and HIR. On the other hand, for FDR and FDR EAS, the reduction decreases with increases in the mill/recycling quantity. For a given milled thickness, the percentage reduction is higher with a thinner overlay for all mitigation activities. For the cases evaluated, the highest possible reduction is around 87% for CIR and CIREAM. The lowest reduction occurs when a large quantity of recycled material is used with FDR (≥ 240 mm thickness), in which case a mere 1% reduction is achieved regardless of the baseline overlay requirement.

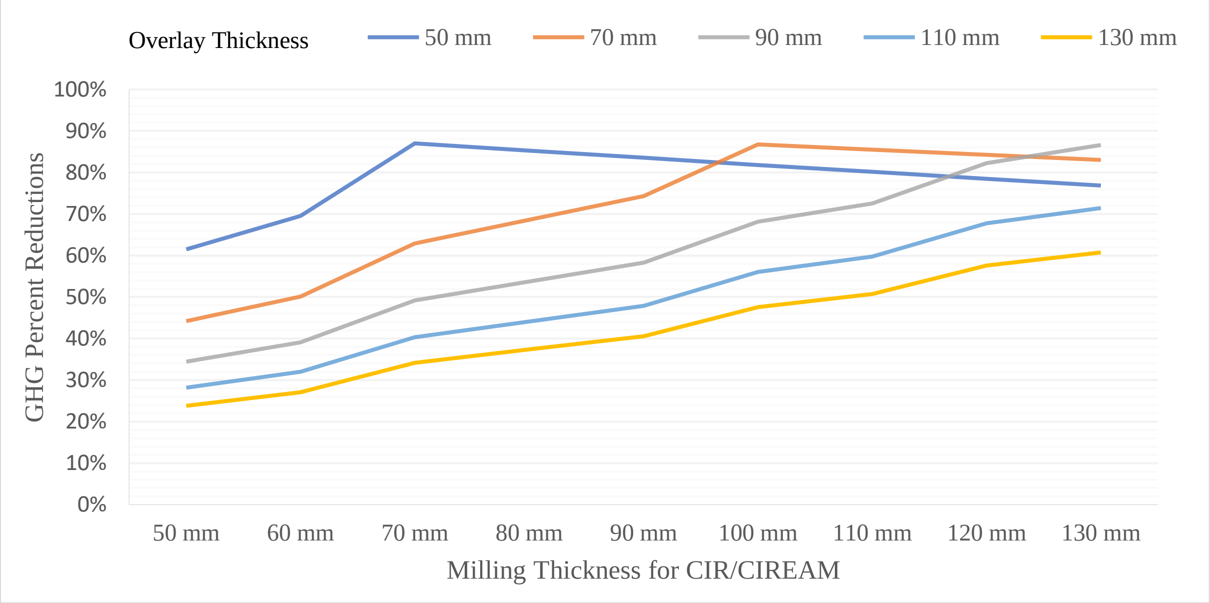


Figure 4-19: GHG Percentage Reductions of CIR/CIREAM using the Selected Combinations of Milling Thickness (mm) and Overlay Thickness (mm)

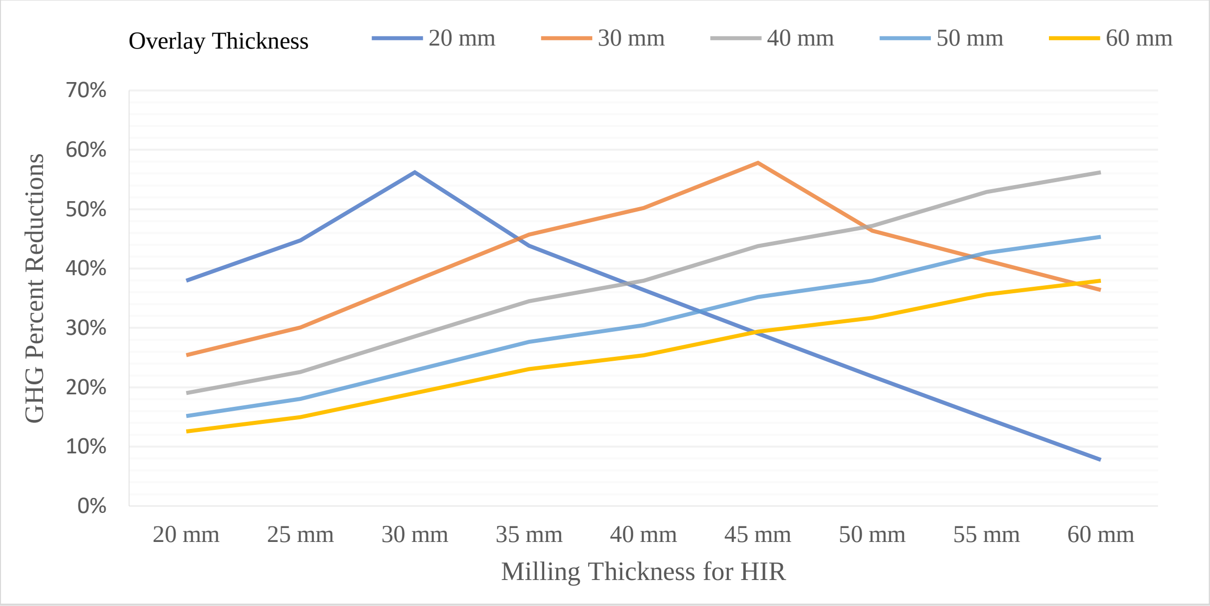


Figure 4-20: GHG Percentage Reductions of HIR using the Selected Combinations of Milling Thickness (mm) and Overlay Thickness (mm)

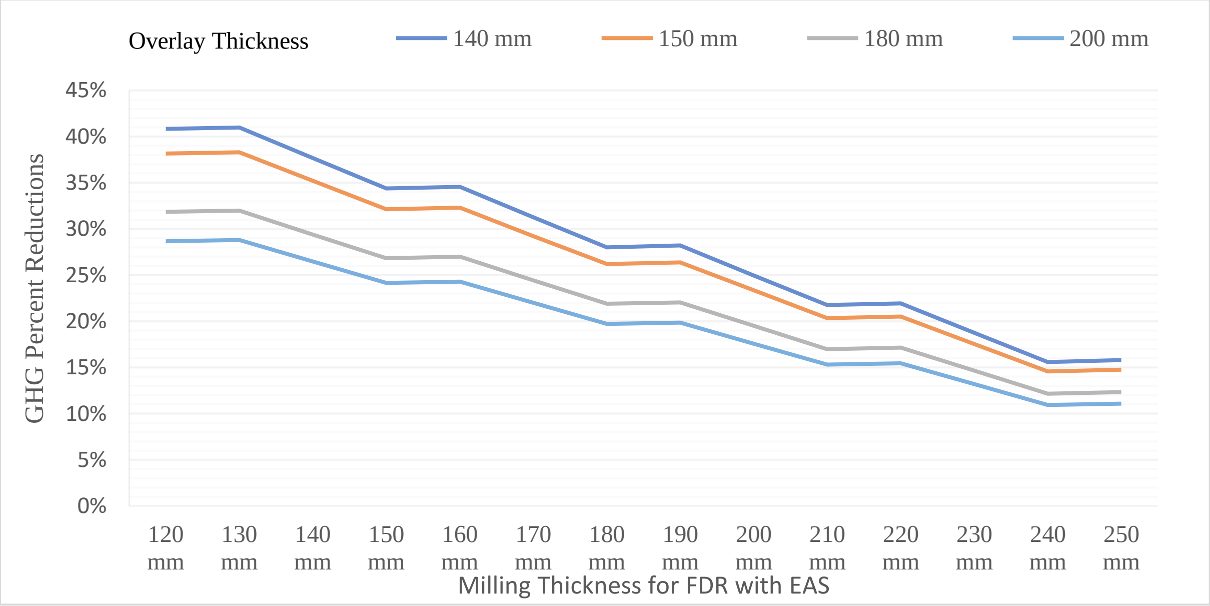


Figure 4-21: GHG Percentage Reductions of HIR with the Selected Combinations of Milling Thickness (mm) and Overlay Thickness (mm)

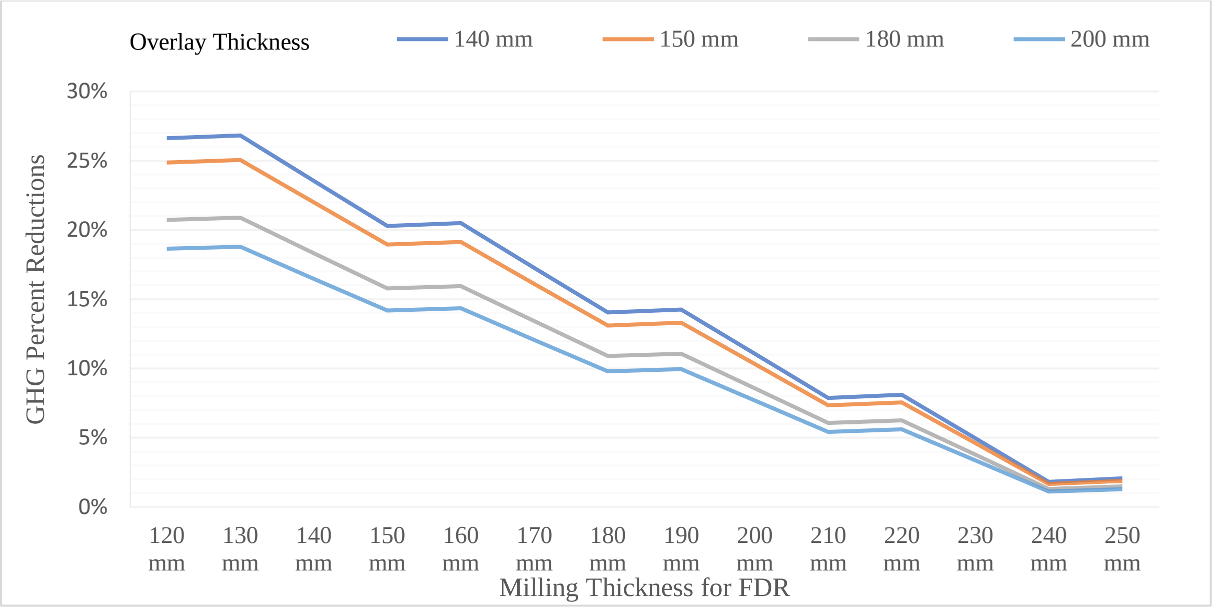


Figure 4-22: GHG Percentage Reductions of FDR with the Selected Combinations of Milling Thickness (mm) and Overlay Thickness (mm)

This sensitivity analysis explores the effect of design variables that will vary based on project requirements. As such, one cannot use it to infer whether a given mitigation activity is the most "environmentally friendly" overall. Instead, greenhouse gas emissions and savings will vary largely based on the project needs, especially for rehabilitation thickness. While HIR has the lowest emissions of the GHG mitigation measures, the resulting GHG reduction is also low because of the thinner pavement thickness involved. Conversely, FDR with EAS emits a relatively large amount of GHGs, and also offers a larger reduction in quantity emitted compared to the baseline, though the percent reductions are generally lower than what is observed for CIR/CIREAM. CIR/CIREAM have relatively small GHG emissions, and high GHG reductions for the selected cases analyzed. Emission savings can be minimal for FDR when the pavement distress is deep, and a very strong pavement is required after the rehabilitation.

4.2.2 Warm Mix Asphalt

Figure 4-23 presents the GHG emission reductions for one tonne of Warm Mix Asphalt (WMA). POETT directly obtains the reduction value from an article submitted by the MTO (Politano, 2012). Comparisons are provided based on three sources: GreenDOT(Gallivan et al., 2010), Frank et al. (2011), and the FHWA Tool (F. Gallivan et al., 2014). Frank et al. (2011) provide a range of WMA alternatives for the three sites the study evaluates. Thus, the reduction values are calculated using the baseline HMA minus the median value of WMA from each site. For the FHWA Tool, F. Gallivan et al. (2014) was cited stating that WMA achieves a 37% GHG reduction. Based on current research, there is not enough information available to quantify emissions of different types of WMA additives (D'Angelo et al., 2008; Wakefield, 2011). For this reason, the emissions associated with the additives are not counted, but expect them to be small given the small quantities added.

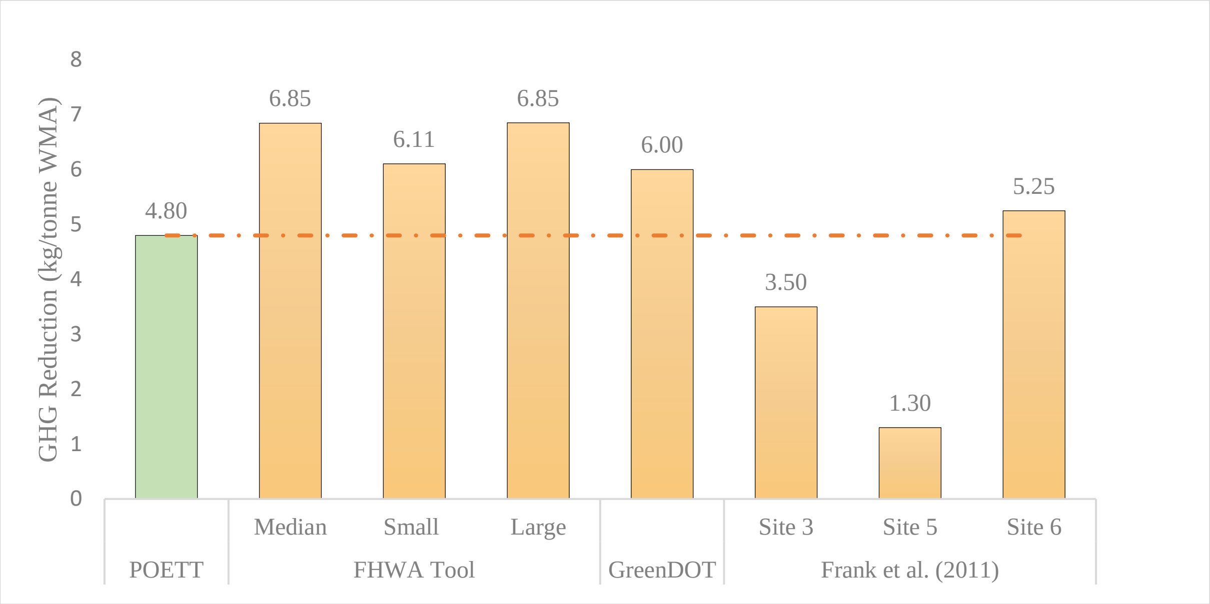


Figure 4-23: GHG Reductions (kg/tonne) of Warm Mix Asphalt

Figure 4-23 shows that WMA achieves reductions ranging from 1.3 to 6.85 kg CO_2/tonne material, with an average of 5.08 kg CO_2/tonne. On a percentage basis, this translates to 37% from FHWA tool and 9% to 29% for results from Frank et al. (2011). A review by Pouranian & Shishehbor (2019) found the median of the percentage CO_2 reduction to be 31%, ranging from 10.9% to 46%.

4.2.3 Concrete NSSP

Figure 4-24 presents the mass of GHG avoided when reducing 10% of the emissions for one tonne of concrete material implemented with the Concrete NSSP. Among the tools presented in Figure 4-24, the Highway England Carbon Tool provides multiple factors that vary with concrete composition. The results show that the NSSP can reduce 6.1 kg to 24.4 kg CO_2e per tonne of concrete material. Some projects, according to the NSSP, can achieve a 20% GHG reduction. POETT allows the user to specify the percentage of the projects that achieve a 20% GHG reduction for the total tonnage of GHG reduction. If 500,000 m^3 (1,219,500 tonnes) of concrete is regularly consumed within MTO related projects yearly, more than 13,040 tonnes of GHGs can be saved by implementing NSSP.

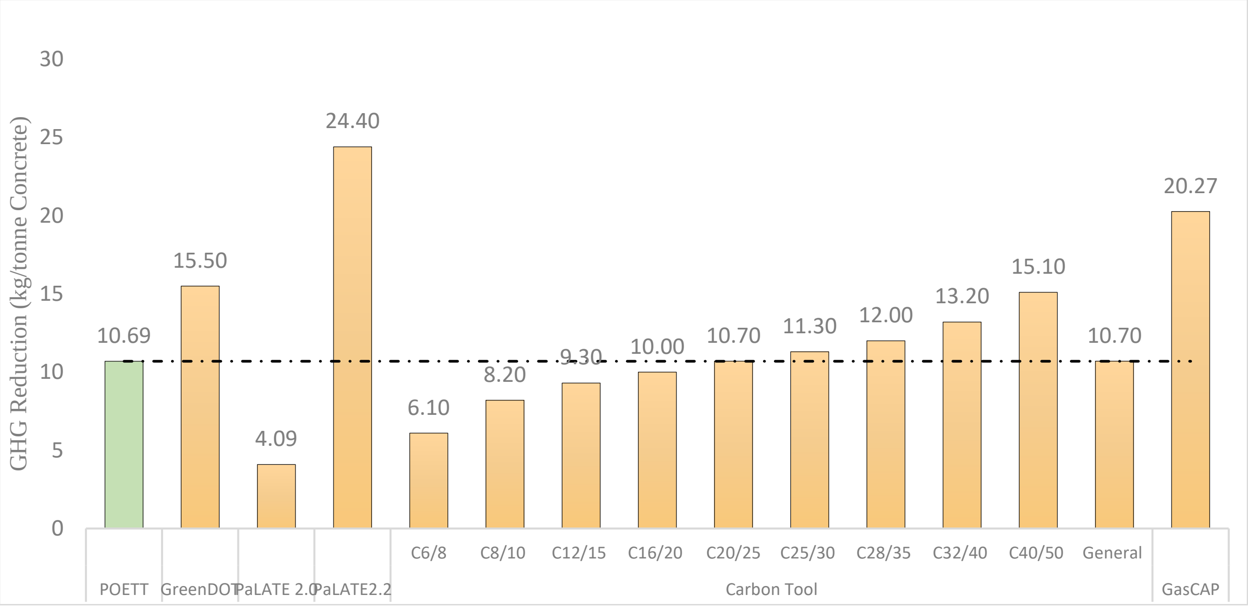


Figure 4-24: GHGs Avoided when Achieving 10% Emission Reduction from Concrete NSSP

4.2.4 Material Substitution

4.2.4.1 SCMs and Limestone Cement

Using SCM and limestone are among the most common methods of reducing GHG emissions from concrete material. In this section, a set of scenarios are presented to quantify potential GHG reductions achieved using SCMs and limestone. Such scenarios are needed because the actual quantities of SCMs and limestone are currently not tracked by MTO's HiCo database. The HiCo system treats them as components of the concrete items. Though this information may be collected by the materials section of MTO, it is not expected to be readily available for those using POETT. The default 10% reduction is applied for concrete NSSP (which are mostly achieved by SCMS and Limestones); however, this is inaccurate in representing the actual reduction, especially at smaller scales that only includes a handful of projects. The SCM and limestone section of the tool can be used to check and test combination of SCMS and limestones to bring concrete products to NSSP compliance.

To calculate sample GHG reductions, a scenario with 10 tonnes of concrete with 20% cement, and SCM replaces 10% (0.2 tonnes or 441lbs) of the cement is developed. This scenario is then assessed using POETT, and four other tools for comparison: GreenDOT, PaLATE2.2, GasCAP, and Highway England's Carbon Tool. The percentage method is used in the tool to match the requirements of concrete NSSP. When a specific SCM is not covered by the tools used for comparison, the value for the "other processing product" option is applied, if available. Note that GasCAP does not specify its assumptions for cement percentage in the concrete mix whereas Carbon Tool has a fixed percentage of SCMs embedded in the emission factors (e.g., emission factor is listed for materials such as ‘Cement with 6%-20% Fly Ash’). As a result, these tools provide more general estimates that are less straightforward to interpret.

Table 4-13 presents the mass of GHGs reduced from each tonne of concrete. Results calculated from the Highway England Carbon Tool show larger GHG reductions across the board. This may be partly explained by higher SCM contents (as specified in the parenthesis). Aside from the Carbon Tool’s results, the percentage reductions compared to the baseline for blast furnace slag, steel slag, Class C fly ash, and Class F fly ash range from 4.14%-9.98%, 4.36%-9.98%, 3.76%-9.98%, and 0.37% -9.98%, respectively, with PaLATE 2.2 showing the largest percentage reduction.

Table 4-13: GHG Reduced by SCMs and Limestone Filler

		GHG Reduced from Tools (kg GHG/tonne Concrete Usage)						
		POETT	GreenDOT	PaLATE2.2	GasCAP	Carbon Tool*		
SCMs	Blast Furnace Slag	70	39	187	238.5	480 (21%-35%)	870 (36-65%)	1260 (66%-80%)
	Steel Slag	102	41	187	243.627			
	Class C Fly Ash	40	41	187		250 (6%-12%)	530 (21%-35%)	
	Class F Fly Ash	4	41	187	243.627			
Limestone Filler		107.855	108					

* In Highway England’s Carbon Tool, the emission factors for cement with specified percentage of SCMs are provided (e.g., Cement with 6%-20% Fly Ash). The emission reductions are calculated by comparing them with baseline Portland cement material.

4.2.4.2 RAP and RCM

Apart from the in-place recycling where GHG savings are obtained from the material, transportation, and construction activities, general material recycling activities contribute a significant share of MTO’s overall mitigation efforts due to their cost-effectiveness and environmental friendliness. Both RAP and RCM can be treated as a raw aggregate when accounting for GHG emissions and assuming no binder replacement is considered in all the tools evaluated. However, the potential GHG reduction for RAP is much larger when binder replacement is considered because RAP helps avoid the high GHG emissions from the consumption of bitumen.

For binder replacement, OPSS 1151 describes how the percentage binder replacement can be calculated and the related mix design property requirement determined. For this calculation, 4.5% binder is assumed in RAP and 15% of RAP is in the mixture. The life-cycle approach is used for calculating the GHG reduction for RAP with binder replacement because of the relatively large emissions from the additional RAP mixing. As a result, the reduction amount will not only be affected by the binder percentage in both RAP and the target mix, but also the percentage RAP allowed in the mixture, as well as the assumptions regarding transportation and processing equipment. Figure 4-25 shows the kilograms of GHG emissions reduced per tonne of RAP and RCM. When binder replacement is not considered, RAP shows emission reductions that are similar to or larger than that of RCM. When binder replacement is considered with the aforementioned assumptions, a higher reduction of 21.2 kg per tonne of RAP is obtained, and the percentage GHG reduction capacity increases to 10.5 % from 5.4% when treating the material as an aggregate.

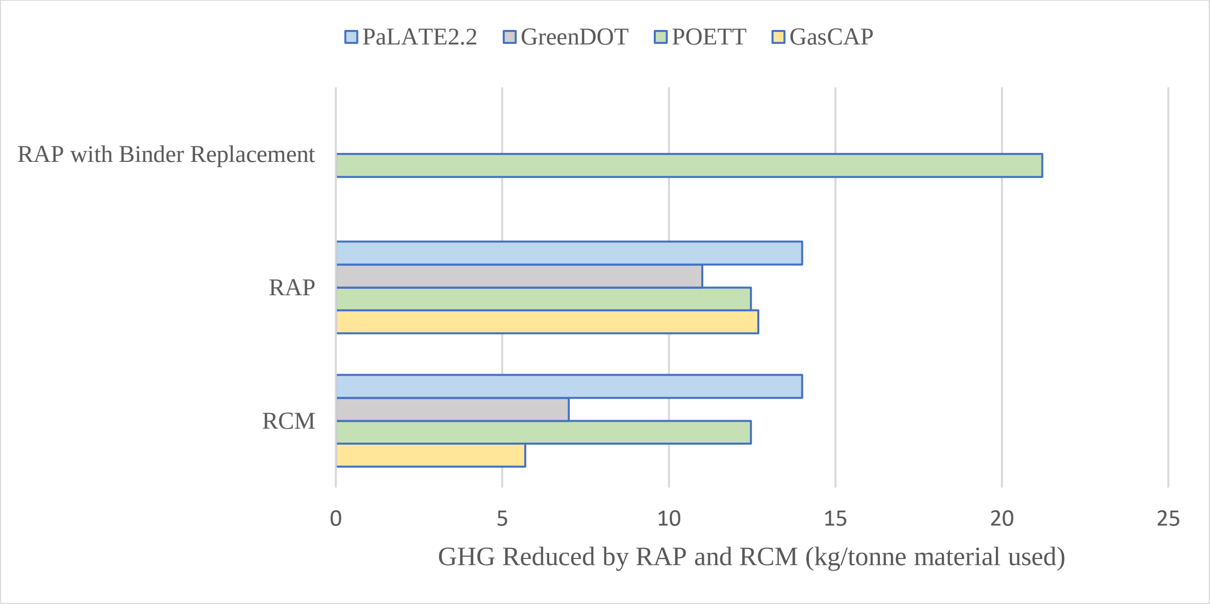


Figure 4-25: GHG Reductions by Using RAP and RCM

When including the binder replacement in the emission reduction calculation for RAP, two important variables are: 1) the percentage RAP in the mixture and 2) the binder content in RAP if the final mixture stays unchanged. Figure 4-26 presents the emission reductions with respect to the percentage of RAP in the mixture for five selected RAP binder percentages. The figure shows that a higher percentage of RAP in the mixture increases the GHG reductions. For example, when increasing RAP in the mixture from 10% to 25%, the reduction per tonne of RAP used increases from 14.2 kg/tonne to 26.9kg/tonne (for 4.5% RAP in the binder). The figure includes reductions up to a RAP percentage of 30% in the mixture. The FHWA suggests that for a maximum deployment of 40% RAP, the maximum percentage GHG reductions achievable by RAP with binder replacement is 84%.

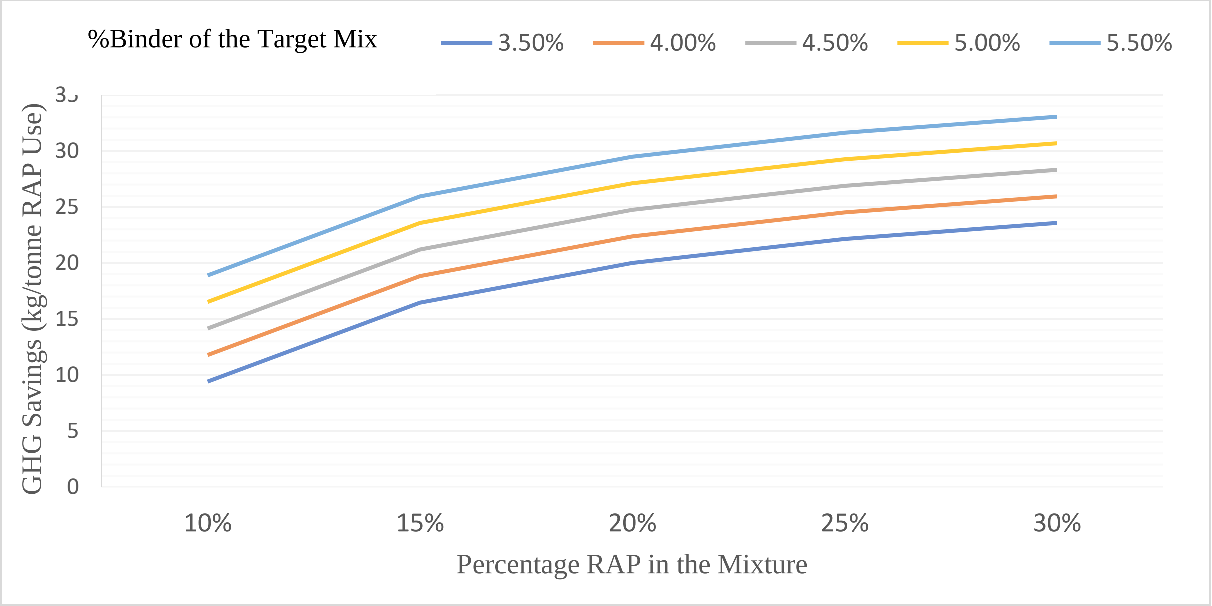


Figure 4-26: Emission reductions with respect to the percentage of RAP in the Mixture and Selected Target Binder Percentage

4.2.4.3 Other Material Substitutions

In addition to RAP and RCM, other aggregates and bitumen substitutions are quantified in POETT. Table 4-14 shows the mass of GHG reduced per tonne of the substitute material used. Note that GasCAP shows a much higher reduction for blast furnace slag. The large result is likely because the tool considers the material as a substitute for bitumen. While POETT applies the same emission factors for recycled tires/crumb rubber as those in GreenDOT, GreenDOT shows a much larger GHG reduction because of its high baseline bitumen emissions.

Table 4-14: GHG Reductions from Other Material Substitutions

Material Substitutions		GHG Reductions from Tools (kg/tonne material replaced)			
		POETT	GreenDOT	PaLATE2.2	GasCAP
Other Aggregate Substitution	Foundry Sand	11	12	28	14.147
	Blast Furnace Slag	11	12	28	1218
	Coal Bottom Ash	11	12	28	14.147
	Glass Cutlet	0.77	2	28	3.162
Other Bitumen Substitution	Recycled Tires/Crumb Rubber	336.37	1093	189	n/a
	Recycled Asphalt Shingles	99.21	n/a	n/a	12.685

4.2.5 Potential Carbonation

The potential carbonation calculation is based on “Global Warming Potential of Pavements” by Santero & Horvath (2009). The calculation has been performed for 1 tonne concrete material for 50 years, with a rate factor of 1.58 and a mass ratio of 0.65 Figure 4-27 shows the results from the tool, and the expected and extreme results calculated based on Santero and Horvath (2009)’s method. POETT’s result falls within the range, but is closer to the minimum, suggesting that its estimates of reductions may be considered conservative for this measure.

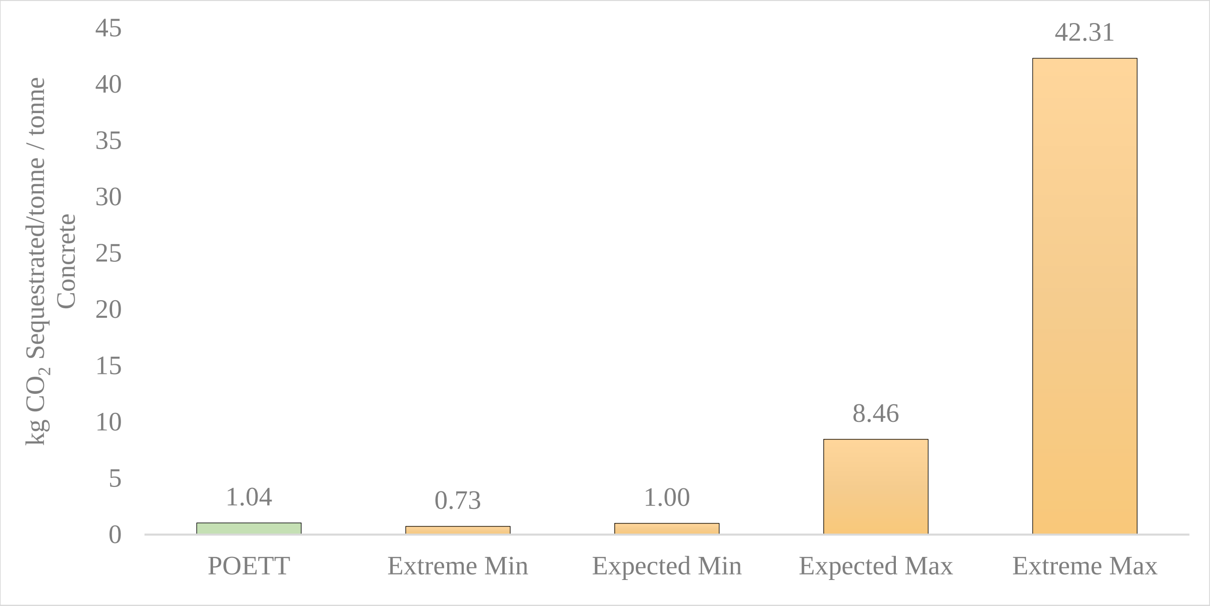


Figure 4-27: CO_2 Sequestered by Concrete Carbonation

4.2.6 Trees

The ability of coniferous and deciduous trees to sequester CO_2 largely depends on the trees’ size, survival rate, and the growth rate at the specific year. The amount of CO_2 sequestered is presented for low, median, and high cases, with and without considering the survival rate. When including survival rate, an analysis period of 50 years is considered. Over each year in this period, the number of trees that did not survive is estimated. Their deaths are assumed to occur at the end of the year, which may overstate their sequestration potential in their final year.

In Figure 4-28, the green bars represent the amount of CO_2 sequestered per year for coniferous and deciduous trees with survival rate and tree size adjustments. The values for CO_2 sequestered per year per tree, displayed on the y-axis, are calculated from the total CO_2 sequestered divided by the number of years and number of trees considered for the analysis. For the “high” conditions, a high tree survival rate, and large sizes for both coniferous and deciduous trees are assumed. The median and low conditions are formed with similar combinations in order to bound the potential reductions. POETT also allows for different setting combinations (e.g., moderate survival rate, large coniferous and small deciduous) to account for different scenarios. The blue bars show the annual CO_2 sequestration rates calculated by POETT for the year specified without the survival rate adjustment. These rates indicate the difference between the total CO_2 sequestered for a specified year and the sequestered value from the following year, divided by the total number of trees.

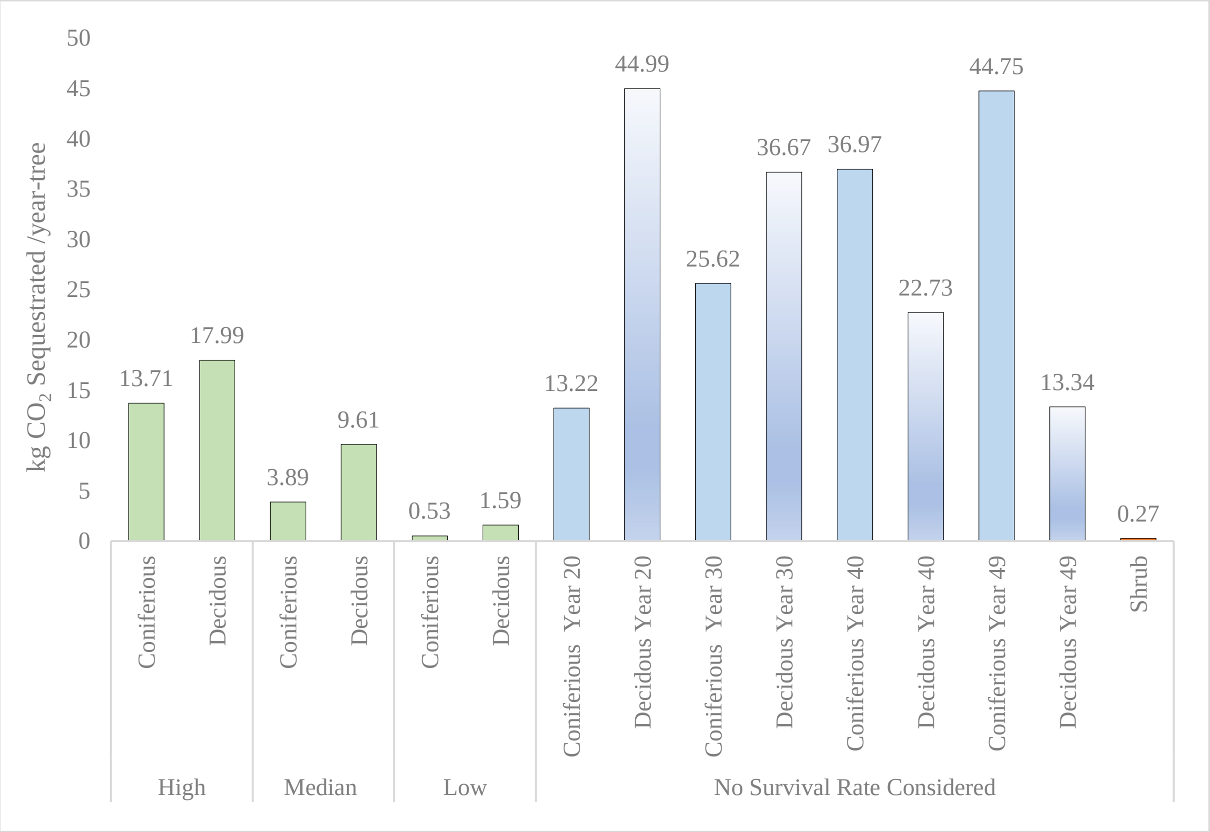


Figure 4-28: CO_2 Sequestered by Trees Calculated for Different Tree Type and Period of Analysis

For shrub CO_2 sequestration, a constant value of 0.32 Mg C/ha-year is assumed (0.27 CO_2 kg/tree-year when assuming 5 feet by 5 feet in spacing). This constant is the mean rate of carbon sequestered across the life of the shrub from Justine et al. (2017) based on a range of 0.92 Mg/ha-year at year 3 to 0.08 Mg/ha-year at year 39. Over time, beyond the 39 years considered in Justine et al. (2017), the carbon stock in the shrub layer will continue to fall. Since this average is applied to a 50-year period in the test case below, the total sequestration by shrubs may be slightly overestimated. However, this overestimation for shrubs will be very small compared to the total sequestration, since trees sequester considerably more carbon, even at the most optimistic sequestration rate for shrubs.

For the growth rate curves selected in POETT, the maximum CO_2 sequestration rate for deciduous trees occurs at year 22 and slowly decreases following that, while the CO_2 sequestration rate for coniferous starts small and steadily grows. With or without considering the survival rate for a 50-year analysis period, deciduous trees show higher CO_2 sequestration potential in total due to the early fast-growing years. To further illustrate the trend, the total CO_2 sequestered for analysis periods of 30, 40 and 50 years plotted. One thousand coniferous (2 m height), one thousand deciduous (45 calipers), and a thousand shrubs are used for the test calculation. As Figure 4-29 shows, despite the growing contribution of the CO_2 sequestered by coniferous trees over time, the amount of CO_2 sequestered by deciduous trees is consistently greater, especially for low survival rates and smaller tree sizes. Note that coniferous trees with 2 m height are selected to avoid the impact of initial tree age adjustment. For one thousand smaller coniferous trees, such as those with 0.5 m height, a much smaller CO_2 sequestration value is expected as a result of the low initial survival rate of these smaller trees.

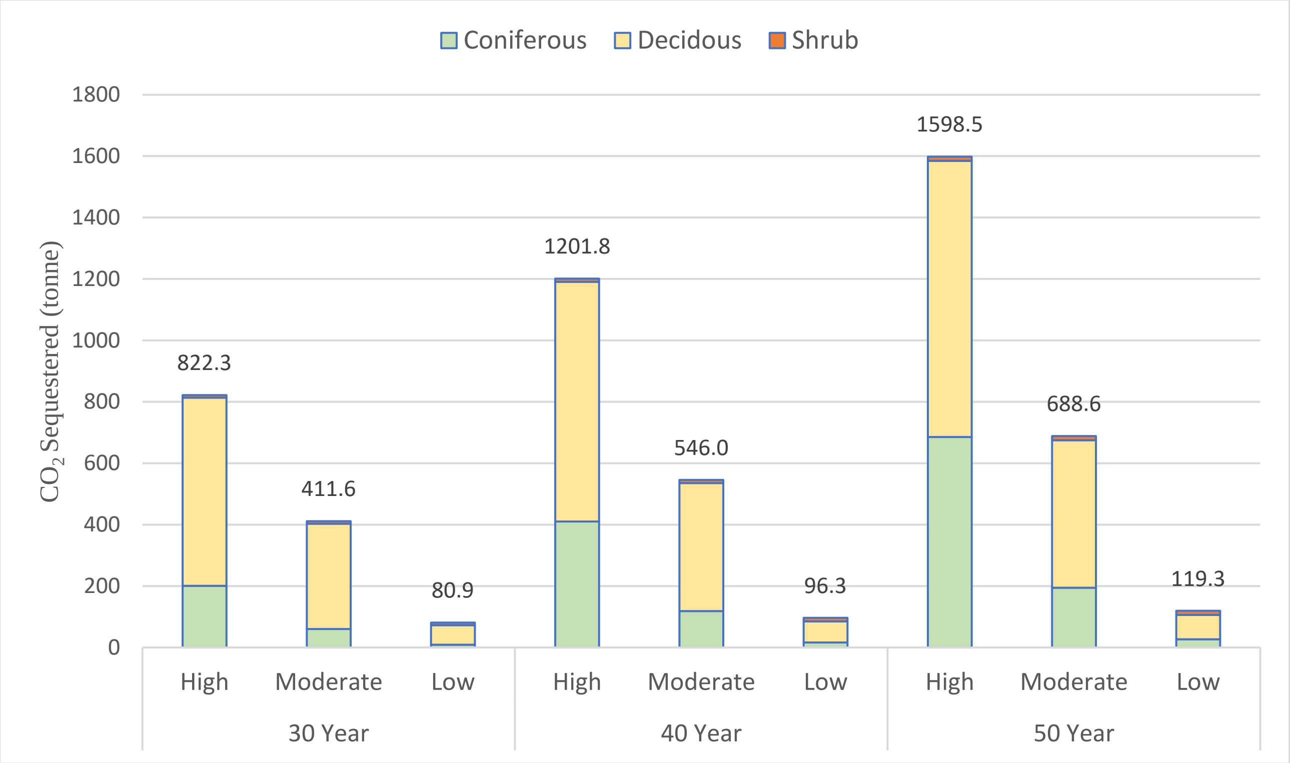


Figure 4-29: CO_2 Sequestration Results for One Thousand Trees of each Type

Figure 4-30 compares the CO_2 sequestration rate calculated by POETT with rates found in the CAPCOA Report (California Air Pollution Control Officers Association, 2010), USDA Forest Service paper (Nowak & Crane, 2002), and results calculated from U.S Department of Energy worksheet. The survival rate is not considered here because most sources provide sequestration rates in kg CO_2/year that do not explicitly consider the tree survival rate, growth rate, or the number of years considered for analysis. As shown in Figure 4-30, the results from POETT for both types of trees range from 13.2 kg/year to 45 kg/year, with a median of 31.1 kg/year. Sequestration rates from the literature range from 12.1 kg/year to 52.1 kg/year, with a median of 28.4 kg/year. The sequestration rate calculated this way compares well with the values from other references. However, in POETT the importance of accounting for tree survival is emphasized, particularly as MTO's trees in HiCo vary in their initial conditions, which considerably alters their potential CO_2 sequestration. One tool that provides even more detailed results for possible tree sequestration is i-Tree by the USDA Forest Service. However, i-Tree has excessive data requirements for MTO's resources and needs, including planting location, weather, and tree species.

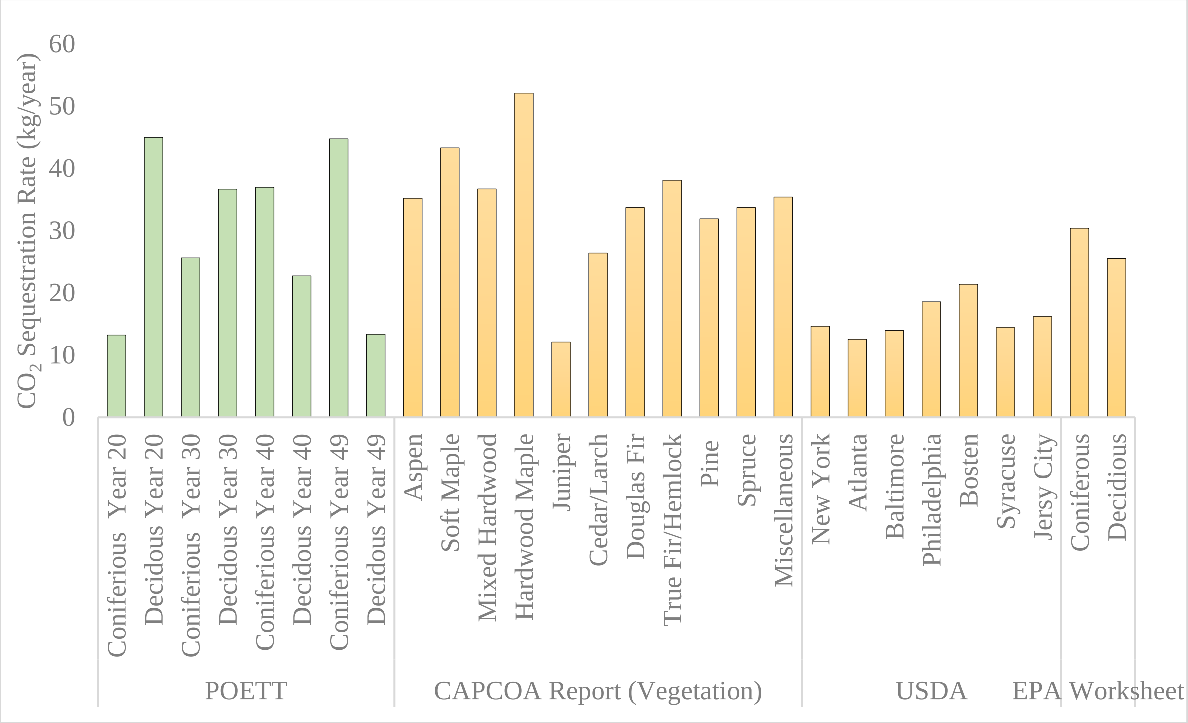


Figure 4-30: CO_2 Sequestration Rates Calculated from the Tool and Retrieved from Reports and Papers

4.2.7 LED Lights and Signals

LED lights can replace traditional roadway lighting. Figure 4-31 shows the GHG reductions for LED lighting along highways (i.e., high mast) and roadways. For this figure, cases that upgrading with 40W, 100W, and 200W LEDs for roadway lights and 200W, 400W, 600W, and 800W for high mast lights. The type of incandescent light replaced is presented on the y axis with the wattage for LED replacement in the parentheses. This calculation assumes that the LED wattage is known and calculates a corresponding HID wattage for the reduction. The tool also provides the option for inputting the HID wattage, if available, and calculating the corresponding LED wattage for a similar lumen. The LED high mast lighting shows a large GHG reduction potential from 400W to 800W, and among the LED roadway lights, using 200W LED to replace the corresponding mercury vapor lamps shows great reduction potential.

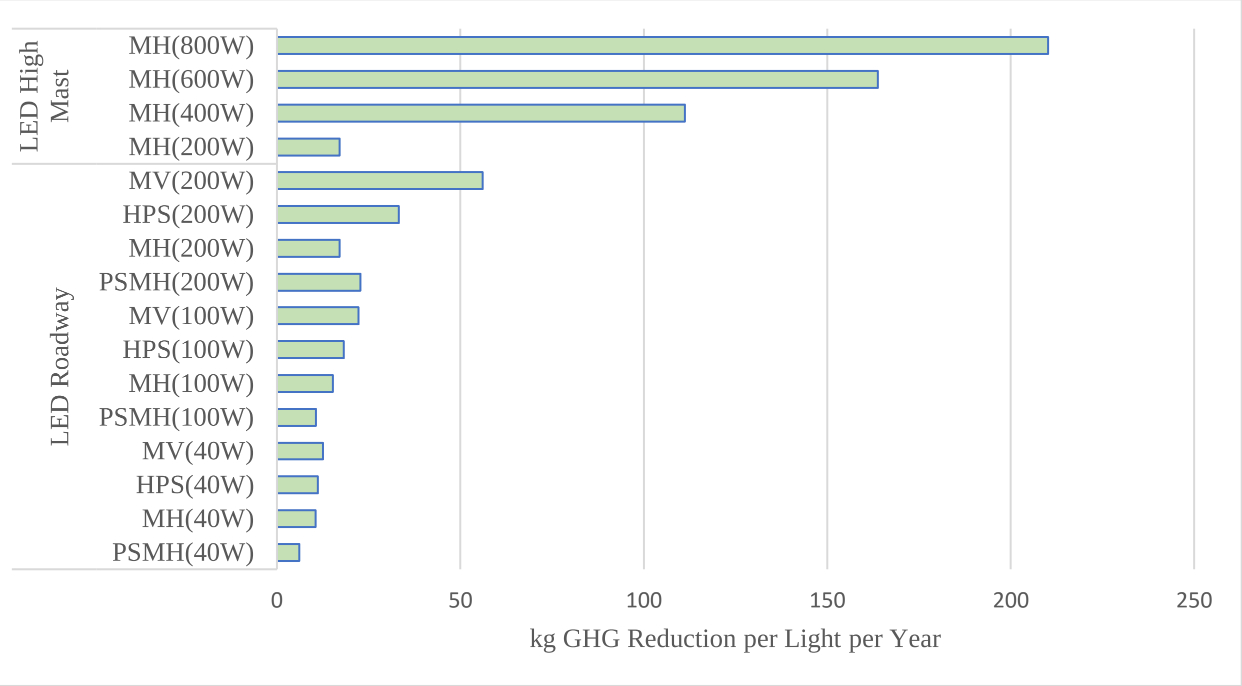


Figure 4-31: GHG Reduction per Light per Year by Replacing HID Lights with Equivalent LED Lights

As with many mitigation measures, the actual quantity of GHGs reduced depends sensitively on the specific details of the implementation. For the case of lighting, this includes variables such as the baseline lighting, the specific replacement technology, the operation schedule, and energy mix on the grid at the given time and place. As the wattage for old and new fixtures, according to 2013 Caltrans report (California Department of Transportation & ICF International, 2013), range from 230W-450W and 100W-200W, respectively, it is difficult to find a specific baseline and mitigated scenario for carrying out a comparative analysis. The CO_2 intensity of electricity in California cited by that report is 200 g/kWh, while the CO_2 intensity for Ontario in 2017 is 40 g/kWh (Environment and Climate Change Canada, 2017), meaning that saving power in Ontario with LEDs has a smaller impact on emissions thanks to its relatively clean grid. For example, Caltrans, in its 2013 report, suggests that each high-pressure sodium fixture replaced by LED roadway lighting avoids 0.4 tons of CO_2e, which is larger than the value calculated by POETT, which is Ontario-focused. To mitigate some of these difficulties in inter-comparison, the percentage of GHGs reduced has been calculated and compared.

Figure 4-32 compares the percentage reductions from LED replacement calculated by POETT with available values from other reports and literature, including the value used by the MTO's existing emission reduction calculation tool (Ahmed, 2018). Note that values from G & Jaganthan (2019) are presented similarly by stating the type of replacement light with the equivalent LED wattage in parentheses. Based on the figure, the percentage reduction calculated from the designed tool ranges from 32.8% to 64.2%, with an average of 51.28%. This is similar to the percentage reduction shown by G & Jaganthan (2019). Other LED reductions in the literature vary from 40%-90%. With the same mitigated LED CO_2 emission, replacing PSMH generally reduces fewer GHG emissions and replacing MV has the largest reduction percentage among the four HID compared. Also, for roadway lighting, a slightly higher percentage reduction can be observed for lower wattages.

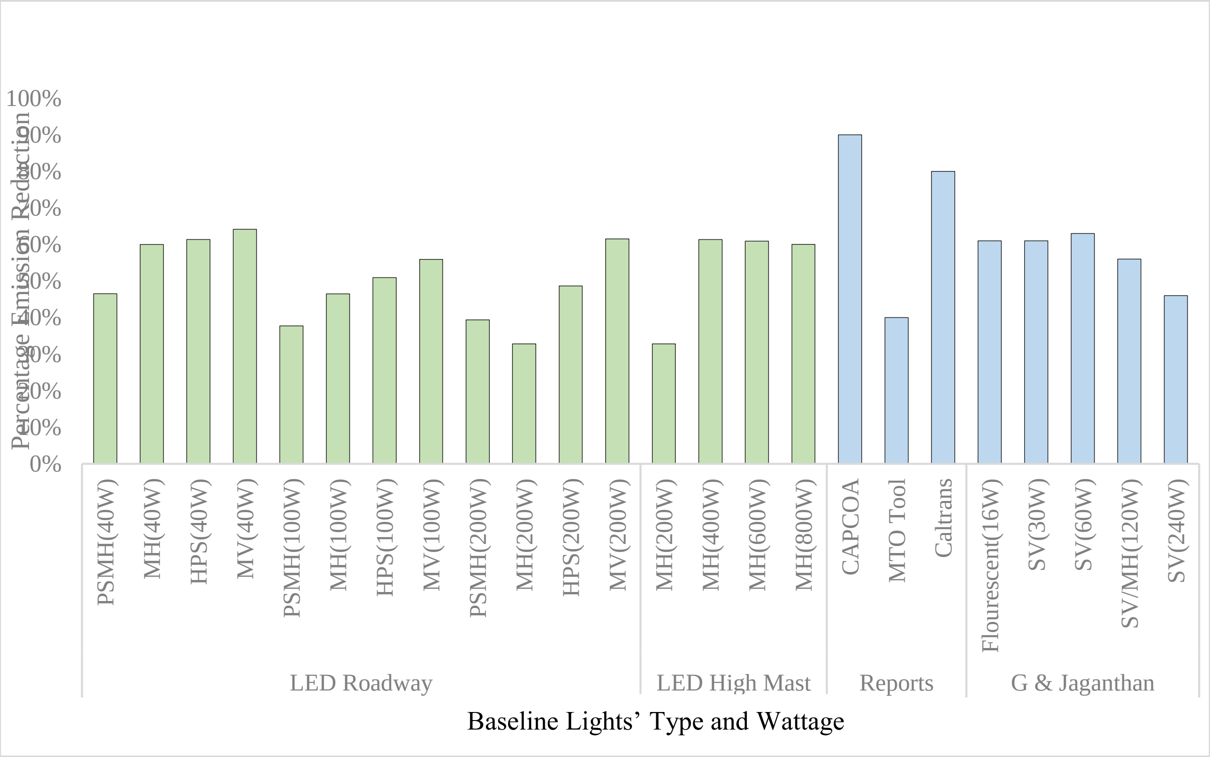


Figure 4-32: Percentage Reduction of GHG Emissions from LED Light Replacement

The GHG reductions for each type of signal is presented in Table 4-15. The wattage of each incandescent powered signal head and their LED equivalents are taken from OPSS 2461 (2017) with the GreenDOT (Gallivan et al., 2010) load factors being applied here. The wattage for every typical signal type, presented in OTM BOOK 12 (*Ontario Traffic Manual - Book 12 - Traffic Signals*, 2012), has then been calculated. Table 4-15 presents the GHG reductions for each signal, estimated by subtracting the improved emissions from the baseline. wind and solar powered signal heads are assumed to have 0 emissions and 100% reductions relative to the baseline emissions of the signal type that wind/solar signal replaced. The percentage GHG reductions for each signal type range from 87.8% to 89.3%.

Table 4-15: Emissions Savings from using LED Signals

	Baseline GHG Emissions (kg)	Mitigation Measure's GHG Emissions (kg)	GHG Emissions Avoided (kg)
Standard Type Signal Head	33.29	4.06	29.23
Highway Type Signal Head	42.44	4.84	37.60
Special Type Signal Head	43.36	4.94	38.42
Pedestrian Type Signal Head	33.29	3.53	29.76

4.2.8 Transportation

GHG reductions calculated in the transportation category covers alternative vehicle types, alternative energy vehicles, distance reduction for transportation, adding idle control technologies, and diesel engine repower/replacement. The emission rates for vehicles or vehicle technologies are mostly taken from the best available sources including the 2019 Canada National Inventory Report (NIR)(Environment and Climate Change Canada, 2019), GHGenius (*GHGenius 5.0d*, 2019), and MOVES (US EPA, 2014). While POETT does not provide evaluation or additional calculation for the emission rates used for transportation, it focuses on providing default values that fit Ontario's practices to simplify the tool's inputs. For example, POETT contains the total number of trucks based on 2018 Ontario vehicle registration and the average truck hotelling hours calculated from the Ontario average truck-driving distance and Ontario's on-road freight work shift rules. The MTO can thereby approximate GHG reductions associated with anti-idling technologies by estimating the percentage of total trucks that adopt them. Table 4-16 to Table 4-20 show the sample results for GHG reductions by alternative energy source and vehicle type, fuel consumption and technology, diesel engine replacement, vehicle idling reduction, and alternative transportation methods, respectively. The user-selected/specified parameters are shaded in grey. Note that with distance-based calculations, for GHG reduction by alternative energy and the vehicle types, as a default, POETT considers the overall life-cycle emissions for CO_2, CH_4, N_2O, respectively. This includes emissions from the fuel production, vehicle operation, and vehicle materials and assembly for forty-three technology and fuel combinations.

As shown in Table 4-16, for the six selected alternative fuel vehicles, the percentage reduction of the emissions range from -1.36% to 87.36%. The negative reduction (i.e., increase in emissions compared to conventional fuels and vehicles) occurs in one example in the Table for a biofuel with emission intensive production. In general, most reductions occur in vehicle operating phase whereas emission reductions in the vehicle material and assembly phase are often negative, depending on the vehicle technology. In other words, alternative technology vehicles and fuels usually emit fewer GHGs overall, thanks to fewer emissions while on the road, but they may create more emissions during production than conventional options. In the biofuel example, compared to running with gasoline oil, a light-duty ICEV operating with Methanol M85 NG 100/C0 has fewer operating emissions; however, the reduction is offset by the additional emissions from fuel and fuel production, leading to a net 1.36% increase in total CO_2e. Note that this is one example biofuel and does not imply that biofuels increase emissions when used for transportation, as their impact depends sensitively on the local context, as well as the fuel sources (e.g., cultivation), transportation, and processing (Staples et al., 2017).

With fuel-based calculations, the on-road emission factors for operation, which are presented in 2019 NIR report, are applied. In the NIR, the options for fuel-based calculations are based only on fuel type and the general standards vehicles have met (e.g., Gasoline Vehicle Tier 2, HGDV advanced control, etc.). As a result, when comparing distance-based and fuel-based results, the "operational only" option in the distance-based calculation needs to be selected.

Table 4-16: Sample GHG Reduction Result (kg/100 km) for Vehicle and Fuel Replacement

Existing Fuel	**Replacement Vehicle Type**	**Fuel Replacement**	CO_2e Difference from Baseline (g/ km)			Total Reduction (g/km)	Total Percentage Reduction
			Operational	Fuel Production	Vehicle Material& Assembly		
Gasoline Oil	Light-duty Vehicle (Recharging EV)	Electricity	136.12	19.93	-9.44	146.61	71.46%
Gasoline Oil	Light-duty Vehicle (ICEV)	Methanol M85 NG 100/C0	17.58	-20.27	-0.11	-2.79	-1.36%
Petro Diesel 0.0015% S	Heavy-duty Vehicle (Fuel Cells)	CH2 Electricity Fuel Cell	1104.07	-206.23	-10.09	887.75	60.36%
Petro Diesel 0.0015% S	Heavy-duty Vehicle (ICEV)	Gasoline Hybrid	254.53	69.55	-12.26	311.82	21.20%
Petro Diesel 0.0015% S	Heavy Duty Vehicle (Biomass Fuels)	Biodiesel Soy D100	1079.15	91.92	-0.03	1171.0	79.62%
Petro Diesel 0.0015% S	Heavy Duty Vehicle (ICEV)	Electricity	1104.07	193.93	-13.37	1284.6	87.34%

Table 4-17: Sample GHG Reduction Result (kg) with Fuel-Based Calculation

	Transportation Mode	**Fuel Consumption (L)**	kg Emissions			
			CO_2	CH_4	N_2O	CO_2e
Baseline	HDDV Advanced Control	22000	58982	2.42	3.322	60032.46
Alternative	HDGV Three-way Catalyst	22000	50754	1.496	4.4	52102.6
Emission Reduction			8228	0.924	-1.078	7929.856

Table 4-18: Sample GHG Reduction Diesel Engine Replacement for each Vehicle Type

Vehicle Type	**Existing Model Year**	Replacement Model Year	**Number of Vehicles**	VKT/year	CO_2e Reduction (kg)
Combination Long-Haul	2000	2019	100	70400	952628.09
Combination Short-Haul	2000	2019	100	70400	782166.16
Single Unit Long Haul	2000	2019	100	70400	409871.84
Single Unit Short Haul	2000	2019	100	70400	467987.97

Table 4-19: Sample GHG Reduction Calculation for Truck Idling Reduction Technologies

Idle Control Technologies	Hotelling Hours (per truck per year)	**Number of Trucks**	CO_2 Reduction (kg/year)
Auxiliary Power Unit	481.3675	100	175,265.91
Fuel Operated Heater	481.3675	100	321,987.20
Engine Off	481.3675	100	344,225.91

Table 4-20: Sample GHG Reduction with Alternative Means of Transportation

Transportation Modes		CO_2e Emission Intensity (kg/1000 RTK)	**Material Quantity (tonnes/vehicle)**	**Distance Transported (km)**	Emissions Savings (kg)
Rail	Class I Freight	14.07	1000	100	3393
	Regional and Short Line Freight	16.75	1000	100	3125
Barge	Liquid Bulk Vessels	20.35	1000	100	2765
	Container Vessels	21.66667	1000	100	2633.333

Figure 4-33 shows the GHG reduction per vehicle among the transportation-related mitigation activities based on sample calculations from the tables above. To get a yearly reduction for comparison, each truck is assumed to travels 70,400 km annually and 22,000 L of fuel (or has an assumed mileage of 36.4 L/100 km) is used. Note that this plot only shows the results of the selected sample scenario. For alternative energy vehicle and fuel-based emission reduction calculations, many combinations can be calculated with POETT depending on the Ministry's practice. The range of emission reductions shown in the figure does not represent the range of possibilities of all alternative energy GHG savings. Idle reduction and diesel engine replacement show less GHG reduction potential, by comparison.

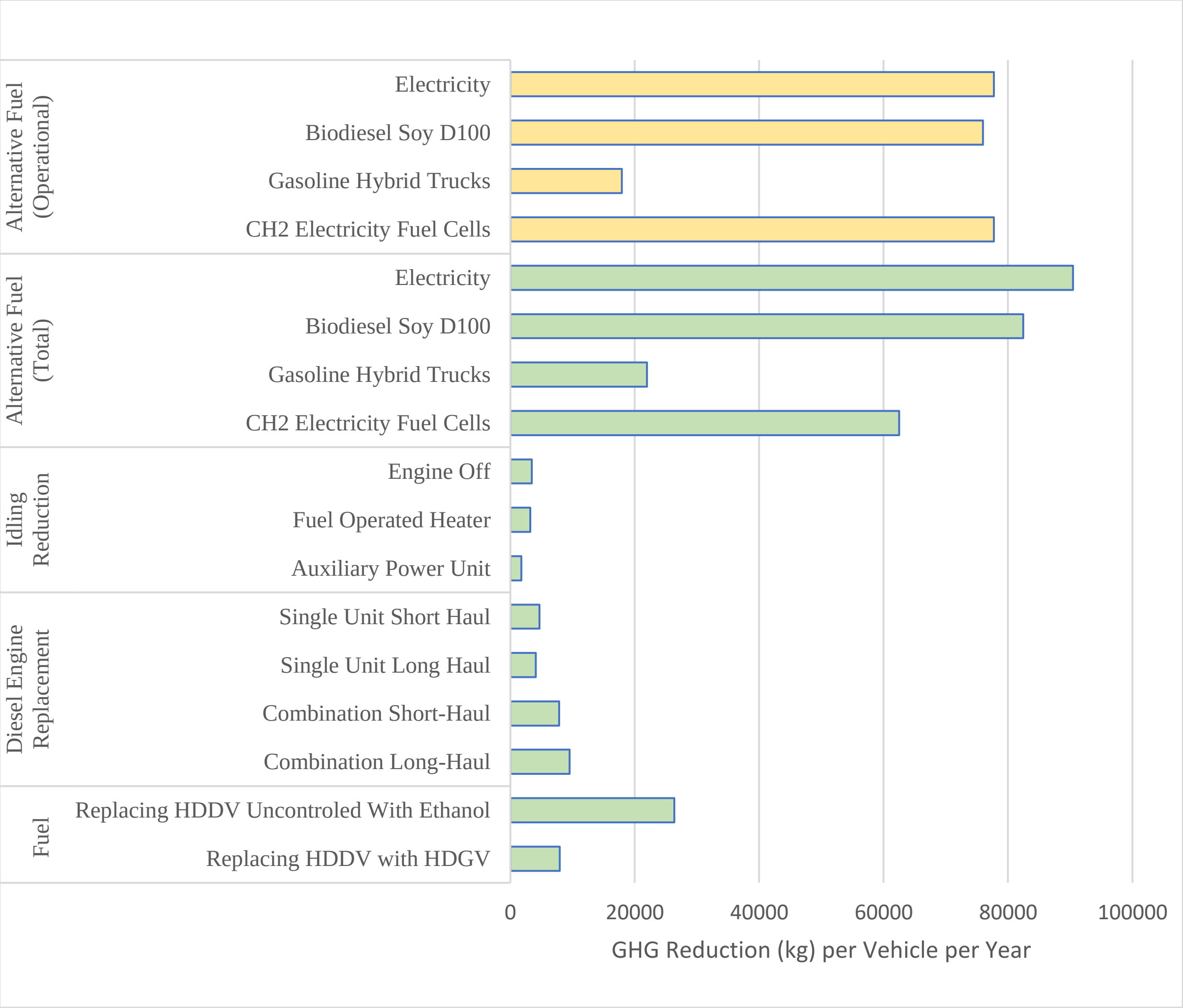


Figure 4-33: GHG Emissions Reductions per Vehicle from Transportation-related Activities

4.2.9 Traffic

Table 4-21 presents sample results for emission reductions related to intersections (roundabouts). Roundabouts can effectively reduce vehicle delays at intersections especially in peak hours. As a result, GHG emissions from vehicle idling can be reduced. Reductions associated with roundabouts for POETT are based on the FHWA CMAQ calculator (Federal Highway Administration (FHWA) Office of Natural Environment, 2020), which accounts for congestion reduction and traffic flow improvements.

Table 4-21: Sample GHG Emission Reductions by Roundabouts

Input			
	Approach 1	Approach 2	Approach 3
Average Annual Daily Traffic Volume (AADT)	20000	20000	20000
Peak-hour Volume	1000	1000	1000
Truck Percentage	6%	6%	6%
Existing Delay per Vehicle (s)	33	33	33
Number of Lanes	2	2	2
Existing Intersection % Left Turns	12%	12%	12%
Existing Intersection % Right Turns	4%	33%	80%
Result			
	Peak	Off-Peak	Sum
Total GHG Reduced by the Roundabout (kg/day)	63.36	346.95	410.31
GHG Avoided (tonne/year)	149.76		

Vehicles require less fuel to traverse smoother roads, so reducing surface roughness, measured by IRI, reduces emissions. Reductions associated with improving surface roughness depend sensitively on the "ratio of percentage fuel savings to IRI decrease". This variable defines how fuel efficiency improves on smoother surfaces. Here, the median value of 4.07% (from a range of 1.51% to 22.22%) is used for passenger cars and 4.55% (from a range of 0.92% to 9.00%) is used for trucks from the literature review performed by Muench et al. (2015). GHG savings by improving pavement surface smoothness for a target IRI of 2 are assumed based on 2017 Ontario road conditions and average AADT from Ontario Transportation Dataset – Pavement Condition for Provincial Highway (Ontario's Open Data, n.d.). This yields an estimated 1435 tonnes/year of GHG reduction if 1% of Ontario roads meet this target, as shown in Table 4-21.

Table 4-22: Sample GHG Reductions based on Improving IRI

IRI Target	2
Truck Percentage	8.0%
Percentage of Road Improved	1.0%
CO_2 Reduction (kg/day)	3931.5
Yearly Reduction (tonne/year)	1435.011

Based on MOVES (US EPA, 2014) results, vehicles have lower GHG emissions per distance when operating at a moderate speed (around 96 km/h). The emission rates drastically increase when the speed is below 15 km/h. Congestion mitigation measures such as 24/7 construction and aggressive closure reduce vehicles' time spent operating at extremely low speed by expediting construction and avoiding peak hour lane closures and thus decrease the overall GHG emissions.

Table 4-23 and Table 4-24 show the sample input and output of the congestion mitigation module, respectively. For a given project where two out of four lanes are closed for construction, the tool compares the project options of constructing 24 hours a day for 14 days and constructing 8 hours a day for 70 days. With the specified road section, 113.8 tonnes of GHG emissions could be avoided if 24/7 construction for 14 days is selected. Note that for a low volume road, lane-closing might decrease overall GHG emissions by requiring the driver to operate at the work zone speed, which often has a low emission rate.

Table 4-23: Sample Input of Congestion Mitigation input Information

Project Overview		
Contract Name / Description	2017-3013	
Mitigation Measure	24/7 Construction	
Permanent Barrier	Yes	
Saving Category	Expedite Construction	
Roadway Information		
AADT	50000	vehicles per direction
Number of Lanes per Direction	4	
Truck Percentage	10	%
Speed Limit	110	km/h
Open Lane Capacity	2400	vph/lane
Free Flow Speed	120	km/h
Jam Density	80	veh/lane-km
Average Car Length	8.25	m
Work Zone Information		
	Mitigated	**Baseline**
Start Time	12:00 AM (0:00)	9:00 AM
Duration of Closure	24 hours	9 hours
Actual Days of Closure	14	days
Closure without Mitigation	70	days
Length of Closure	2	km
Work Zone Speed Limit	60	km/h
No. Lanes Remain Open	2	lanes
Work Zone Capacity	3840	vph

Table 4-24: Sample Output of Reduced GHG for Congestion Mitigation

Summary of the Project Level Results				
Additional GHG Emissions Generated Through Baseline Scenario				
	CO_2	CH_4	N_2O	CO_2e
Baseline Total (kg)	30128.80	0.60	0.17	30195.43
Work Zone Total (kg)	32116.34	0.69	0.32	32227.96
Additional Emissions/day Due to Lane Closure (kg)	1987.55	0.09	0.14	2032.52
Total Additional Emissions	139128.29	6.17	10.06	142276.73
Additional GHG Emissions Generated Through Mitigated Scenario				
Mitigated - Additional Emission	CO2	CH4	N2O	CO2e
Baseline Total (kg)	30128.80	0.60	0.17	30195.43
Work Zone Total (kg)	32116.34	0.69	0.32	32227.96
Additional Emissions/day Due to Lane Closure (kg)	1987.55	0.09	0.14	2032.52
Total Additional Emissions	27825.66	1.23	2.01	28455.35
Total Reductions				
Emissions Reductions	111302.64	4.94	8.05	113821.38

4.2.10 Summary of Per Unit GHG Emissions Reductions

The potential per unit GHG savings presented earlier in this section are summarized in Figure 4-34. The dots represent the default values used in POETT and the box represents the upper and the lower bound of the per unit GHG emissions reductions potential. For items colored in yellow, the resulting ranges are obtained from tools and literature, while the ranges for items colored in blue are generated through sensitivity analysis, as shown in previous sections. Sources and values of per unit emission reduction rates are presented with more details in Appendix E. Note that the units and time horizons for each mitigation measure are not necessarily the same. For example, reductions for trees per year are based on a tree lifetime of 50 years, and LED lights and signals generally last for longer than five years. All emission savings are attributed to the year in which the measure is implemented. To compare across mitigation measures on a more equal footing, different metrics would be needed, such as an equivalent annual reduction, or annual GHG reduction potential per unit cost. However, this does not fall in the purview of this research, which aims to track reductions rather than rank mitigation measures.

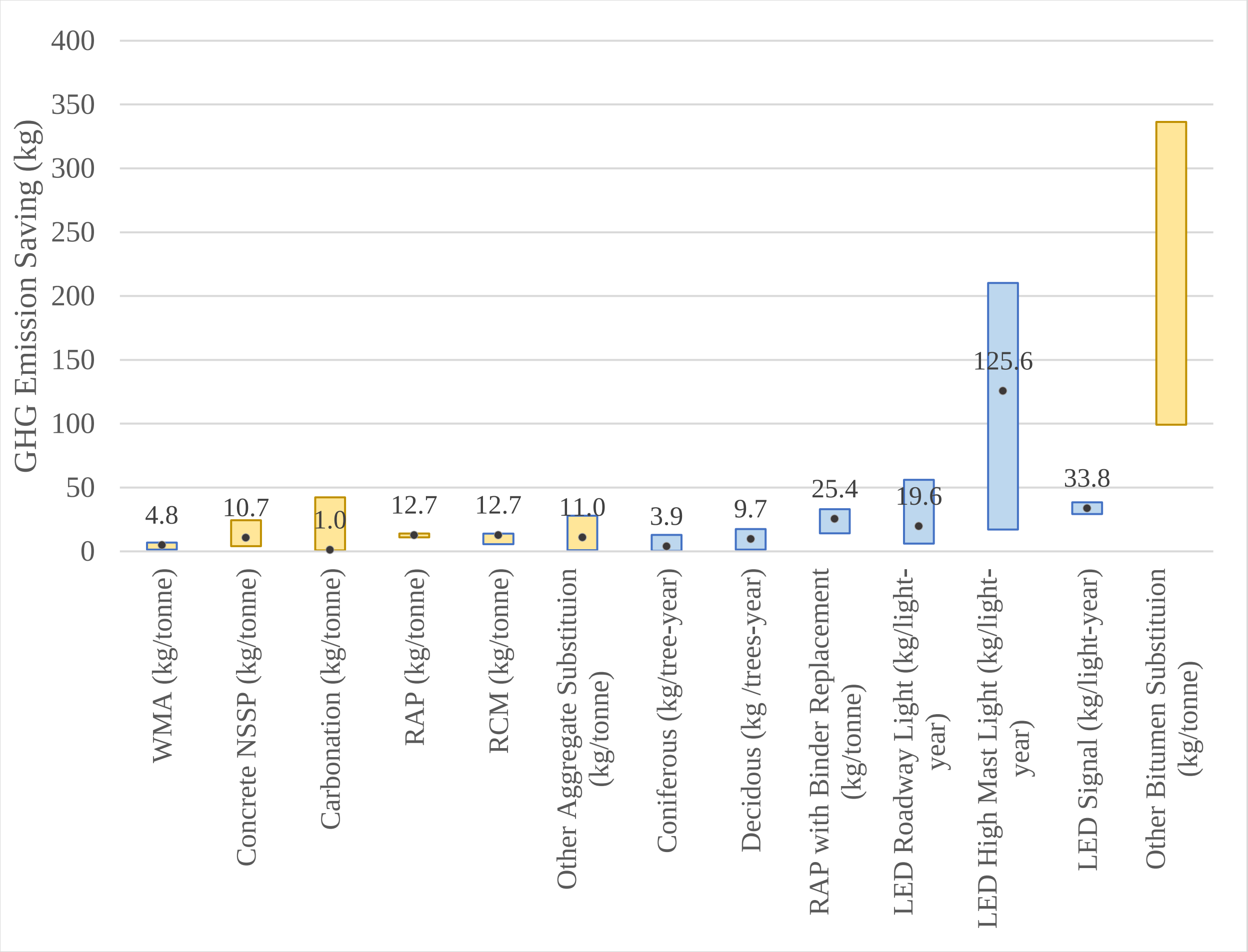


Figure 4-34: Summary of Per Unit GHG Reduction of each Mitigation Measure

Percent reductions are calculated for applicable mitigation measures. In Figure 4-35, each dot represents a typical value of GHG percent reductions. And for mitigation activities that are not linearly dependent on one single activity value (e.g., tonnes of WMA used, transport one kg material for one kilometer), a range of possible percent reductions are calculated. Different combinations of layer thicknesses and a range of LED wattages are used for finding the upper and lower bound of GHG percent reductions for in-place recycling and LED lights and signals, respectively. Sources and values of the percentage reductions are presented with more details in Appendix E

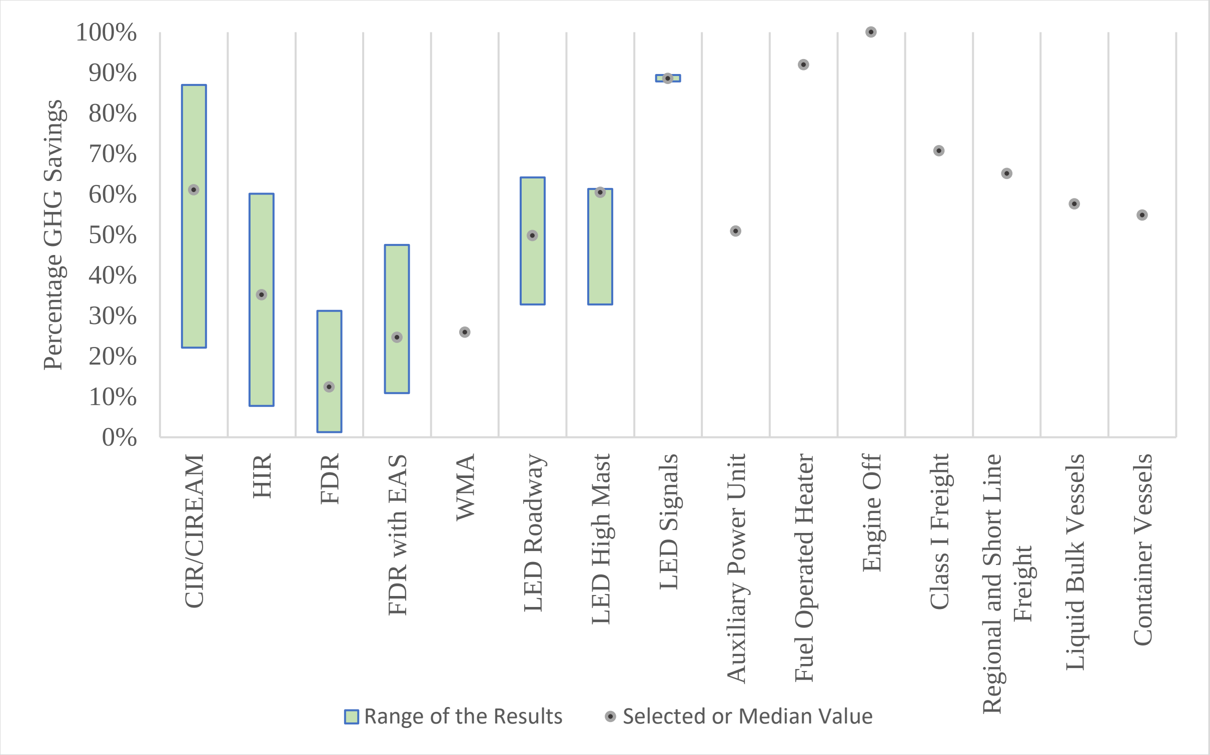


Figure 4-35: Summary of Per Unit GHG Reduction of each Mitigation Measure

4.3 2017 MTO Emissions Based on HiCo Items

Annual emissions avoided by the MTO for the year 2017, based on available data, have been calculated and evaluated using POETT. The available 2017 HiCo items have been copied from the data collection tabs in the MTO's Emission Reduction Calculator (Ahmed, 2018). The available data covers most mitigation measures in materials, lights, and trees, as well as quantities for RAP and RCM. Note that, quantities for RAP and RCM are not available in HiCo and were provided by the MTO (personal communication with Kyle Perdue, Design & Contract Standards Engineer at MTO). Some assumptions made include: 1) For FDR, FDR with 2% Expanded Asphalt has been assumed, and 2) For lighting, 300W and 800W are assumed as the existing HID, which are replaced by LED roadways and LED high masts, respectively. Due to lack of data, mitigation measures such as transportation and IRI are not included in this calculation. The items quantified are listed in Table 4-25.

Table 4-25: List of Items for Quantification and Quantity from HiCo 2017 Data

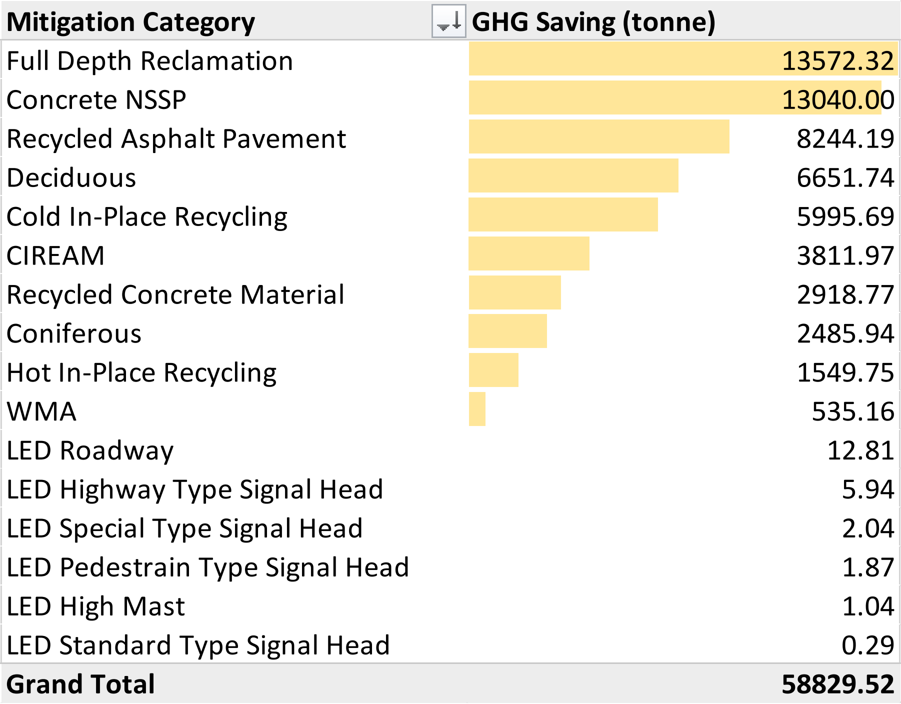
Item	Quantity	Unit	Category
Warm Mix	27008	tonne	WMA
Warm Mix - 40 mm Lift Thickness	346052	m^2	WMA
Warm Mix - 50 mm Lift Thickness	238137	m^2	WMA
Warm Mix - 60 mm Lift Thickness	0	m^2	WMA

Item	Quantity	Unit	Category
Warm Mix - 70 mm Lift Thickness	59752	m^2	WMA
Warm Mix - 80 mm Lift Thickness	0	m^2	WMA
Warm Mix - 90 mm Lift Thickness	55323	m^2	WMA
Warm Mix - 100 mm Lift Thickness	0	m^2	WMA
Warm Mix - 110 mm Lift Thickness	0	m^2	WMA
Cold In-Place Recycle	684131	m^2	In-Situ Recycling
Cold In-Place Recycled Expanded Asphalt Mix	435506	m^2	In-Situ Recycling
Hot In-Place Recycle	573007	m^2	In-Situ Recycling
In-Place Full Depth Reclamation	1968845	m^2	In-Situ Recycling
LED Roadway	757	Each	Electricity
LED High Mast	11	Each	Electricity
Coniferous Tree, 500 mm Height	752	Each	Tree
Coniferous Tree, 1.0 m Height	2637	Each	Tree
Coniferous Tree, 1.5 m Height	2821	Each	Tree
Coniferous Tree, 2.0 m Height	209	Each	Tree
Deciduous Tree, 2.0 m Height	2779	Each	Tree
Deciduous Tree, 45 mm Caliper	955	Each	Tree
Deciduous Tree, 50 mm Caliper	19	Each	Tree
Deciduous Tree, 60 mm Caliper	156	Each	Tree
Deciduous Tree, Whip	3437	Each	Tree
Highway Type Signal Head	158	Each	Electricity
Standard Type Signal Head	10	Each	Electricity
Special Type Signal Head	53	Each	Electricity
Pedestrian Type Signal Head	63	Each	Electricity

Table 4-26 presents the total emissions avoided for each mitigation measure. Based on the available HiCo data, 58,829.5 tonnes of GHG emissions (approximately 60 kt) were saved in 2017 by the MTO. Since this is based on available data, and many of POETT's estimates are conservative compared to other tools, this should be considered a lower bound of reductions achieved in 2017. In 2013, the California Department of Transportation reported 161 kt of GHG reductions from its activities. Per Chapter 2, this was the sole department-level estimate of GHG emission reductions could be found in existing literature. While these results should be compared with caution, given that both are compared to status quo activities, it does offer positive indications of MTO's level of efforts in GHG mitigation, especially considering MTO serves a population about one third the size of California. This initial application of POETT suggests that MTO's mitigation efforts yield meaningful reductions.

Of those efforts, FDR and Concrete NSSP contribute the most to reductions because of the large quantities of material use involved in these two activities and their high per unit GHG reductions. Lights and signals, on the other hand, do not avoid many emissions. Even though the percentage reductions for individual lights often reach 60%, relatively few lights are replaced in a given year.

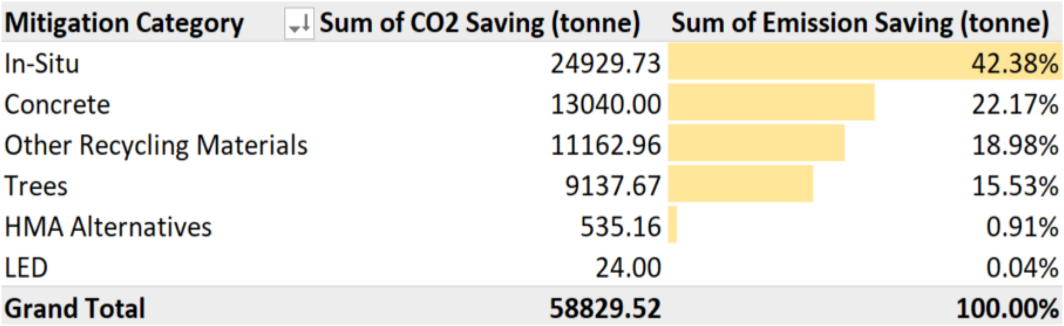
Table 4-26: Tonnes Emissions Savings from Each Mitigation Activity from 2017 HiCo Data



Mitigation Category	GHG Saving (tonne)
Full Depth Reclamation	13572.32
Concrete NSSP	13040.00
Recycled Asphalt Pavement	8244.19
Deciduous	6651.74
Cold In-Place Recycling	5995.69
CIREAM	3811.97
Recycled Concrete Material	2918.77
Coniferous	2485.94
Hot In-Place Recycling	1549.75
WMA	535.16
LED Roadway	12.81
LED Highway Type Signal Head	5.94
LED Special Type Signal Head	2.04
LED Pedestrain Type Signal Head	1.87
LED High Mast	1.04
LED Standard Type Signal Head	0.29
Grand Total	**58829.52**

Table 4-27 shows the GHG savings and percentage contributions by category. In-place recycling contributes to nearly half of the emission savings while HMA Alternatives (WMA) and LEDs add up to around 1%. The saving percentage is largely based on the level of activity and the number of mitigation measures included in a given category. Nevertheless, avoiding emissions associated with new material production (via recycling) is expected to yield much larger reductions for MTO than those achievable by lights and trees.

Table 4-27: GHG Savings (tonnes) and Percentage Contribution from each Mitigation Category



Mitigation Category	Sum of CO2 Saving (tonne)	Sum of Emission Saving (tonne)
In-Situ	24929.73	42.38%
Concrete	13040.00	22.17%
Other Recycling Materials	11162.96	18.98%
Trees	9137.67	15.53%
HMA Alternatives	535.16	0.91%
LED	24.00	0.04%
Grand Total	**58829.52**	**100.00%**

4.3.1 Detailed Results

4.3.1.1 In-Situ

For the year-round calculation, POETT's default values (e.g., density, emission factors, etc.) and assumptions, which are listed in the previous section, are applied. A quantity of 500,000 m^3 of concrete (1,219,500 tonnes) was assumed for concrete NSSP and 234,000 tonnes was assumed for RCM. For in-place recycling, the structural designs for the baseline mill and overlay, and recycling activities are listed in Table 4-28. The calculation applies the same thicknesses for mitigation design as in MTO's existing emission reduction calculator (Ahmed, 2018), thus differing slightly from those used to estimate the unit GHG calculations.

Table 4-28: Layer Thickness for Baseline and Mitigated Scenario Used for HiCo 2017 Data Calculation

Mitigation Measure	Baseline Design (Thickness in mm)		Mitigation Design (Thickness in mm)		
	Mill	Overlay	Mill/Pulverizing	Recycling	Overlay
FDR	150	150	150	150	100
CIR	75	90	75	75	40
HIR	50	50	50	50	15
CIREAM	75	90	75	75	40

Emissions for each in-place activity are listed below in Table 4-29

Table 4-29: GHG Emissions for each Mitigation Activity, Divided by Emission Component

GHG Emission Reduction (tonne)		Mitigation Activity			
		CIR	CIREAM	HIR	FDR with EAS
Emission Component	Quantity (m^2)	684131	435506	573007	1968845
Material	Baseline	8766.39	5580.53	3671.23	30274.30
	Mitigated	3361.69	2139.99	1407.82	17664.30
	Reduction	5404.70	3440.54	2263.40	12610.00
Transportation	Baseline	846.29	538.73	354.41	3155.05
	Mitigated	193.99	123.49	81.24	1300.94
	Reduction	652.30	415.25	273.17	1854.11
Construction	Baseline	138.52	83.40	58.01	548.52
	Mitigated	199.83	127.21	1044.84	1440.31

GHG Emission Reduction (tonne)		Mitigation Activity			
		CIR	CIREAM	HIR	FDR with EAS
	Reduction	-61.31	-43.81	-986.83	-891.79

The distribution of reductions from emissions due to material use, transportation, and construction for in-place recycling for all MTO contracts from 2017 are shown in Figure 4-36. Positive numbers indicate a reduction (decrease in emissions compared to baseline), and negative numbers indicate an increase in emissions compared to the baseline. As discussed previously, recycling activities require more processing and thus increase construction-related emissions, while total emissions drop.

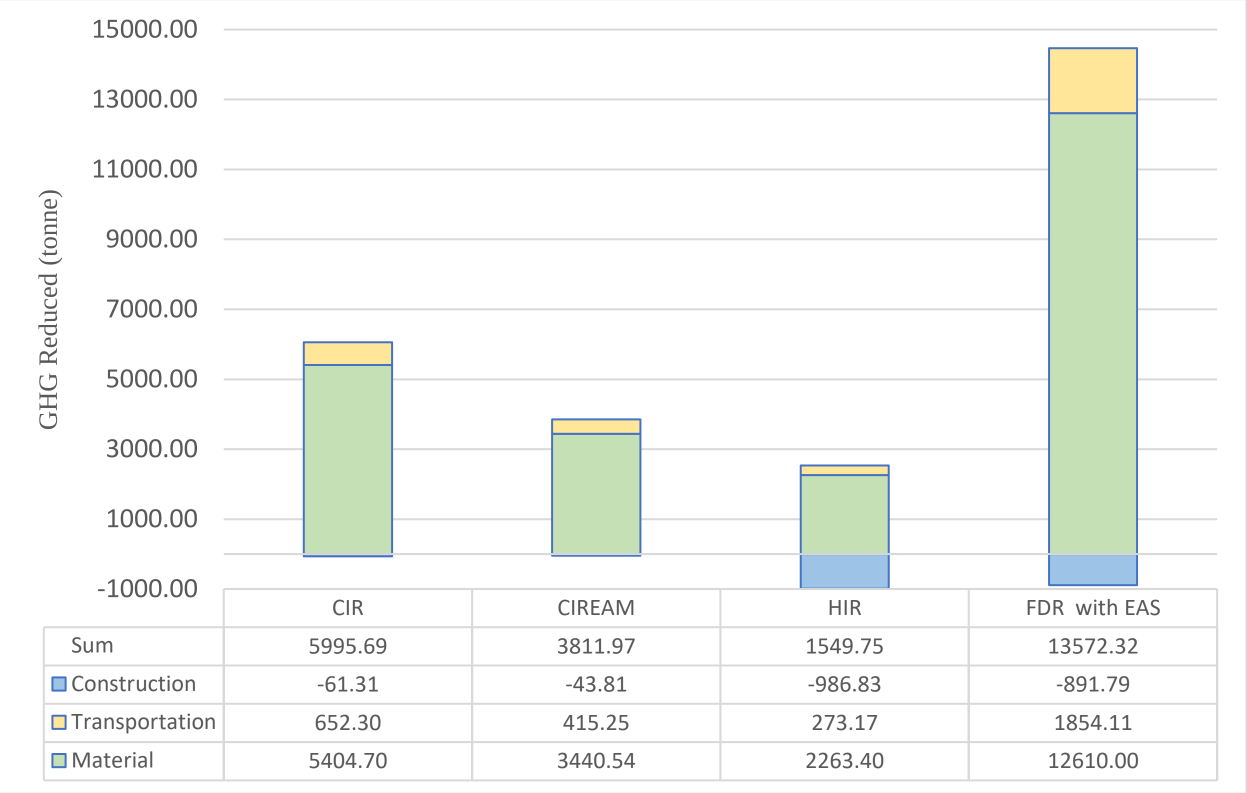


Figure 4-36: Distribution of GHG Emission Reductions from each Component

Among the 24,297 tonnes of GHG reduced from in-place recycling in 2017, 55% of the reductions are contributed by FDR (with EAS, in this case), as shown in Figure 4-37. The large reductions from FDR are due primarily to its widespread use. This is evidenced by Figure 4-38, which shows that its per unit reductions are less than that of CIR or CIREAM. Table 4-29 further shows that CIR and CIREAM have greater percentage reductions.

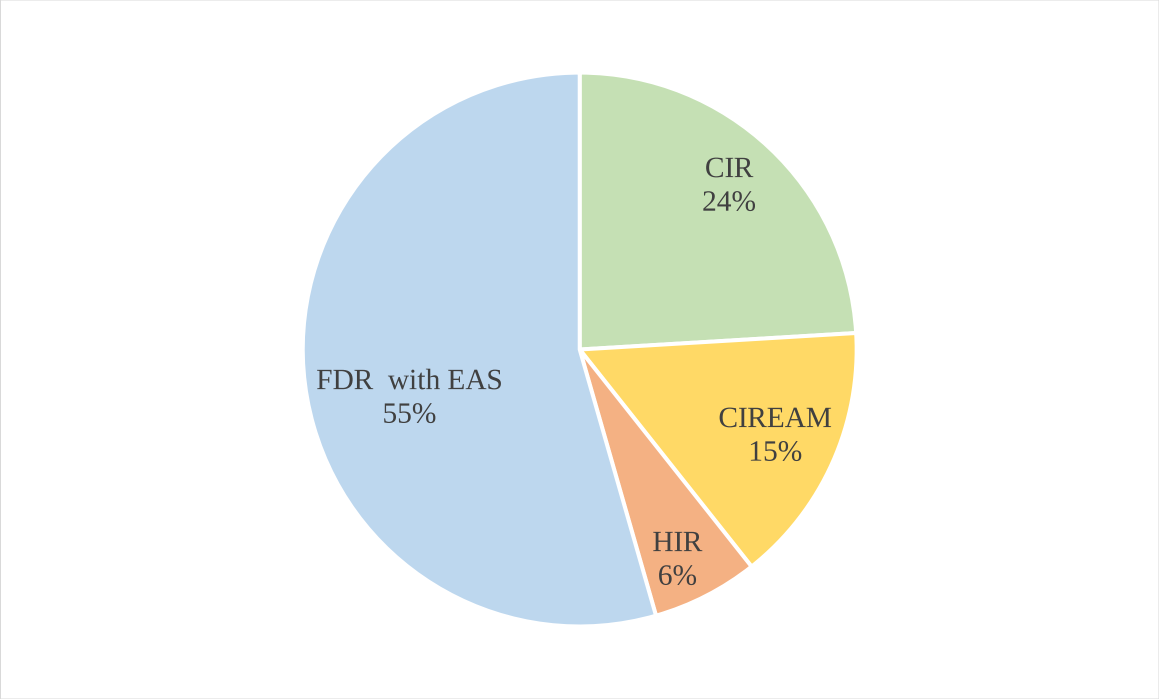
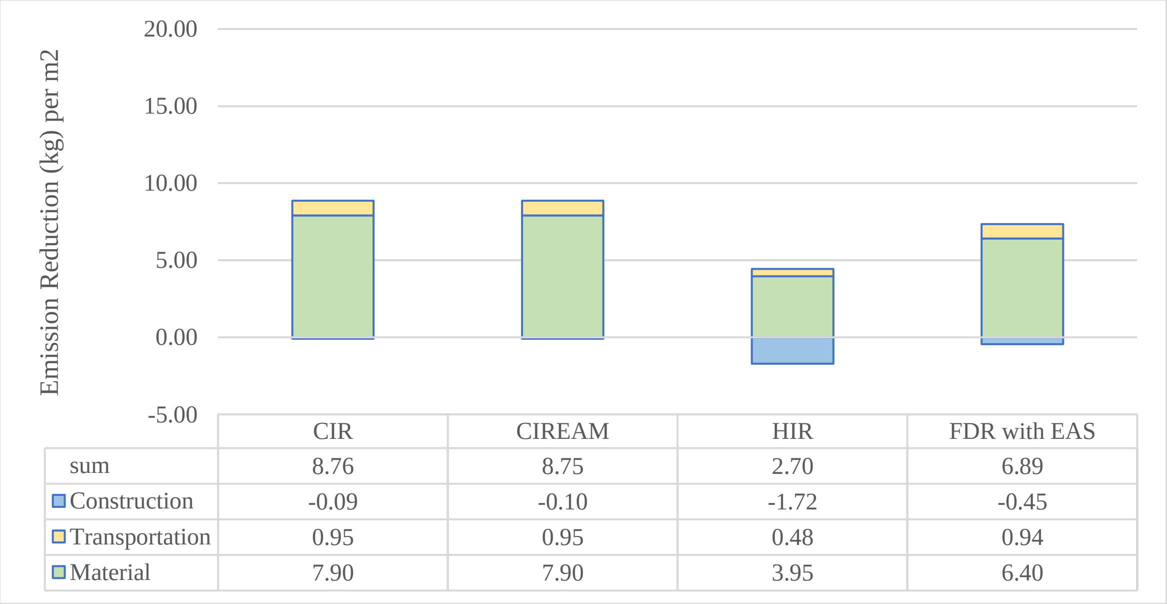


Figure 4-37: Percentage Contribution of GHG Reductions of each In-Place Recycling Activity within the Category



	CIR	CIREAM	HIR	FDR with EAS
sum	8.76	8.75	2.70	6.89
🟦 Construction	-0.09	-0.10	-1.72	-0.45
🟨 Transportation	0.95	0.95	0.48	0.94
🟩 Material	7.90	7.90	3.95	6.40

Figure 4-38: Unit Emission Reductions for In-place Recycling

The percentage reduction for each activity is shown in Table 4-30.

Table 4-30: Percentage Reduction for Each In-Situ Recycle Activity

	CIR	CIREAM	HIR	FDR with EAS
Percentage Reduction	61.49%	61.46%	37.95%	39.94%

4.3.1.2 *Other Materials Quantified Based on HiCo 2017*

For concrete NSSP calculations, it is assumed that the concrete material (500,000 m^3) in general has a 10% GHG reduction regardless of the technique used. A quantity of 234,000 tonnes of RCM is used for the calculation and a total of 3,560,000 tonnes of RAP is assumed to be applied with a binder content assumption of 4.5%, based on the value used in MTO’s existing emission reduction calculator (Ahmed, 2018). This could be an overestimation because some RAPs are used strictly as aggregate. If RAP is only used as an aggregate, a minimum of 444,059 kg of CO_2 is avoided.

Table 4-31: CO_2 Emissions Avoided from all other Material Related Activities

Mitigation Measures	CO_2 Emissions Avoided (kg)
Concrete NSSP	13040000
RCM	2918768.26
RAP	8244191.34
WMA	535160.4

4.3.1.3 *Trees*

Table 4-32 to Table 4-34 show the detailed results for tree CO_2 sequestration. The typical 50-year period is assumed for the tree CO_2 sequestration lifetime. Results are provided for three scenarios based on the tree size and survival rate. Deciduous trees show much higher CO_2 sequestration in comparison to coniferous trees because: (1) deciduous trees have higher sequestration rates, and (2) planted coniferous trees are smaller in size, therefore have relatively low survival rates with the age adjustment. For coniferous and deciduous trees with low survival rates and smaller sizes, both contribute similarly to the total reduction. Note that information on shrubs, while included in HiCo, was not available in the data provided by MTO for this research, and therefore it is not included here.

Table 4-32: CO_2 Sequestered by Large-sized Tree with High Survival Rate for 50 Years

Input Scenario	Adjustment	High for All
	No. of Year for Analysis without Shrub	50
General Sequestration	Total CO_2 Sequestration to Date	9138.99
	CO_2 Sequestration Per Year	182.78
	Total Tree Decomposition CO_2 Release	53.03

Reduction (tonne)	Net CO_2 Benefit Up to the Specified Year	9085.96
	kg CO_2 Sequestrated the Year Before	175.08
CO_2 Reduction by Tree Type (tonne)	Coniferous	2478.42
	Deciduous	6607.54

Table 4-33: CO_2 Sequestered by Median-sized Tree with Moderate Survival Rate for 50 Years

Input Condition	Adjustment	Medium for All
	No. of Year for Analysis without Shrub	50
General Sequestration Result (tonne)	Total CO_2 Sequestration to Date	4198.99
	CO_2 Sequestration Per Year	83.98
	Total Tree Decomposition CO_2 Release	49.82
	Net CO_2 Benefit Up to the Specified Year	4149.16
	kg CO_2 Sequestrated the Year Before	61.99
CO_2 Reduction by Tree Type (tonne)	Coniferous	621.17
	Deciduous	3527.99

Table 4-34: CO_2 Sequestered by Small-sized Tree with Low Survival Rate for 50 Years

Input Condition	Adjustment	Low for All
	No. of Year for Analysis without Shrub	50
General Sequestration Result (tonne)	Total CO_2 Sequestration to Date	1404.45
	CO_2 Sequestration Per Year	28.09
	Total Tree Decomposition CO_2 Release	18.03
	Net CO_2 Benefit Up to the Specified Year	1386.42
	kg CO_2 Sequestrated the Year Before	41.82
CO_2 Reduction by Tree Type (tonne)	Coniferous	802.80
	Deciduous	583.62

4.3.1.4 Lights and Signals

For the 2017 MTO HiCo quantities, all existing roadway lights are assumed to be 485W Metal Halide lights and all existing high mast lights are 800 W Metal Halide. No Wind/Solar powered signs were calculated because the relevant data is not recorded in HiCo. The results for lights and signals are presented in Table 4-35 and Table 4-36.

Table 4-35: Emissions Avoided from using LED Lights, Calculated with 2017 HiCo Quantity

Lights Information			Emissions			
LED Type	Quantity	HID Type and Wattage	Corresponding LED Wattage	Baseline (kg)	Mitigated (kg)	Emissions Savings (kg)
LED Roadway	757	485 (MH)	240.0	64323.8	31831.9	32491.9
LED High Mast	11	800 (MH)	258.3	1541.8	497.9	1043.9
Total LED Light Saving (kg/year)			33535.8			

Table 4-36: Emissions Avoided from using LED Signals, Calculated with 2017 HiCo Quantity

Signal Type	Quantity	Emissions		
		Baseline (kg)	Mitigated (kg)	Emissions Savings (kg)
LED Standard Type Signal Head	10	332.9	40.6	292.3
LED Highway Type Signal Head	158	6705.9	765.4	5940.5
LED Special Type Signal Head	53	2298.1	261.8	2036.3
LED Pedestrian Type Signal Head	63	2097.1	222.4	1874.7
Total LED Signal GHG Reduction (kg/year)		10143.8		

Chapter 5: Conclusions and Recommendations

Quantifying GHG emissions and emission reductions for mitigation activities planned and implemented by MTO helps the Ministry track overall reductions and evaluate the efficacy of each mitigation measure. This research sought to develop a tool that can quantify these annual reductions, and to apply it to available data from 2017. This involved several steps. First, the scope, method, and comprehensiveness of GHG emission and emission reduction quantifications included in calculation tools, literature, and transportation agencies' reports were examined. Based on this review, and in collaboration with MTO, a set of requirements for the Ministry-wide tracking tool were developed. Then the measures for quantification were selected based on MTO's current practice, the popularity of the mitigation measures, and the GHG reduction potential, and developed baseline and mitigated scenarios accordingly. Common GHG tracking methods were adopted or revised to accommodate MTO's data availability and data collection processes. Default values, including location-specific emission factors, equipment specifications, and material properties were collected or generated from tools such as EPA MOVES, PaLATE, and GHGenius. The resulting tool is POETT, an excel-based tracking template developed to comprehensively capture the GHG emission reductions of MTO's mitigation practices.

POETT tracks five mitigation categories, including materials, transportation, lights, trees, and traffic. The tool is set up so that quantity information for in-place recycling, trees, and lights can be obtained from HiCo reports, tender item sheets, or direct user input. Emission reductions for these activities can be directly generated with the tool's default settings. For other mitigation measures such as idle reduction, congestion mitigation, and pavement smoothness improvement, more detailed inputs are required, such as the number of the vehicles assessed, speed limits, length, and capacity for road sections and work zones, and IRI target. The result tab displays the total annual emissions reduction, and the breakdown of reductions by mitigation category and measure. POETT also provides visualizations of the percent contribution of each mitigation category, and the percent contribution of mitigation measures to their respective categories. Based on comparisons of each POETT mitigation category with other calculation tools and literature, its results appear valid and consistent, if somewhat conservative.

POETT was applied to estimate that approximately 59,000 tonnes (about 60 kt) of GHG emission reductions were achieved by MTO in 2017. This annual reduction of approximately 60 kt CO2e should be considered a lower bound, given gaps in data currently collected and available, meaning that not all mitigation activities could be captured. This annual reduction of approximately 60 kt CO_2e compares favourably with the single other department-wide estimate available, namely 161 kt CO_2e reduced in 2013 by the California Department of Transportation, which serves a population three times as large as MTO.

The largest source of GHG reductions from MTO's activities is attributable to full depth reclamation (13,572 tonnes), followed by concrete NSSP (13,040 tonnes), recycled asphalt pavement with binder replacement (8,244 tonnes), and deciduous trees (6,651 tonnes). The larger reductions generally correspond to the most common activities of the year. Among the mitigation activities evaluated, in-situ recycling contributes to 42% of total emission reductions, while LED lights and signals and HMA alternatives (i.e. WMA) contribute to less than 1%, combined.

For in-place recycling, GHG emissions and emission reductions per square meter highly depend on the layer thickness involved. On average, FDR generates the highest GHG emissions (17.49 kg/m^2) while HIR generates the lowest emissions (4.03 kg/m^2) given the assumptions made in this study. FDR with EAS achieves 10.25 kg/m^2 of GHG emission reductions whereas HIR has a much lower rate of 1.67 kg/m^2. In comparison to their corresponding baseline designs, percent emission reductions achieved by CIR/CIREAM, HIR, FDR, FDR with EAS are 61%, 35%, 12%, and 25%, respectively. Note that, since the typical applications for these measures vary, the reductions are not directly comparable since they reflect varying baseline activities.

Among all activities for which a unit emission reduction rate can be calculated, bitumen substitutions show the highest GHG reduction potential, reducing 99 to 335 kg of GHG per one-tonne of material use. These reduction rates are much higher than the potential reduction rates from other mitigation measures in the material category (e.g., WMA, RAP), ranging from 0.73 to 42.3 kg per tonne of material use. For lights and trees, LED high mast and deciduous trees show higher emission reductions when compared with mitigation measures of the same category. Despite the relatively low quantity of GHGs reduced per unit, LED lights and signals, idle reduction technologies and practices, and alternative transport modes all have percent reductions higher than 50%. Alternative fuel vehicles within the heavy-duty vehicle category can reduce up to 90% of GHG emissions from this source category. In the light-duty vehicle category, alternative fuel vehicles can reduce up to 72% of GHG emissions compared to conventional fuel vehicles.

5.1 Limitations

5.1.1 Gaps in Data Collection

The accuracy of the emissions estimatesis constrained by the input and default values used. When quantifying agency-wide GHG emission reductions, limited data for activity levels are available from sources other than the HiCo database. HiCo quantities, while essential, do not address measures that are related to transportation, traffic, and material substitution. Further, they often lack the details needed to accurately quantify the emissions for measures such as in-place recycling, trees, and lights. For example, the database provides in-place recycling material in square meters without the values for layer thicknesses, which are required for calculating the weight or the volume of the material. Similarly, the HiCo quantity called "LED roadway" is presented without specifying the lights' wattage. Assumptions are therefore needed to complete the estimations.

While relevant information is straightforward to find on a project level, obtaining representative designs or LED wattage for a selected year requires investigation of a number of individual projects. Currently, the tool provides the default values based on the median emissions and the values set as default could deviate from actual practice.

Data limitations also restrict the system boundary for each mitigation activity. For example, with WMA, the tool only accounts for the emission reductions attributable to lower fuel consumption in comparison to HMA, while excluding the additional emissions from manufacturing and transporting WMA additives due to the data limitations. With growing access to testing reports, and manufacturer specification sheets, additional processes and phases could be included in the current system boundary.

5.1.2 Limitations in Methodology

Various models and methods are available for GHG emissions quantification, especially in the transportation and traffic category. To limit the number of inputs and reduce POETT's complexity, relatively simple models are generally selected. By using alternative methods that are more comprehensive and data-intensive, the accuracy of the results can be improved. For example, in POETT, vehicle speeds from the Greenshields model and linearly interpolated emission factors generated from MOVES are applied for calculating vehicle congestion. Accuracy of the results can be improved further by applying traffic simulation tools, more advanced demand capacity models, and real-time estimates of delay, and providing more options for work zone capacity adjustment and alternative routes.

5.1.3 Validation and Comparison Data

POETT's results are compared with relevant validation data drawn from the literature and with findings from other GHG mitigation tools. Sensitivity analysis is performed to better understand uncertainty (e.g., measurement uncertainty in emission rates) and variability (e.g., across processes and designs) within POETT and to assess its agreement within errors. In general, POETT's results are in the range of other models and studies for most activities, including in-situ recycling, WMA, concrete NSSP, RAP and RCM, trees, lights and signals. It is within the range but on the conservative end (lower reductions) for Fly Ash, and some other material substitution. Transportation and traffic results rely on project-level detail, so representative results are provided and are not compared directly. While these comparisons are promising, study and design differences make validation and comparison of results complicated.

While exist many studies in the literature have sought to understand GHG emissions from pavement, transportation, traffic, lights, and trees, only a few have directly addressed the emissions from mitigation activities and their corresponding hypothetical baselines. For studies that do focus on emissions mitigation, many vary in equivalent baseline designs, components included, and underlying assumptions, making it hard to interpret different results. For instance, when quantifying emission reductions in CIR, the thickness for M&O, CIR base, the overlay on CIR used, and the assumptions for transportation and construction in Pakes et.al (2018), Alkins, Lane, & Kazierowski (2008), and Cross et. al (2011) differ from each other, therefore providing distinct results ranging from 20% to 52% despite the fact that each of these studies use the PaLATE tool for calculations. Schvallinger (2011) quantifies emission reductions for CIR to be 80%. The variations in reduction results are attributable to the differences in design and desired performance. For POETT's default, a relationship between the thickness of baseline M&O and overlay on CIR is established to reduce the user's input, which further creates some uncertainties introduced by the layer coefficients. Given these differences and challenges, some variation in results between POETT and other methods and findings is expected.

5.1.4 Scope

GHG emission reductions within the transportation sector are often achieved through collaboration among agencies, contractors, and drivers. For items that are not covered by the HiCo database, there is limited understanding of which practices directly fall within the MTO's jurisdiction and how much credit the MTO can take when participating. Before gaining a clear understanding of these issues, the annual reduction should only account for items that are directly controlled by the MTO (e.g., agency owned alternative fuel vehicles).

5.2 Recommendations

5.2.1 Use of the Tool

POETT is capable of calculating annual emission reductions for mitigation measures that are covered in HiCo (e.g., in-place recycling, lights, trees, WMA) and additional activities that are likely to be planned or implemented by the MTO (e.g., alternative fuel vehicles). Excel macros have to be enabled. Macros are used to extract and aggregate mitigation related data, clear data, reset cells to default values, and record results for some mitigation measures. When a master sheet, which contains compiled HiCo items and their quantities, is not available, two macro workbooks can be used to generate a formatted HiCo quantity sheet from HiCo reports (downloaded from the HiCo system) or tender items (downloaded from MTO RAQs), respectively. Once the HiCo quantities are filled, the annual GHG reductions for the associated measures are calculated with default designs, material properties, and assumptions. The results are directly presented and visualized in the Results tab after the user clicks "refresh all". For other mitigation activities not covered by HiCo, the user has to utilize the Input tab to provide more detailed information for each activity.

When default values do not reflect general practice, the user can make changes through the Input tab and individual calculation tabs. The Input tab allows the user to alter more general information including pavement designs. More detailed information such as construction equipment specifications and the trip distance for transporting each type of material can be changed through individual calculation sheets. The user has the option to change any default data when needed and reset to default values or relationships. For example, for in-place recycling, by default, thicknesses for HMA overlay above the recycled material are calculated based on the relationship between thicknesses of the mill and overlay and the recycled material. The user can overwrite the relationship with any desired thickness and restore the default equations with the reset button.

For a quick estimate of reductions for a given measure, the user can use unit GHG reduction rates or percentage reductions (Figure 4.34 and Figure 4.35 of the Results section). The user needs to apply emission reduction rates with great care and ensure the units, period of analysis, and underlying assumptions of the desired results match the rates provided. For LED lights, specifying the actual wattages is highly recommended as the combinations of the replaced HID types and wattage provide a large range of values for possible reductions that cannot be accurately reflected by the selected medians. Note that the summarized values for per unit rate and percentage reductions do not apply to alternative fuel vehicles, diesel engine repower, and all traffic-related measures because they either contain many options for calculating or require relatively detailed input.

5.2.2 Interpreting Results

The Result tab provides GHG emissions reductions in a variety of forms including total annual emissions reductions, reduction results from each mitigation activity (e.g., CIR, HIR), subcategory (e.g., in-place recycling), and emission category (e.g., material), the category and measurement with the largest reduction, and contribution of each mitigation activity to its corresponding category and subcategory. These values, with accompanying visualizations, assist the user in understanding the overall reductions the MTO achieved for the selected year, the emission reduced for each mitigation measure among different categories, and mitigation activities' percent contributions.

Because POETT is designed to track the MTO's overall emission reductions among identified mitigation activities for a selected year, the results are heavily dependent on activity levels that year (i.e., HiCo quantities and user input), and should not be confused with the activities' emission reduction potential. For example, assume that the MTO uses 5000 tonnes of aggregate substitution and 10 tonnes of bitumen substitution for a selected year. POETT results will show higher reductions from substituting aggregate because of the large material quantity. However, for the same functional unit (per tonne material), bitumen substitutions such as recycled tires and recycled shingles offer substantially greater GHG reductions.

The wide variety of mitigation measures covered in POETT poses some challenges for comparing their effectiveness. Often, activities that belong to different subcategories serve drastically different functions (e.g., WMA and LED lights), and have different system boundaries and functional units (e.g., tonne for WMA and m^2 for CIR). For a general understanding of the GHG reduction potential, unit GHG reduction rates can be used for comparing emission reductions within each emission subcategory. Percentage reductions also provide useful insights for the extent of the reduction that can be achieved. Note that two mitigation measures with identical percentage reduction values could have a large difference in the quantity of GHGs reduced because of the disparities in baseline emissions and functional units, if the comparison was made outside one specific subcategory. For example, both LED lights and CIR achieve percentage reductions of 60%, however, the corresponding kilograms of GHGs reduced are 42.9 kg/year-light and 5.07 kg/m^2, respectively, which are not comparable.

Some subcategories, including idle reduction technologies, alternative fuel vehicles, trees and shrubs, and recycled materials, are comprised of mitigation activities that share a similar system boundary, underlying assumptions, and purpose. These activities are easy to compare as a result. However, for the in-situ recycling, each recycling measure serves a different purpose: HIR aims to correct shallow depth surface distress, CIR/CIREAM corrects deeper surface distress, and FDR/FDR with EAS helps address structural distress. Even when the goals of the recycling measures are not considered, pavement-related treatment alternatives are harder to compare from a life cycle perspective without a project-based study. For pavement sections with the same length and layer thickness design, varying climate conditions, underground conditions, traffic levels, and material and construction quality could lead to different pavement performance and service life.

One possible way to better utilize the results generated from POETT is to track changes in total emissions and emission reductions achieved by the MTO throughout the years. In doing so, a trend can be identified showing the changes in the deployment of each mitigation measure, emission category, and the resulting emission reductions. If the GHG emissions from all MTO activities are tracked, the reduction results can be used to track the progress in achieving GHG reduction targets. Cost-benefit analysis and performance evaluations could offer more direct insights about the relative value of mitigation measures.

5.2.3 Future Work

In the future, the MTO could benefit from further efforts to expand and validate POETT. Below, future actions that could aid MTO in effectively and comprehensively tracking the mitigation of GHG emissions are identified.

Updating Emission Factors

Regular review and updating of the emission factors is recommended so that they continue to reflect the latest knowledge and practice. The precise timing of such a review will depend factors such as the amount of new emission studies, the extent of changes in common practices, and ministry internal resourcing and priorities. In the current version of the tool, the median of various emission factors obtained from studies and tools are selected to represent the unit emissions for raw material extractions. Using the median of existing studies helps to reflect both uncertainty in emission factors as well as variability in emitting activities. Over time, that uncertainty may decrease, and the emission intensity of different activities may change. With a growing number emission inventory databases, emission factors that are more relevant for a process, time, and location could become available. Emission intensity values from Canadian industrial averages and actual plant operations are preferred, which could also vary in time. For example, the GHG emissions for bitumen production show a 25% GHG increase between 2004 and 2014 due to the growth of more emission-intensive mining operations to access more challenging sources of bitumen, e.g., deeper bitumen that is further away from the processing facilities (Israel, 2016).

Similarly, baseline practices and emissions should be regularly reviewed and updated. Emissions from baseline activities could also gradually change with more stringent fuel standards, material composition requirements, or change in standard practices in the industry. There are two approaches to take that affect the interpretation of results from POETT. The first is to keep current baseline emissions constant in POETT, and reflect cleaner standard practices as mitigation. The second is to adjust baseline emissions to reflect changing industry standards. The first option would show mitigation progress against a 2017 baseline, while the second would continue to only count mitigation above and beyond standard practice in a given year. Either option could be adopted, depending on which implementation is more useful to MTO.

Additional Material and Processes

For simplicity, the current tool only covers materials and processes that potentially have a large impact on emission reductions. In the future, POETT could expand the system boundaries of the mitigation activities by including materials such as tack coat and subbase materials, vehicles including water trucks, and additional processes such as fuel production and on-site transportation of materials. The tool could also include materials such as chemical additives, for which the emissions are not quantified due to the current lack of data. Having a more comprehensive list of materials and processes allows the user to obtain a more complete life-cycle inventory and to better inform the contributions of each process and phase (e.g., design, construction, rehabilitation) to the total emission reductions achievable.

Improving Data Collection

Given the current information collection practices at MTO, there remains a trade-off between ease and accuracy in emission mitigation tracking. Enhancing the regular recording of additional items would allow for additional emission mitigation to be credited. For example, the MTO does not currently record the quantities for some essential emission-reducing items, including recycled tires and furnace slag. More detailed tracking could also provide project-level details to better reflect the variety of MTO’s activities. Default activity levels in POETT rely on average values (e.g., the average kilometers travelled for Ontario trucks per year) and common practices (e.g., the five foot spacing rule for shrub planting). Expanding the scope of the data collection exercise enables the full utilization of the existing tool and provides opportunities for the future improvement of the models. For completing the template and obtaining more accurate results that reflect the Ministry's practices, collecting the following information, as shown in Table 5-1 is recommended. To use POETT to its full extent, this information needs to be collected, and was not routinely available in HiCo at this time. Additional "nice-to-have" suggestions are provided in italics. The italicized items are not currently required by POETT but could enhance its accuracy or capability.

Table 5-1: Additional Items for Template Completion and Future Improvement of the Tool

Category	**Additional Information Needed for Template Completion/Future Improvement**
Material Quantities	Quantities of SCMs, limestone filler, and other aggregate and bitumen substitutions
	Areas where FDR with EAS is applied, or the percentage of FDR with EAS among all in-place FDR activities
	Quantity of RAP materials for which binder replacement is considered (i.e., RAP not used as granular base or subbase material)
	Material details including heating temperature and moisture percentage
	Additional items including tack coat, steel bars, concrete barriers, chemical admixtures, etc.
Transportation Activities	Number of the regular and alternative fuel vehicles owned by the MTO and the average VKT for these vehicles
	Number of trucks that are equipped with different idle reduction technologies
	The year and make of newly purchased trucks and replaced trucks by the MTO
	Quantities of the materials transported using alternative transport modes and the respective distances transported
	Total fuel consumption for trucks
	Fuel consumption rate of popular MTO owned vehicle models
	Any initiatives that reduce the vehicle traveling distance and hoteling hours
Construction Equipment	*Typical make, engine year, and specifications of the construction equipment used in Ontario*
	Fuel consumption rate for typical MTO owned construction equipment
	Equipment powered by alternative fuel, if any
Trees and Shrubs	*Age and number of existing trees and shrubs planted by MTO*
	Detailed tree species, diameter, and location
	Tree locations, conditions, exposure to sunlight, and if there are any surrounding buildings
Lights and Signals	Number of new solar/wind powered signals

Category	**Additional Information Needed for Template Completion/Future Improvement**
	Number of existing solar/wind powered signals
	Number of existing LED lights and signals by Type and Wattage
	Most common wattage for roadway and high mast light and their respective operation hours and life expectancy
Traffic	For each roundabout: AADT, peak hour volume, existing delay, and percentage left and right turns for each approach
	Lane closure: AADT, hourly traffic distribution, lane capacity, road capacity, work zone capacity, closure time and duration
	MPD (mean profile depth) of the pavement segment for which IRI values are presented (to better estimating vehicle fuel consumption rate regarding pavement roughness based on Wang et al., 2014)
	AADT and truck percentage values corresponding to each improved road section

In the HiCo database, information for each existing item must be retrieved separately, thus requiring a large amount of work with the current practice. A database dedicated to activities relating to GHG emissions would be preferable for simpler, faster data management and calculations.

Case studies offer a particular data collection effort that could serve to improve details within POETT. As part of the original project kick-off, the MTO team noted two case studies underway by the Ministry of Infrastructure to estimate lifecycle GHG emissions. These cases and other documents (e.g., environmental assessment, project construction reports) were noted as potential sources of information for case applications of POETT. While current research only covers available HiCo items, future work could usefully involve evaluation of representative cases. Useful case data could include: (1) quantities of materials at the construction site and the actual material usage, (2) the quantities of excessive material that are disposed or transported away, (3) hauling distance from one site to another, (4) numbers, productivity, hours worked, and fuel consumption of each type of equipment, and (5) traffic delay because of the construction site.

With the activity levels collected from case studies, MTO can (1) compare the actual material usage with the contract listed quantity, (2) apply representative specifications of each type of construction equipment in Ontario, (3) estimate the average hauling distance among sites, (4) obtain representative in-place recycling design corresponding to traffic level, if possible, and generate results for typical projects with representative designs, (5) provide more accurate traffic delay estimates for congestion events and roundabouts. As a result of site-specific data collection, in the future, the Ministry could extrapolate results from the representative projects, if possible, find correlations between GHG emissions and various inputs, and have sufficient data to apply more advanced models for more accurate results.

Ontario 511 can serve as an additional source for project-level traffic data that are compatible with current practices at the MTO. Ontario 511 contains information including road segments that are under construction or have incidents, construction length, regulatory speed reduction, reduced lane width after the lane closure, project duration, and expected delays. The website also provides Waze reports where real-time standstill traffic jams are reported.

In addition to the activities that are currently tracked in the POETT template, some other GHG mitigation measures during provincial highway design, construction, and maintenance can be included are:

- HOV/HOT Lane
- Reducing Heat Island Effect of Roads (e.g. light-colored Pavement)
- Green Construction through Wood (e.g., timber bridges)
- Permanent Pavement
- LEED Certified Infrastructures
- Alternative Fuel for Heating Asphalt
- Cold Mix Asphalt and Half Warm Mix Asphalt
- Alternative Materials for Pipework

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Appendices

Appendix A :User Manual

1.Prepare Relevant Quantity Information. The quantity information can include, but is not limited to, folders with relevant HiCo reports or tender item lists of the year. For proper data extraction, the sheet has to contain information including item name, item quantity, and units.

2. Ensure **Macro is enabled** in this workbook.

HiCo Tab

3. Go to ‘HiCo’ Tab. Click the ‘HiCo List Import’ Button and choose the folder or file that contains the relevant information . No change will appear on HiCo Sheet after this step, and all data in the folder will be imported and reformatted to a hidden sheet (DNT). If the import is successful, an import file location will show up under the cell that says ‘Imported File Location’.

*Note: if the user input their own quantity sheet/tender item, the excel sheet has to contain the header ‘title’, ‘unit’, and ‘quantity’ as the header of the dataset. Also, the sheet of concern has to be the first (leftmost) worksheet in the workbook. If not, the data will not be extracted successfully - an error message will be shown, and the message will prompt the user to input another sheet that meets the formatting requirements. For folder’s that contains only HiCo generated reports or contract tender listing sheets, two excel files, as described in Data Collection and Extraction section, are available to organize and format the reports to generate the input file with one click.

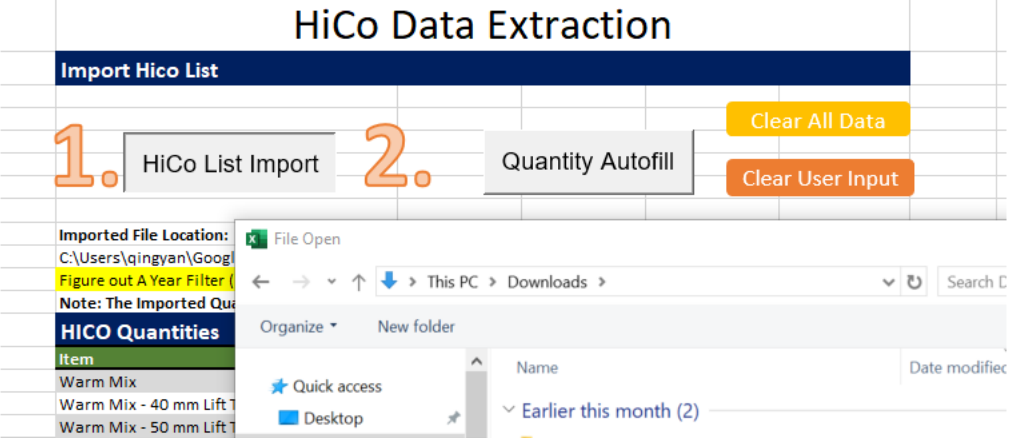
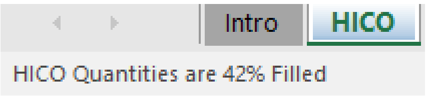


Figure A-1: Interface for HiCo Data Extraction

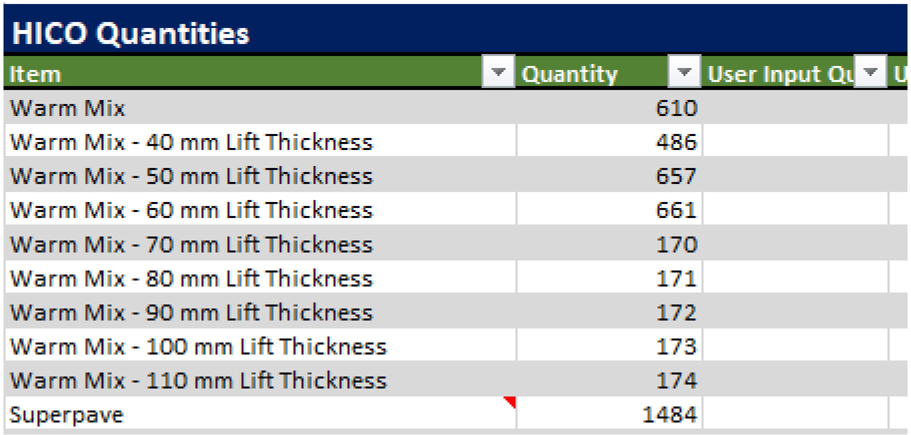
3.2 Click ‘Quantity Autofill’ Button. Depending on the amount of data needed for processing and the computer’s speed, it could take a few minutes to aggregate and complete this step. The progress is shown as a percent completion at the on the bottom left side in the Excel status bar as shown below.



HICO Quantities are 42% Filled

Figure A-2: Sample Status Bar Showing the Data Fill and Aggregation Progress

The Item under HiCo quantities for extraction can be added or deleted as needed. For adding new items, input the new item information including the item name, unit and category at the bottom of the Excel Table (Table Name: HiCoTable). For deleting unnecessary items, select the row in the HiCoTable and click ‘Delete Table Rows’.



HICO Quantities

Item	Quantity	User Input Qu	U
Warm Mix	610		
Warm Mix - 40 mm Lift Thickness	486		
Warm Mix - 50 mm Lift Thickness	657		
Warm Mix - 60 mm Lift Thickness	661		
Warm Mix - 70 mm Lift Thickness	170		
Warm Mix - 80 mm Lift Thickness	171		
Warm Mix - 90 mm Lift Thickness	172		
Warm Mix - 100 mm Lift Thickness	173		
Warm Mix - 110 mm Lift Thickness	174		
Superpave	1484		

Figure A-3: Sample for Partially Auto-filled HiCo Quantity Table

3.3 If needed, enter numbers in ‘User Input Quantity’ (the right of the HiCo extracted Quantity Column) to override the HiCo extracted quantity.

3.31 If needed, Press ‘Clear User input’ to the user input quantity column; Hit ‘Clear All Data’ to clear all quantities in the HiCo tab, including the imported sheet from the folder.

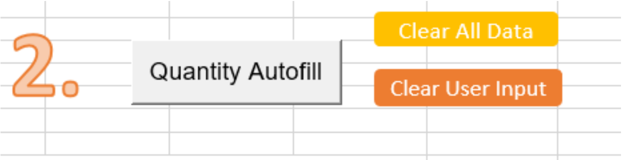


Figure A-4: Clear Buttons

Input Tab

4. Input the required information for Material, Transportation, Lights, Trees, and Traffic.

The ‘Required’ Input are marked in red, the ones marked in blue are the default values that are selected for Ontario. The user can input project information to override the defaults. The yellow values are dropdowns, where users can choose one option from the list provided.

Required information includes: %SCM, the number of alternative fuel vehicles assessed, the number of truck with idle reduction, the number of solar powered signal, project level traffic, AADT, etc. Those values are not provided in HiCo but are important quantity values for emission reductions from these mitigation activities.

Default information includes: In-Place Recycling structural coefficient, material density, truck load and empty runs, pavement material mix design, etc. Those values are collected from government reports, research papers, etc. Collecting data from projects can provide better results but takes more time and resources. It is recommended the user review and adjust the default information and tailor it to meet project needs as those values greatly affect the emission results.

Dropdowns include: Fuel Type for Baseline and Alternative Energy in Vehicle Transportation, Engine year for the engine replacement, survival rate and the size of the tree, the type of the HID light, etc.

4.1 Most input data should be entered through the input tab. To change detailed assumptions, including transportation distance for each trip, transportation mode (dropdown), and the construction equipment usage for in-situ recycling, the user should navigate to the materials tab to make the change. Those options are not given in the input tab because they take a lot of space, and are not likely to be changed for annual quantifications.

Result Tab

5. To View Results, the user must hit ‘**Refresh All**’ from the data bar first to ensure values are calculated and up to date.

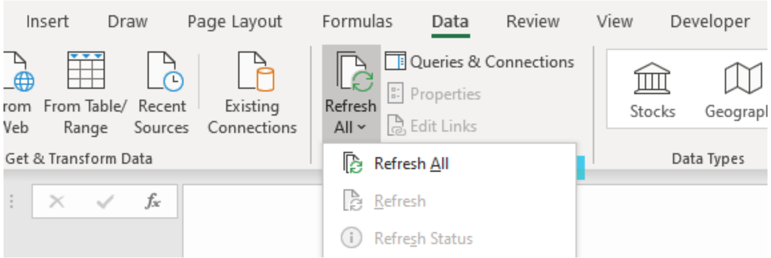
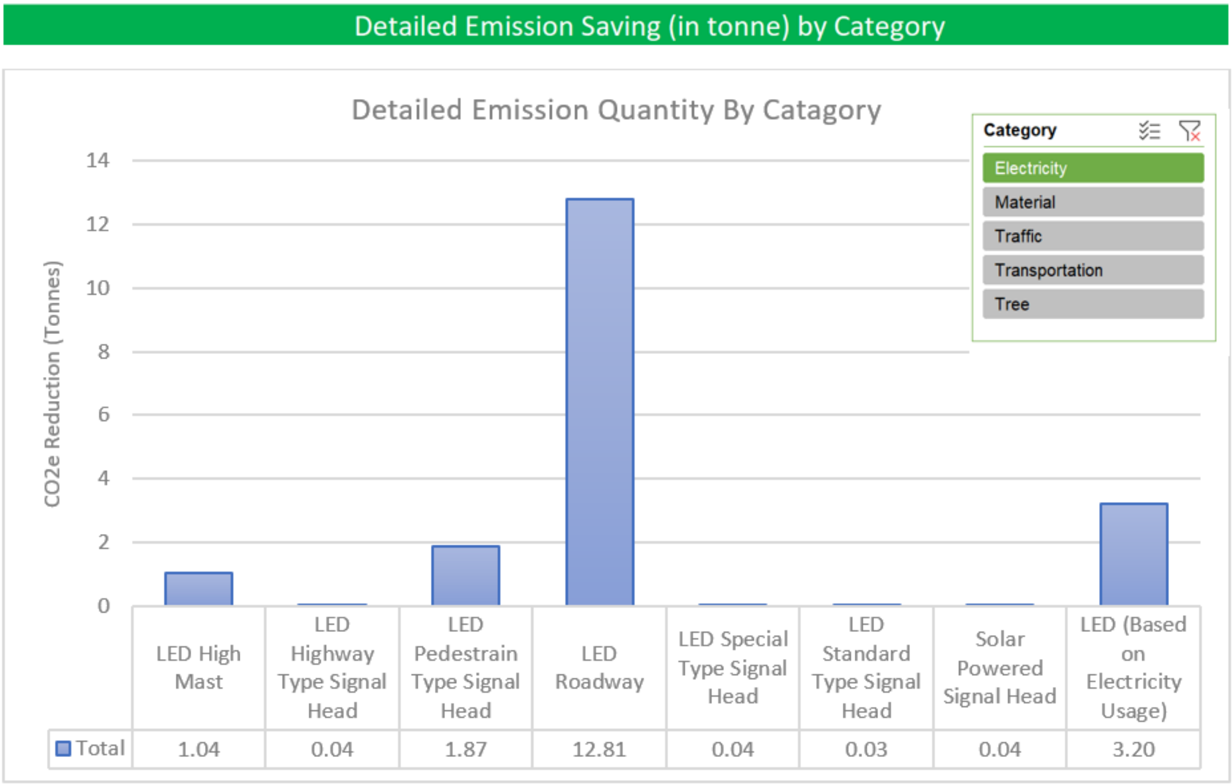


Figure A-5: Refresh All Button to Update Results

6. The user can view the detailed results from each category and mitigation strategy through the bar charts and pie charts, as shown below. The user can also use two slicers (category & method) to obtain more information about each individual mitigation measures’ reduction result, to

compare with other mitigation measures, and understand their percent contribution. The savings that are not directly counted in the reduction (carbonation, roundabout, engine repower, and IRI) are also presented, and the amount reduction is compared to the total reductions that are directly quantified.



	LED High Mast	LED Highway Type Signal Head	LED Pedestrain Type Signal Head	LED Roadway	LED Special Type Signal Head	LED Standard Type Signal Head	Solar Powered Signal Head	LED (Based on Electricity Usage)
▪ Total	1.04	0.04	1.87	12.81	0.04	0.03	0.04	3.20

Figure A-6: Sample Bar Chart Showing Emission Reduction of each Mitigation Activity by Category

Note: Press “Alt” to select more than one category or method

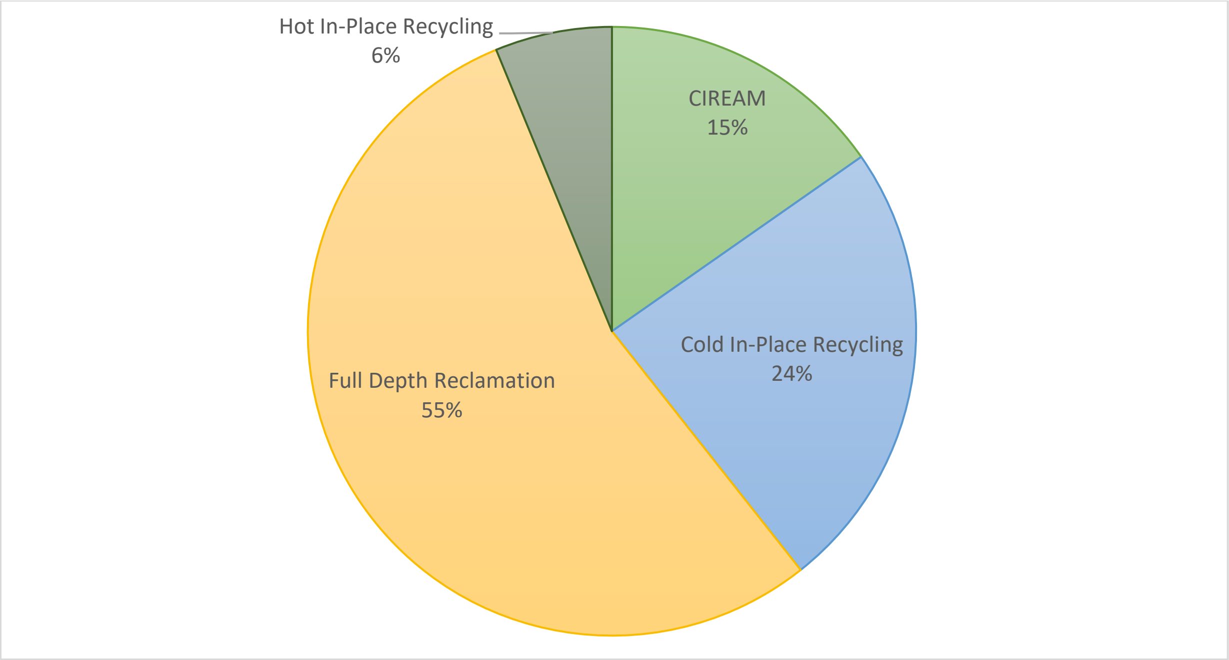


Figure A-7: Sample Pie Chart Showing Contribution of Emission Reductions for each Mitigation

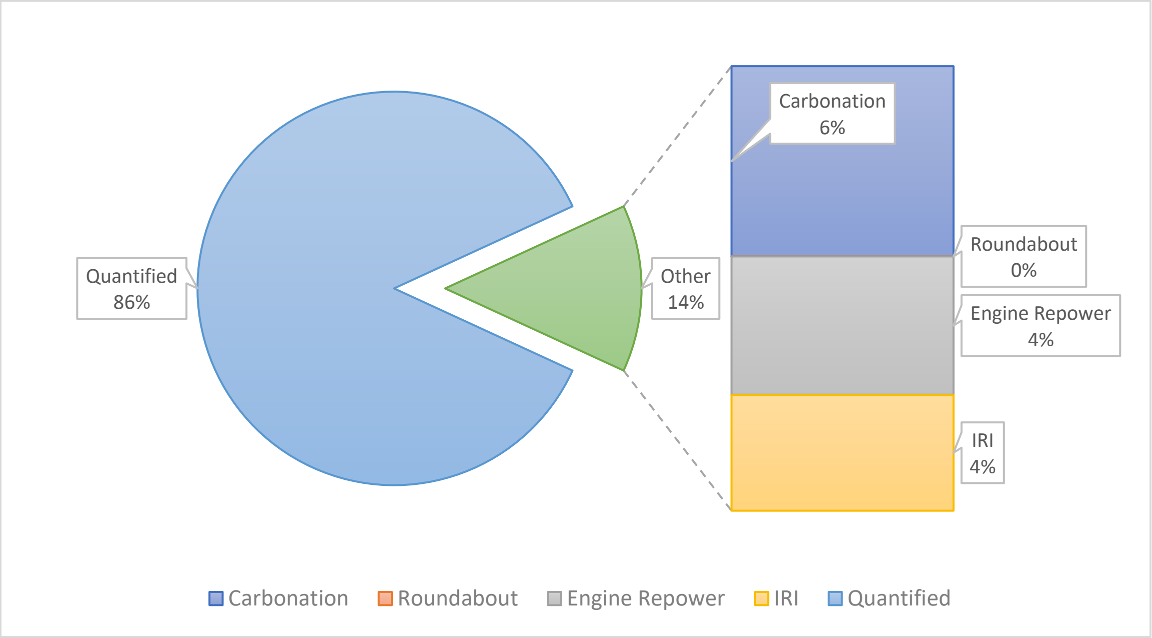


Figure A-8: Contribution of the Additional Emissions Towards the Yearly Saving

Appendix B : Supporting Documents for Tools

Table B-1: Light Duty Vehicle and Fuel Pathways Combinations Options in GHGenius (Version 5.0d, 2019)

	Gasoline	**Diesel**	**Biodiesel**	**FTD**	**Methanol**	**Ethanol**	**Butanol**	**Mixed Alcohols**	**NG**	**LPG**	**Hydrogen**	**Hythane**	**Elec**
Crude Oil	ICE FC	ICE								ICE	FC		EV
Coal				ICE	ICE FC				ICE		FC		EV
Natural Gas				ICE FC	ICE FC			ICE	ICE	ICE	ICE FC	ICE	EV
Landfill Gas				ICE	ICE FC				ICE		FC		
Manure									ICE				
Wood or Grass	ICE	ICE		ICE	ICE FC	ICE FC		ICE	ICE		FC		EV
Corn						ICE FC	ICE				FC		
Sugar Cane						ICE FC							
Sugar Beets						ICE FC							
Wheat						ICE FC					FC		
Barley						ICE FC							
Peas						ICE FC							
Sorghum						ICE FC							
Wheatstover						ICE FC							
Soybeans	ICE	ICE	ICE										
Canola	ICE	ICE	ICE										
Palm	ICE	ICE	ICE										
Camelina	ICE	ICE	ICE										
Tallow	ICE	ICE	ICE										
Yellow Grease	ICE	ICE	ICE										
Jatropha	ICE	ICE	ICE										
Algae	ICE	ICE	ICE										
Marine Oils	ICE	ICE	ICE										
Palm Sludge	ICE	ICE	ICE										

	Gasoline	**Diesel**	**Biodiesel**	**FTD**	**Methanol**	**Ethanol**	**Butanol**	**Mixed Alcohols**	**NG**	**LPG**	**Hydrogen**	**Hythane**	**Elec**
SBE	ICE	ICE	ICE										
RDF				ICE				ICE					
Electricity											ICE FC	ICE	

Table B-2:Heavy Duty Vehicle and Fuel Pathways Combinations Options in GHGenius (Version 5.0d)

	Diesel or Blends	**FTD**	**DME**	**Methanol**	**Ethanol**	**Butanol**	**Mixed Alcohols**	**Biodiesel**	**HRD**	**HRJ**	**NG**	**LPG**	**Hydrogen**	**Hythane**
Crude Oil	ICE											ICE	FC	
Coal		ICE		ICE FC							ICE			
Natural Gas		ICE	ICE	ICE FC			ICE				ICE	ICE	ICE FC	ICE
Landfill Gas				ICE FC							ICE		FC	
Manure											ICE			
Wood or Grass		ICE		ICE	ICE		ICE				ICE		FC	
Corn					ICE	ICE							FC	
Sugar Cane					ICE									
Sugar Beets					ICE									
Wheat					ICE								FC	
Barley					ICE									
Peas					ICE									
Sorghum					ICE									
Wet stover					ICE									
Soybeans								ICE	ICE	ICE				
Canola								ICE	ICE	ICE				
Palm Oil								ICE	ICE	ICE				
Camelina								ICE	ICE	ICE				
Tallow								ICE	ICE	ICE				

	Diesel or Blends	**FTD**	**DME**	**Methanol**	**Ethanol**	**Butanol**	**Mixed Alcohols**	**Biodiesel**	**HRD**	**HRJ**	**NG**	**LPG**	**Hydrogen**	**Hythane**
Jatropha								ICE	ICE	ICE				
Algae								ICE	ICE	ICE				
Yellow Grease								ICE	ICE	ICE				
Marine Oils								ICE	ICE	ICE				
Palm Sludge								ICE	ICE	ICE				
SBE								ICE	ICE	ICE				
RDF		ICE					ICE							
Electricity													ICE FC	ICE
Nuclear													FC	

Appendix C : Emission Baselines

Table C-1: Median, Large, and Small GHG Baseline Emission (in kg/7000 m^2) Values for each In-Situ Recycling Option Calculated using POETT with Testing Scenarios

		CIR	CIREAM	HIR	FDR with EAS	FDR
Median	Material	89697	89697	44849	107637	107637
	Transportation	8659	8659	4330	11217	11217
	Construction	1417	1340	709	1950	1950
	Sum	**99774**	**99697**	**49887**	**120804**	**120804**
Large	Material	158675	158675	79338	190410	190410
	Transportation	23186	23186	11593	30127	30127
	Construction	1417	1340	709	1950	1950
	Sum	**183279**	**183202**	**91640**	**222488**	**222488**
Small	Material	59381	59381	29690	71257	71257
	Transportation	6485	6485	3243	8388	8388
	Construction	1417	1340	709	1950	1950
	Sum	**67283**	**67206**	**33642**	**81595**	**81595**

Table C-2: Baseline GHG Emissions Values for each In-Situ Recycling Option Calculated using Selected Tools with Testing Scenarios

	CIR	CIREAM	HIR	FDR with EAS	FDR
POETT	99774	99697	49887	120804	120804
PaLATE 2.0	154423	154423	77144	186096	186096
PaLATE2.2	63965	63965	31251	86558	86558
Adapted PaLATE (Similar Design)	84220	84220	42111	101449	100449
Adapted PaLATE (MTO)	92458	92458	46229	110811	110811
Athena	154520	154520	89618	182050	182050

Appendix D : Minimum and Maximum Per Unit Reduction

Table D-1: Values, Ranges, and Sources for the Selected Unit Reduction in Figure 4-34

Mitigation Measure	**Unit**	**Value**		**Source**	**Comments**
WMA	kg/tonne	Selected	4.8	Median from MTO Report (Politano, 2012)	
		Min	1.3	Frank et. al 2011 Result for Site 5	
		Max	6.9	FHWA with 37**%** Reduction Rate with High Emission factor for HMA	
Concrete NSSP	kg/tonne	Selected	10.69	POETT Result	POETT result is similar to the reduction result of “General Concrete” from the Carbon Tool
		Min	4.09	Result from PaLATE 2.0	
		Max	24.4	Result from PaLATE 2.2	
Carbonation	kg/tonne	Selected	1.04	One tonne concrete material for 50 years with the rate factor of 1.58	According to Santero & Horvath 2009, expected min is 1.0, expected max is 8.46. The total sequestration mostly depend on the rate factor selected, which can vary from 0.75 to 42
		Min	0.73	Extreme minimum calculated with the assumptions in Santero & Horvath, 2009	
		Max	42.31	Extreme Maximum Calculated with the assumptions in Santero & Horvath, 2009	
RAP with Binder Replacement	kg/tonne	Selected	14.15	Average reduction values from the sensitivity analysis, which evaluates 4.5%-5.5% binder in RAP, and 10%-30% RAP in the mixture	Emission saving increases with higher binder percentage in RAP as well as higher percentage of RAP used in the pavement material
		Min	25.4	4.5% Binder in RAP, 10% RAP in the mixture	
		Max	33.05	5.5% Binder in RAP, 30% RAP in the mixture	
RCM	kg/tonne	Selected	12.74	POETT Result	
		Min	5.69	Result from GasCAP	
		Max	14	Result from PaLATE 2.2	

Mitigation Measure	Unit	Value		Source	Comments
RAP	kg/tonne	Selected	11	POETT result	
		Min	12.74	Result from GreenDOT	
		Max	14	Result from PaLATE 2.2	
Other Aggregate Substitution	kg/tonne	Selected	11	Emission reduction calculated for Foundry Sand, Blast Furnace Slag, and Coal Bottom Ash	The selected value (11) represents is a generalized result that applies to most type of the aggregate substitution. The user should look at individual material to generate a more representative result
		Min	0.77	Glass Cutlet Result from POETT	
		Max	28	Result from PaLATE 2.2 (All Aggregate Substitution)	
Other Bitumen Substitution	kg/tonne	Selected	NA		Not Selecting one value due to the large variance among reductions
		Min	99.21	Recycled Asphalt Shingles	
		Max	336.37	Recycled Tires/Crumb Rubber	
LED Roadway Light	kg/light-year	Selected	56.064	Average value of reduction for replacing HID with corresponding 40W, 100W, 200W LED	
		Min	19.63	Using 40W LED to replace corresponding PSMH	
		Max	6.09	Using 200W LED to replace corresponding MV	
LED High Mast Light	kg/light-year	Selected	125.58	Average value of reduction for replacing HID with 200, 400, 600, 800W LED	
		Min	17.1	Using 200W LED to replace corresponding MH light	
		Max	210.24	Using 800W LED to replace corresponding MH light	
LED Signal	kg/signal-year	Selected	33.8	Average reduction value of the four signal type	
		Min	29.23	Replace with average LED Special Type Signal	
		Max	38.42	Replace with LED Standard Type Signal	
Coniferous	kg/tree-year	Selected	3.89	Evaluated with median survival rate and median-sized tree for 50 years	Range from 0.31-13.74 when evaluating for 30

Mitigation Measure	Unit	Value		Source	Comments
		Min	0.53	Evaluated with low survival rate and small-sized trees for 50 years	year, 40 year, 50 year, respectively
		Max	13.71	Evaluated with high survival rate and large-sized trees for 50 years	
Deciduous		Selected	9.61	Evaluated with median survival rate and median-sized tree for 50 years	Range from 1.59 to 20.44 when evaluating for 30 year, 40 year, 50 year, respectively
		Min	1.59	Evaluated with low survival rate and small-sized trees for 50 years	
		Max	17.99	Evaluated with high survival rate and large-sized trees for 50 years	

Table D-2: Values, Ranges, and Sources for the Selected Percentage Reduction in Figure 4-35

Mitigation Measure	Value		Source
CIR/CIREAM	Selected	61.11%	Median of the Reduction Results from the sensitivity analysis, which evaluates the combinations of Mill 50-140mm and Overlay 50mm-140mm, with 10mm increment. The selected value occurs when having the same Mill and Overlay thicknesses
	Min	22.09%	Mill 50 mm, Overlay 140 mm
	Max	87.01%	Mill 70mm, Overlay 50 mm
HIR	Selected	35.19%	Median of the Reduction Results from the sensitivity analysis, which evaluates the combinations of Mill and Overlay 20mm - 60 mm, respectively, with 5 mm increment. The selected value value occurs when having the same Mill and Overlay thicknesses
	Min	7.77%	Mill 60mm, Overlay 20mm
	Max	60.12%	Mill 55mm, Overlay 30mm
FDR	Selected	12.38%	Median of the Reduction Results from the sensitivity analysis, which evaluates the combinations of Mill 120mm-250mm and Overlay 120mm-200mm, with 10mm increment. Median Value occurs around when milling 200 mm to 210 mm

Mitigation Measure	Value		Source
	Min	1.30%	Mill 250mm, Overlay 200mm
	Max	31.22%	Mill 130mm, Overlay 120mm
FDR with EAS	Selected	24.67%	Median of the Reduction Results from the sensitivity analysis, which evaluates the combinations of Mill 120mm-250mm and Overlay 120mm-200mm, with 10mm increment. Median Value occurs around when milling 200 mm to 210 mm
	Min	10.94%	Mill 240mm, Overlay 200mm
	Max	47.49%	Mill 120mm, Overlay 120mm
WMA	Selected	25.90%	POETT result
	Min	9.70%	Result from Frank et al (2011) Site 3
	Max	37.00%	FHWA tool result
LED Roadway Light	Selected	49.80%	Median of replacing with LED lights from 40W, 100W, 200W for all four HID types
	Min	32.80%	Replacing MH with 200W Corresponding LED
	Max	64.16%	Replacing MV with 40W Corresponding LED
LED High Mast Light	Selected	60.46%	Median of Replacing MH with 200W, 400W, 800W LED
	Min	32.80%	Replacing MH with 200W Corresponding LED
	Max	61.34%	Replacing MH with 800W Corresponding LED
LED Signal	Selected	88.60%	Median Emission Reduction from Standard, Highway, Special, and Pedestrian Signal Head
	Min	87.80%	Emission Reduction from Per Standard Type Signal Head
	Max	89.40%	Emission Reduction from Per Pedestrian Type Signal Head
Auxiliary Power Unit	Selected	50.90%	POETT result (obtained from emission factor difference)
Fuel Operated Heater	Selected	91.90%	POETT result (obtained from emission factor difference)
Engine Off	Selected	100.00%	Zero emission when engine off

Mitigation Measure	**Value**		**Source**
Class I Freight	Selected	70.69%	POETT Result; Obtained from Comparing the intensity (g/CO2-tonne-km) of the selected transport mode with that of truck with 20 tonne per load and 0% empty run
Regional Short Line Freight	Selected	65.00%	
Liquid Bulk Vessels	Selected	57.60%	
Container Vessels	Selected	54.90%	

Appendix E : Additional Data

Material Emission Factors

Various studies have been done for GHG emissions generated from the upstream production of the material. For POETT, the emission factors for major pavement-related materials are collected through tools, studies, and project reports. The sources, year, and the location of the emission factors were presented below. For most materials, the selected emission factors, which are presented in the data section of the report, are the median values of the various data gathered.

Table E-1: Emission Factors Collected for Materials

Item	Value	Unit	ton/ton	Source	Year	Location
Aggregate	10922.34639	g/ton (us)	0.01203983	PaLATE 2.0 (1997 EIO-LCA)	2003	US
Aggregate	0.005	kg/kg	0.005	ROADEO	2010	World Bank
Aggregate	0.0032	kg/kg	0.0032	Loijos	2011	US
Aggregate	10	kg/t	0.01	Jim & Galehouse	2010	US
Aggregate	14	kg/t	0.014	Adapted PaLATE	2018	Canada
Aggregate	10.7429	kg/ton (us)	0.01184202	PaLATE 2.2 (2002 EIO-LCA)	2011	Washington
Aggregate	0.006157828	mt/mt	0.00615783	PE2 (used in Stripple and Athena)	2012	US
Aggregate	0.005	t/t	0.005	UK Carbon Tool (ICE inventory)	2012	UK
Aggregate	0.012	ton/ton (US)	0.012	GreenDOT	2010	US
Aggregate	2.36	kg/t	0.00236	Chai et.al	2017	China
Aggregate	9.98	kg/t	0.00998	Quarry Products Association	2006	UK
Aggregate	4107.22	g/ton (us)	0.00452744	Hansen et.al	2012	US
Bitumen	1121978.108	g/ton (us)	1.23676916	PaLATE 2.0 (1997 EIO-LCA)	2003	US
Bitumen	0.48	kg/kg	0.48	ROADEO	2010	World Bank
Bitumen	190	kg/t	0.19	asPECT (2011 Eurobitume)	2011	UK
Bitumen	285	kg/t	0.285	Jim & Galehouse	2010	US
Bitumen	358.4	kg/t	0.3584	Adapted PaLATE	2018	Canada

Item	Value	Unit	ton/ton	Source	Year	Location
Bitumen	170.9913	kg/ton (us)	0.18848564	PaLATE 2.2 (2002 EIO-LCA)	2011	Washington
Bitumen	0.156993129	mt/mt	0.15699313	PE2 (used in Stripple and Athena)	2012	US
Bitumen	1.236980864	ton/ton (US)	1.23698086	GreenDOT	2010	US
Cement	264925.1826	g/ton (us)	0.29203003	PaLATE 2.0 (1997 EIO-LCA)	2003	US
Cement	1.067	kg/kg	1.067	Loijos	2011	US
Cement	0.83	kg/kg	0.83	ROADEO	2010	World Bank
Cement	0.89	kg/kg	0.89	Winnipeg Report	2012	Winnipeg
Cement	913	kg/t	0.913	asPECT (2009 BCA)	2012	UK
Cement	980	kg/t	0.98	Jim & Galehouse	2010	US
Cement	1100	kg/t	1.1	Adapted PaLATE	2018	Canada
Cement	851.324	kg/ton (us)	0.93842407	PaLATE 2.2 (2002 EIO-LCA)	2011	Washington
Cement	0.8417127	mt/ton (us)	0.92782943	PE2	2012	US
Cement	0.95	t/t	0.95	UK Carbon Tool (ICE inventory)	2012	UK
Cement	0.583	ton/ton (US)	0.583	GreenDOT	2010	US
Cement	532	g/kg	0.532	Canada NIR (Cement Association of Canada)	2016	Ontario
Concrete	37098.84554	g/ton (us)	0.04089448	PaLATE 2.0 (1997 EIO-LCA)	2003	US
Concrete	0.209	kg/kg	0.209	ROADEO	2010	World Bank
Concrete	0.15	kg/kg	0.15	Winnipeg Report	2012	Winnipeg
Concrete	263	kg/m3	0.11191489	Winnipeg Report	2012	Winnipeg
Concrete	0.2568	t/t	0.2568	UK Carbon Tool (ICE inventory)	2012	UK
Concrete	282	kg/m3	0.12	Athena Report	2006	Ontario
Concrete	137998	g/ton (us)	0.15211676	Hansen et.al	2012	US
Emulsion	969317.9427	g/ton (us)	1.06849013	PaLATE 2.0 (1997 EIO-LCA)	2003	US

Item	Value	Unit	ton/ton	Source	Year	Location
Emulsion	0.185	kg/kg	0.185	ROADEO	2010	World Bank
Emulsion	220	kg/t	0.22	asPECT (2011 Eurobitume)	2011	UK
Emulsion	221	kg/t	0.221	Jim & Galehouse	2010	US

Table E-2: Median, Min, Max Value used for Calculating Material Related Emissions

Emission Factors (tonCO$_2$e/ton)	**Median**	**Min**	**Max**	**StdDev**
Aggregate	0.011	0.00453	0.014	0.00361
Bitumen	0.48	0.285	1.23698	0.42706
Cement	0.7065	0.29203	1.1	0.2773
Concrete	0.15212	0.04089	0.209	0.06981
Emulsion	0.221	0.185	1.06849	0.40826
Hot Mix Plant	0.0185	0.0165	0.01852	0.00095
Lime	0.74	0.44	2.5	0.90867
Water	0.00015	0	0.0003	0.00015
Additive	0.4			
Fly Ash	0.0148	0.01	0.0196	0.00678823
Ground Limestone	0.044			

Construction Equipment Specifications

Table E-3: Equipment Specification Applied in POETT

Equipment	**Load Factor**	**Productivity Value**	**Productivity Unit**	**hp**	**EF (kg CO$_2$ /hp-hr)**
Asphalt Paver	0.62	151.875	tonne/hr	161	0.527
Asphalt Remixer	0.62	8.3025	tonne/hr	295	0.527
Black Topper	0.62	10000	m2/hr		0.586
Cold In-Place Recycler	0.62	1713	tonne/hr	800	0.527
Compactor	0.56	340.75	tonne/hr	150	0.527
Crushing and Screening	0.56	599.5	tons/hr	310	0.527
Roller (Pneumatic)	0.56	151.875	tonne/hr	100	0.586
Heating Machine	0.62	8.3	tonne/hr	49	0.586
HMA Transfer	0.59	151.875	tonne/hr	300	0.527
Breaker	0.78	125	m2/day	350	0.527

Equipment	**Load Factor**	**Productivity Value**	**Productivity Unit**	**hp**	**EF (kg CO_2 /hp-hr)**
Diamond Grinder	0.78	15.625	m2/day	910	0.527
Milling Machine	0.78	40	m3/hr	433	0.527
Road Reclaimer	0.42	4354	tonne/hr	670	0.527

LED Wattage and Equivalent HID Wattage

To find the HID wattage that is equivalent to the specified LED input wattage, the information for PSMH, MH, HPS, and MV from sources including specification sheets from Howard Lighting Products and Cooper Lighting, project reports for Iowa City's street light, and high mast light sales website were collected. The collected HID Wattage and their equivalency information was then complied, and the average LED wattage corresponding to each specified type of HID was recorded in the table below.

Table E-4: HID Wattage and their Corresponding LED Wattage Applied in POETT

HID Wattage	**Corresponding LED Wattage for each Type of HID**			
	HPS	**MH**	**MV**	**PSMH**
70	36	53		38
75	20	20	20	
100	38	40	34	51
150	70	68	62	88
175		94		
200				147
250	126	132	112	166
320		232		183
350				235
400	206	216	175	271
1000	300	386	300	
1500		585		
2000		800		

LED Signals

Table E-5: Incandescent Signal Head Wattage and Corresponding LED Wattage

Description	**Incandescent Power** ***(Watts)***	**LED Power** ***(Watts)***	**Load Factor**
Red Ball 300mm Traffic Signal Head	142.5	14	0.45
Amber Ball 300mm Traffic Signal Head	142.5	23.5	0.10
Green Ball 300mm Traffic Signal Head	142.5	15	0.45
Red Ball 200mm Traffic Signal Head	95	10.5	0.45
Amber Ball 200mm Traffic Signal Head	95	14.5	0.10
Green Ball 200mm Traffic Signal Head	95	12	0.45
300 mm Square Pedestrian Signal Head	95	10.75	1.00
300mm Red Arrow	120	14	0.05
300mm Amber Arrow	120	23.5	0.05
300mm Green Arrow	120	15	0.05

Table E-6: Calculated Wattage for each MTO Signal Type based on Signal Head Arrangements and Load Factors

Type Signal		**Incandescent (Watts)**	**LED (Watts)**
Standard		95	11.575
Highway		121.125	13.825
Special	Type 1-7	106.25	12.925
	Type 8	116.705	13.705
	Type 8A	140.455	15.75
	Type 9,10	121.071	14.286
	Type 9A,10A,11A	141.429	14.667
	Type 11	116.548	13.238
	Averaged Special Type Signal Head	123.743	14.095
Pedestrian		95	10.075

Trees

Table E-7: Tree Age Adjustment based on the Initial Size

Type	**Initial Condition**	**Age Adjustment**
Coniferous Tree	500 mm Height	0.665
Coniferous Tree	1.0 m Height	0.762
Coniferous Tree	1.5 m Height	0.873
Coniferous Tree	2.0 m Height	1
Deciduous Tree	45 mm Caliper	1
Deciduous Tree	50 mm Caliper	1
Deciduous Tree	60 mm Caliper	1
Deciduous Tree	Whip	1
Deciduous Tree	2.0 m Height	1

Table E-8: Moderate, High, and Low Survival Factors Correspond to the Age of the Tree

Tree Age	**Survival Factors**		
	Moderate	**High**	**Low**
1	0.75	0.85	0.65
2	0.742	0.846	0.64
3	0.734	0.842	0.63
4	0.726	0.838	0.62
5	0.718	0.834	0.61
6	0.71	0.83	0.6
7	0.704	0.824	0.59
8	0.698	0.818	0.58
9	0.692	0.812	0.57
10	0.686	0.806	0.56
11	0.68	0.8	0.55
12	0.672	0.796	0.54
13	0.664	0.792	0.53
14	0.656	0.788	0.52
15	0.648	0.784	0.51
16	0.64	0.78	0.5
17	0.632	0.774	0.49
18	0.624	0.768	0.48

Tree Age	Survival Factors		
	Moderate	High	Low
19	0.616	0.762	0.47
20	0.608	0.756	0.46
21	0.6	0.75	0.45
22	0.592	0.744	0.44
23	0.584	0.738	0.43
24	0.576	0.732	0.42
25	0.568	0.726	0.41
26	0.56	0.72	0.4
27	0.554	0.716	0.39
28	0.548	0.712	0.38
29	0.542	0.708	0.37
30	0.536	0.704	0.36
31	0.53	0.7	0.35
32	0.522	0.694	0.34
33	0.514	0.688	0.33
34	0.506	0.682	0.32
35	0.498	0.676	0.31
36	0.49	0.67	0.3
37	0.49	0.67	0.3
38	0.49	0.67	0.3
39	0.49	0.67	0.3
40	0.49	0.67	0.3
41	0.49	0.67	0.3
42	0.49	0.67	0.3
43	0.49	0.67	0.3
44	0.49	0.67	0.3
45	0.49	0.67	0.3
46	0.49	0.67	0.3
47	0.49	0.67	0.3
48	0.49	0.67	0.3
49	0.49	0.67	0.3
50	0.49	0.67	0.3

Table E-9: Constants used in Equation 3.19 for Calculating dbh for Coniferous and Deciduous of each Size

Tree Growth Curve (North)			
	dbh (inch)		
Tree Type	B0	B1	B2
Small Deciduous	8	-0.07	1.9
Med Deciduous	14	-0.07	1.9
Large Deciduous	16	-0.07	1.9
Small Coniferous	13	-0.0176	1.415
Med Coniferous	24	-0.0176	1.415
Large Coniferous	35	-0.0176	1.415

MOVES Emission Rate

Table E-10: Ontario Specific EPA MOVES Emission Rates Correspond to Speed (kg/km)

MOVES Ontario Emission Factor Look Up Table (kg/km)								
Speed (mph)	**Light-Duty Vehicles**				**Heavy-Duty Vehicles**			
	CO_2	**CH_4**	**N_2O**	**CO_2e**	**CO_2**	**CH_4**	**N_2O**	**CO_2e**
2.5	1.37025294	2.49384E-05	4.97472E-05	1.38569484	4.8828715	0.000233228	0.00002055	4.8948119
3	1.247384042	2.27547E-05	4.47825E-05	1.26128959	4.4293184	0.000212733	0.0000185	4.4401365
3.5	1.124515145	2.05711E-05	3.98177E-05	1.13688434	3.9757653	0.000192238	0.00001645	3.9854611
4	1.001646247	1.83874E-05	3.4853E-05	1.01247909	3.5222122	0.000171742	0.0000144	3.5307857
4.5	0.87877735	1.62038E-05	2.98882E-05	0.88807384	3.0686591	0.000151247	0.00001235	3.0761103
5	0.755908452	1.40201E-05	2.49235E-05	0.76366859	2.615106	0.000130752	0.0000103	2.6214349
5.5	0.725137629	1.34663E-05	2.36741E-05	0.73251327	2.5095565	0.000124568	9.78393E-06	2.5155779
6	0.694366806	1.29124E-05	2.24247E-05	0.70135795	2.404007	0.000118385	9.26786E-06	2.4097209
6.5	0.663595983	1.23586E-05	2.11753E-05	0.670202629	2.2984575	0.000112201	8.75179E-06	2.3038638
7	0.63282516	1.18048E-05	1.99259E-05	0.639047309	2.1929081	0.000106017	8.23572E-06	2.1980068
7.5	0.602054337	1.12509E-05	1.86765E-05	0.607891989	2.0873586	9.98338E-05	7.71966E-06	2.0921498
8	0.571283514	1.06971E-05	1.74271E-05	0.576736669	1.9818091	9.36502E-05	7.20359E-06	1.9862928
8.5	0.540512691	1.01433E-05	1.61777E-05	0.545581349	1.8762596	8.74666E-05	6.68752E-06	1.8804357
9	0.509741868	9.58944E-06	1.49283E-05	0.514426028	1.7707102	8.1283E-05	6.17145E-06	1.7745787
9.5	0.478971045	9.0356E-06	1.36789E-05	0.483270708	1.6651607	7.50993E-05	5.65538E-06	1.6687217
10	0.448200222	8.48177E-06	1.24295E-05	0.452115388	1.5596112	6.89157E-05	5.13931E-06	1.5628647
10.5	0.438823547	8.2771E-06	1.2015E-05	0.442610151	1.5350005	6.67851E-05	4.96788E-06	1.5381496
11	0.429446872	8.07242E-06	1.16005E-05	0.433104914	1.5103899	6.46544E-05	4.79645E-06	1.5134345
11.5	0.420070197	7.86775E-06	1.1186E-05	0.423599676	1.4857792	6.25238E-05	4.62502E-06	1.4887195
12	0.410693522	7.66307E-06	1.07715E-05	0.414094439	1.4611685	6.03931E-05	4.45359E-06	1.4640044
12.5	0.401316847	7.4584E-06	1.0357E-05	0.404589202	1.4365578	5.82625E-05	4.28216E-06	1.4392894
13	0.391940172	7.25372E-06	9.94246E-06	0.395083965	1.4119471	5.61319E-05	4.11072E-06	1.4145743
13.5	0.382563497	7.04904E-06	9.52794E-06	0.385578728	1.3873364	5.40012E-05	3.93929E-06	1.3898592

MOVES Ontario Emission Factor Look Up Table (kg/km)								
Speed (mph)	**Light-Duty Vehicles**				**Heavy-Duty Vehicles**			
	CO_2	**CH_4**	**N_2O**	**CO_2e**	**CO_2**	**CH_4**	**N_2O**	**CO_2e**
14	0.373186822	6.84437E-06	9.11343E-06	0.37607349	1.3627258	5.18706E-05	3.76786E-06	1.3651442
14.5	0.363810147	6.63969E-06	8.69891E-06	0.366568253	1.3381151	4.97399E-05	3.59643E-06	1.3404291
15	0.354433472	6.43502E-06	8.2844E-06	0.357063016	1.3135044	4.76093E-05	0.000003425	1.315714
15.5	0.348847454	6.31221E-06	8.07796E-06	0.35141218	1.2979032	4.65042E-05	3.3395E-06	1.3000599
16	0.343261437	6.18941E-06	7.87152E-06	0.345761344	1.2823019	4.53992E-05	0.000003254	1.2844058
16.5	0.337675419	6.0666E-06	7.66507E-06	0.340110508	1.2667007	4.42942E-05	3.1685E-06	1.2687517
17	0.332089402	5.94379E-06	7.45863E-06	0.334459672	1.2510995	4.31891E-05	0.000003083	1.2530976
17.5	0.326503384	5.82098E-06	7.25219E-06	0.328808836	1.2354982	4.20841E-05	2.9975E-06	1.2374435
18	0.320917366	5.69818E-06	7.04575E-06	0.323158	1.219897	4.09791E-05	0.000002912	1.2217894
18.5	0.315331349	5.57537E-06	6.83931E-06	0.317507164	1.2042958	3.9874E-05	2.8265E-06	1.2061353
19	0.309745331	5.45256E-06	6.63286E-06	0.311856328	1.1886945	3.8769E-05	0.000002741	1.1904812
19.5	0.304159314	5.32976E-06	6.42642E-06	0.306205492	1.1730933	3.7664E-05	2.6555E-06	1.1748271
20	0.298573296	5.20695E-06	6.21998E-06	0.300554656	1.1574921	3.65589E-05	0.00000257	1.159173
20.5	0.295520625	5.14768E-06	6.09545E-06	0.297463498	1.1491335	3.59027E-05	2.5185E-06	1.1507823
21	0.292467954	5.0884E-06	5.97093E-06	0.29437234	1.1407749	3.52464E-05	0.000002467	1.1423916
21.5	0.289415283	5.02913E-06	5.8464E-06	0.291281183	1.1324163	3.45902E-05	2.4155E-06	1.134001
22	0.286362612	4.96985E-06	5.72188E-06	0.288190025	1.1240577	3.3934E-05	0.000002364	1.1256103
22.5	0.283309941	4.91058E-06	5.59735E-06	0.285098867	1.1156991	3.32777E-05	2.3125E-06	1.1172196
23	0.28025727	4.85131E-06	5.47282E-06	0.282007709	1.1073405	3.26215E-05	0.000002261	1.108829
23.5	0.277204599	4.79203E-06	5.3483E-06	0.278916551	1.098982	3.19653E-05	2.2095E-06	1.1004383
24	0.274151928	4.73276E-06	5.22377E-06	0.275825394	1.0906234	3.1309E-05	0.000002158	1.0920476
24.5	0.271099257	4.67348E-06	5.09925E-06	0.272734236	1.0822648	3.06528E-05	2.1065E-06	1.083657
25	0.268046586	4.61421E-06	4.97472E-06	0.269643078	1.0739062	2.99965E-05	0.000002055	1.0752663
25.5	0.266567015	4.60821E-06	4.89217E-06	0.268138656	1.0725404	2.95493E-05	2.0205E-06	1.0738792
26	0.265087444	4.60221E-06	4.80962E-06	0.266634235	1.0711746	2.9102E-05	0.000001986	1.0724922
26.5	0.263607874	4.59621E-06	4.72707E-06	0.265129813	1.0698088	2.86548E-05	1.9515E-06	1.0711051
27	0.262128303	4.59021E-06	4.64452E-06	0.263625392	1.068443	2.82075E-05	0.000001917	1.069718

MOVES Ontario Emission Factor Look Up Table (kg/km)								
Speed (mph)	**Light-Duty Vehicles**				**Heavy-Duty Vehicles**			
	CO_2	**CH_4**	**N_2O**	**CO_2e**	**CO_2**	**CH_4**	**N_2O**	**CO_2e**
27.5	0.260648732	4.58421E-06	4.56197E-06	0.26212097	1.0670772	2.77603E-05	1.8825E-06	1.0683309
28	0.259169161	4.57822E-06	4.47942E-06	0.260616548	1.0657114	2.7313E-05	0.000001848	1.0669439
28.5	0.25768959	4.57222E-06	4.39687E-06	0.259112127	1.0643456	2.68658E-05	1.8135E-06	1.0655568
29	0.25621002	4.56622E-06	4.31432E-06	0.257607705	1.0629798	2.64185E-05	0.000001779	1.0641697
29.5	0.254730449	4.56022E-06	4.23177E-06	0.256103284	1.061614	2.59713E-05	1.7445E-06	1.0627826
30	0.253250878	4.55422E-06	4.14922E-06	0.254598862	1.0602482	2.5524E-05	0.00000171	1.0613956
30.5	0.253214391	4.60566E-06	4.09018E-06	0.254545922	1.0487581	2.52714E-05	0.000001686	1.0498913
31	0.253177904	4.6571E-06	4.03114E-06	0.254492981	1.037268	2.50187E-05	0.000001662	1.038387
31.5	0.253141417	4.70854E-06	3.9721E-06	0.254440041	1.0257779	2.4766E-05	0.000001638	1.0268827
32	0.25310493	4.75998E-06	3.91306E-06	0.2543871	1.0142878	2.45133E-05	0.000001614	1.0153784
32.5	0.253068443	4.81142E-06	3.85402E-06	0.25433416	1.0027977	2.42606E-05	0.00000159	1.0038741
33	0.253031956	4.86286E-06	3.79498E-06	0.25428122	0.9913076	2.4008E-05	0.000001566	0.9923698
33.5	0.252995469	4.9143E-06	3.73594E-06	0.254228279	0.9798176	2.37553E-05	0.000001542	0.9808655
34	0.252958982	4.96574E-06	3.6769E-06	0.254175339	0.9683275	2.35026E-05	0.000001518	0.9693612
34.5	0.252922495	5.01719E-06	3.61786E-06	0.254122398	0.9568374	2.32499E-05	0.000001494	0.957857
35	0.252886008	5.06863E-06	3.55882E-06	0.254069458	0.9453473	2.29972E-05	0.00000147	0.9463527
35.5	0.252753872	5.09839E-06	3.51403E-06	0.253924845	0.9441147	2.27496E-05	0.000001451	0.9451087
36	0.252621736	5.12816E-06	3.46924E-06	0.253780232	0.9428822	2.2502E-05	0.000001432	0.9438647
36.5	0.252489599	5.15793E-06	3.42444E-06	0.253635619	0.9416496	2.22544E-05	0.000001413	0.9426208
37	0.252357463	5.18769E-06	3.37965E-06	0.253491006	0.9404171	2.20068E-05	0.000001394	0.9413768
37.5	0.252225327	5.21746E-06	3.33486E-06	0.253346393	0.9391845	2.17592E-05	0.000001375	0.9401328
38	0.252093191	5.24723E-06	3.29007E-06	0.25320178	0.9379519	2.15116E-05	0.000001356	0.9388889
38.5	0.251961055	5.277E-06	3.24528E-06	0.253057167	0.9367194	2.1264E-05	0.000001337	0.9376449
39	0.251828918	5.30676E-06	3.20049E-06	0.252912554	0.9354868	2.10164E-05	0.000001318	0.936401
39.5	0.251696782	5.33653E-06	3.15569E-06	0.252767941	0.9342542	2.07688E-05	0.000001299	0.935157
40	0.251564646	5.3663E-06	3.1109E-06	0.252623328	0.9330217	2.05212E-05	0.00000128	0.933913
40.5	0.251330401	5.3844E-06	3.07637E-06	0.252379197	0.9317145	2.03323E-05	0.000001266	0.9325972

MOVES Ontario Emission Factor Look Up Table (kg/km)								
Speed (mph)	**Light-Duty Vehicles**				**Heavy-Duty Vehicles**			
	CO_2	**CH_4**	**N_2O**	**CO_2e**	**CO_2**	**CH_4**	**N_2O**	**CO_2e**
41	0.251096155	5.40251E-06	3.04183E-06	0.252135066	0.9304074	2.01434E-05	0.000001252	0.9312813
41.5	0.25086191	5.42061E-06	3.0073E-06	0.251890936	0.9291002	1.99545E-05	0.000001238	0.9299655
42	0.250627664	5.43872E-06	2.97276E-06	0.251646805	0.9277931	1.97656E-05	0.000001224	0.9286497
42.5	0.250393419	5.45682E-06	2.93822E-06	0.251402674	0.9264859	1.95767E-05	0.00000121	0.9273338
43	0.250159174	5.47493E-06	2.90369E-06	0.251158543	0.9251788	1.93878E-05	0.000001196	0.926018
43.5	0.249924928	5.49304E-06	2.86915E-06	0.250914412	0.9238716	1.91989E-05	0.000001182	0.9247021
44	0.249690683	5.51114E-06	2.83462E-06	0.250670282	0.9225645	1.901E-05	0.000001168	0.9233863
44.5	0.249456437	5.52925E-06	2.80008E-06	0.250426151	0.9212573	1.88211E-05	0.000001154	0.9220704
45	0.249222192	5.54735E-06	2.76555E-06	0.25018202	0.9199502	1.86322E-05	0.00000114	0.9207546
45.5	0.248616076	5.54174E-06	2.73823E-06	0.249567488	0.9170818	1.84783E-05	0.000001129	0.9178791
46	0.24800996	5.53613E-06	2.71091E-06	0.248952957	0.9142134	1.83245E-05	0.000001118	0.9150036
46.5	0.247403843	5.53052E-06	2.68359E-06	0.248338425	0.9113451	1.81707E-05	0.000001107	0.9121281
47	0.246797727	5.52492E-06	2.65627E-06	0.247723894	0.9084767	1.80168E-05	0.000001096	0.9092526
47.5	0.246191611	5.51931E-06	2.62895E-06	0.247109362	0.9056084	1.7863E-05	0.000001085	0.9063771
48	0.245585495	5.5137E-06	2.60163E-06	0.24649483	0.90274	1.77091E-05	0.000001074	0.9035016
48.5	0.244979379	5.50809E-06	2.57431E-06	0.245880299	0.8998716	1.75553E-05	0.000001063	0.9006261
49	0.244373262	5.50248E-06	2.54699E-06	0.245265767	0.8970033	1.74014E-05	0.000001052	0.8977506
49.5	0.243767146	5.49687E-06	2.51967E-06	0.244651236	0.8941349	1.72476E-05	0.000001041	0.8948751
50	0.24316103	5.49126E-06	2.49235E-06	0.244036704	0.8912665	1.70937E-05	0.00000103	0.8919996
50.5	0.24255936	5.46484E-06	2.46966E-06	0.243427685	0.8881688	1.69642E-05	1.02039E-06	0.8888959
51	0.241957689	5.43842E-06	2.44697E-06	0.242818665	0.8850711	1.68347E-05	1.01079E-06	0.8857923
51.5	0.241356019	5.41199E-06	2.42428E-06	0.242209646	0.8819733	1.67052E-05	1.00118E-06	0.8826886
52	0.240754348	5.38557E-06	2.40159E-06	0.241600626	0.8788756	1.65757E-05	9.91572E-07	0.8795849
52.5	0.240152678	5.35915E-06	2.3789E-06	0.240991607	0.8757779	1.64462E-05	9.81966E-07	0.8764813
53	0.239551008	5.33273E-06	2.35621E-06	0.240382588	0.8726801	1.63167E-05	9.72359E-07	0.8733776
53.5	0.238949337	5.30631E-06	2.33351E-06	0.239773568	0.8695824	1.61872E-05	9.62752E-07	0.8702739
54	0.238347667	5.27988E-06	2.31082E-06	0.239164549	0.8664847	1.60577E-05	9.53145E-07	0.8671703

MOVES Ontario Emission Factor Look Up Table (kg/km)								
Speed (mph)	**Light-Duty Vehicles**				**Heavy-Duty Vehicles**			
	CO_2	**CH_4**	**N_2O**	**CO_2e**	**CO_2**	**CH_4**	**N_2O**	**CO_2e**
54.5	0.237745996	5.25346E-06	2.28813E-06	0.238555529	0.863387	1.59282E-05	9.43538E-07	0.8640666
55	0.237144326	5.22704E-06	2.26544E-06	0.23794651	0.8602892	1.57987E-05	9.33931E-07	0.8609629
55.5	0.236659936	5.20794E-06	2.24656E-06	0.237455992	0.8586783	1.56756E-05	9.26181E-07	0.8593466
56	0.236175546	5.18884E-06	2.22768E-06	0.236965474	0.8570674	1.55525E-05	9.18431E-07	0.8577302
56.5	0.235691156	5.16975E-06	2.20881E-06	0.236474957	0.8554566	1.54293E-05	9.10681E-07	0.8561139
57	0.235206766	5.15065E-06	2.18993E-06	0.235984439	0.8538457	1.53062E-05	9.02931E-07	0.8544975
57.5	0.234722376	5.13155E-06	2.17105E-06	0.235493921	0.8522348	1.51831E-05	8.95181E-07	0.8528812
58	0.234237986	5.11246E-06	2.15217E-06	0.235003403	0.8506239	1.506E-05	8.87431E-07	0.8512648
58.5	0.233753596	5.09336E-06	2.13329E-06	0.234512885	0.849013	1.49369E-05	8.79681E-07	0.8496485
59	0.233269206	5.07426E-06	2.11441E-06	0.234022368	0.8474021	1.48138E-05	8.71931E-07	0.8480321
59.5	0.232784816	5.05516E-06	2.09553E-06	0.23353185	0.8457912	1.46906E-05	8.64181E-07	0.8464157
60	0.232300426	5.03607E-06	2.07665E-06	0.233041332	0.8441803	1.45675E-05	8.56431E-07	0.8447994
60.5	0.23240948	5.03651E-06	2.06059E-06	0.233145648	0.8474062	1.44573E-05	8.49831E-07	0.8480201
61	0.232518534	5.03696E-06	2.04452E-06	0.233249963	0.850632	1.43472E-05	8.43231E-07	0.8512408
61.5	0.232627588	5.0374E-06	2.02846E-06	0.233354279	0.8538578	1.4237E-05	8.36631E-07	0.8544615
62	0.232736642	5.03785E-06	2.01239E-06	0.233458594	0.8570836	1.41268E-05	8.30031E-07	0.8576822
62.5	0.232845696	5.03829E-06	1.99633E-06	0.23356291	0.8603094	1.40167E-05	8.23431E-07	0.8609029
63	0.23295475	5.03874E-06	1.98026E-06	0.233667226	0.8635352	1.39065E-05	8.16831E-07	0.8641236
63.5	0.233063804	5.03918E-06	1.9642E-06	0.233771541	0.8667611	1.37963E-05	8.10231E-07	0.8673443
64	0.233172858	5.03963E-06	1.94813E-06	0.233875857	0.8699869	1.36861E-05	8.03631E-07	0.870565
64.5	0.233281912	5.04007E-06	1.93207E-06	0.233980172	0.8732127	1.3576E-05	7.97031E-07	0.8737857
65	0.233390966	5.04052E-06	1.916E-06	0.234084488	0.8764385	1.34658E-05	7.90431E-07	0.8770064
65.5	0.233937349	5.0766E-06	1.90234E-06	0.234627799	0.8792692	1.33676E-05	7.84781E-07	0.8798332
66	0.234483733	5.11268E-06	1.88868E-06	0.235171109	0.8820998	1.32693E-05	7.79131E-07	0.8826601
66.5	0.235030116	5.14876E-06	1.87502E-06	0.23571442	0.8849305	1.31711E-05	7.73481E-07	0.885487
67	0.2355765	5.18484E-06	1.86136E-06	0.23625773	0.8877611	1.30729E-05	7.67831E-07	0.8883139
67.5	0.236122883	5.22092E-06	1.84771E-06	0.236801041	0.8905917	1.29747E-05	7.62181E-07	0.8911408

MOVES Ontario Emission Factor Look Up Table (kg/km)								
Speed (mph)	**Light-Duty Vehicles**				**Heavy-Duty Vehicles**			
	CO_2	**CH_4**	**N_2O**	**CO_2e**	**CO_2**	**CH_4**	**N_2O**	**CO_2e**
68	0.236669266	5.257E-06	1.83405E-06	0.237344352	0.8934224	1.28764E-05	7.56531E-07	0.8939677
68.5	0.23721565	5.29308E-06	1.82039E-06	0.237887662	0.896253	1.27782E-05	7.50881E-07	0.8967945
69	0.237762033	5.32916E-06	1.80673E-06	0.238430973	0.8990837	1.268E-05	7.45231E-07	0.8996214
69.5	0.238308417	5.36524E-06	1.79307E-06	0.238974283	0.9019143	1.25818E-05	7.39581E-07	0.9024483
70	0.2388548	5.40132E-06	1.77941E-06	0.239517594	0.904745	1.24835E-05	7.33931E-07	0.9052752
70.5	0.239686725	5.46355E-06	1.76715E-06	0.240347468	0.9090417	1.23993E-05	7.29031E-07	0.9095681
71	0.240518651	5.52577E-06	1.7549E-06	0.241177343	0.9133385	1.2315E-05	7.24131E-07	0.913861
71.5	0.241350576	5.588E-06	1.74265E-06	0.242007217	0.9176352	1.22307E-05	7.19231E-07	0.9181539
72	0.242182502	5.65022E-06	1.7304E-06	0.242837092	0.9219319	1.21464E-05	7.14331E-07	0.9224469
72.5	0.243014427	5.71244E-06	1.71814E-06	0.243666966	0.9262287	1.20621E-05	7.09431E-07	0.9267398
73	0.243846352	5.77467E-06	1.70589E-06	0.24449684	0.9305254	1.19778E-05	7.04531E-07	0.9310327
73.5	0.244678278	5.83689E-06	1.69364E-06	0.245326715	0.9348222	1.18935E-05	6.99631E-07	0.9353256
74	0.245510203	5.89912E-06	1.68139E-06	0.246156589	0.9391189	1.18092E-05	6.94731E-07	0.9396185
74.5	0.246342129	5.96134E-06	1.66913E-06	0.246986464	0.9434157	1.17249E-05	6.89831E-07	0.9439114
75	0.247174054	6.02357E-06	1.65688E-06	0.247816338	0.9477124	1.16406E-05	6.84931E-07	0.9482043

GHGenius Results for Alternative Fuel Vehicles

The table below presents the selected vehicle type and fuel pathways combinations and their emission rates incorporated in POETT. The results are generated from GHGenius 5.0d (S&T Squared Consultants Inc, 2019) for central Canada 2020 emission projections. Petrol Diesel 0.0015% S ICEV and gasoline oil ICEV are the baseline for HDV and LDV, respectively. To calculate the emission differences among fuel and vehicle technologies, an estimate in vehicle distance travelled is needed.

Table E-11: CO2 Emission Rate for Alternative Fuel Vehicles (g/km)

Vehicle Category	**Vehicle Type**	**Fuel Description**	**CO_2**			**CH_4**			**N_2O**			**CO_2e**		
			Vehicle Operation	**Fuel Production**	**Vehicle Material & Assembly**	**Vehicle Operation**	**Fuel Production**	**Vehicle Material & Assembly**	**Vehicle Operation**	**Fuel Production**	**Vehicle Material & Assembly**	**Vehicle Operation**	**Fuel Production**	**Vehicle Material & Assembly**
HDV	**Internal Combustion Engine**	**Petrol diesel 0.0015% S**	**1090.38**	**275.18**	**30.76**	**0.06**	**2.22**	**0.06**	**0.04**	**0.01**	**0.00**	**1104.07**	**334.41**	**32.36**
HDV	Internal Combustion Engine	Gasoline RFG30ppm S	1325.78	347.08	30.66	0.05	2.77	0.06	0.04	0.02	0.00	1338.37	421.91	32.25
HDV	Internal Combustion Engine	Gasoline NG	1325.78	392.84	30.66	0.05	4.79	0.06	0.04	0.02	0.00	1338.37	517.21	32.25
HDV	Internal Combustion Engine	Natural gas CNG	917.10	125.32	40.48	1.06	3.65	0.08	0.01	0.00	0.00	946.60	218.09	42.77
HDV	Internal Combustion Engine	LNG/Diesel LNG95/D5	802.20	127.88	35.38	0.83	3.30	0.07	0.04	0.01	0.00	835.25	212.06	37.37
HDV	Internal Combustion Engine	Hydrogen CH2(NG0/Water 100)	11.64	1027.04	42.84	0.01	4.35	0.08	0.04	0.12	0.00	23.59	1172.81	45.11
HDV	Internal Combustion Engine	LPG NGL51/RF49	1053.22	144.11	35.62	0.06	2.54	0.07	0.04	0.01	0.00	1066.99	209.27	37.57

Vehicle Category	Vehicle Type	Fuel Description	CO_2			CH_4			N_2O			CO_2e		
			Vehicle Operation	**Fuel Production**	**Vehicle Material & Assembly**	**Vehicle Operation**	**Fuel Production**	**Vehicle Material & Assembly**	**Vehicle Operation**	**Fuel Production**	**Vehicle Material & Assembly**	**Vehicle Operation**	**Fuel Production**	**Vehicle Material & Assembly**
HDV	Internal Combustion Engine	Diesel Hybrid	695.06	175.42	41.65	0.04	1.42	0.08	0.03	0.01	0.00	704.18	213.18	43.99
HDV	Internal Combustion Engine	Gasoline Hybrid	835.75	217.88	42.31	0.06	1.74	0.08	0.04	0.01	0.00	849.53	264.86	44.62
HDV	Internal Combustion Engine	EV	0.00	121.65	43.31	0.00	0.56	0.08	0.00	0.02	0.00	0.00	140.48	45.72
HDV	Internal Combustion Engine	PHEV Diesel	347.53	148.53	43.28	0.02	0.99	0.09	0.01	0.01	0.00	352.09	176.83	45.78
HDV	Internal Combustion Engine	PHEV Gasoline	417.87	169.77	43.75	0.03	1.15	0.09	0.02	0.01	0.00	424.77	202.67	46.24
HDV	Fuel Cells	Methanol Fuel Cell NG100/C0	655.24	309.85	38.88	0.00	2.65	0.08	0.00	0.01	0.00	655.24	380.45	41.16
HDV	Fuel Cells	CH2 Natural Gas Fuel Cell	0.00	776.44	40.10	0.00	2.74	0.08	0.00	0.01	0.00	0.00	848.95	42.44
HDV	Fuel Cells	CH2 Corn Ethanol Fuel Cell	0.00	555.34	40.10	0.00	0.00	0.08	0.00	0.61	0.00	0.00	737.34	42.44
HDV	Fuel Cells	CH2 Electricity Fuel Cell	0.00	473.44	40.10	0.00	2.01	0.08	0.00	0.06	0.00	0.00	540.63	42.44
HDV	Fuel Cells	CH2 LPG Fuel Cell	0.00	1167.04	40.10	0.00	3.02	0.08	0.00	0.02	0.00	0.00	1248.43	42.44
HDV	Fuel Cells	CH2 Gasoline Fuel Cell	0.00	379.69	40.10	0.00	2.54	0.08	0.00	0.03	0.00	0.00	452.68	42.44
HDV	Biomass Fuels	Biodiesel CanD100	11.21	-22.22	30.79	0.06	0.55	0.06	0.04	0.46	0.00	24.92	128.47	32.39
HDV	Biomass Fuels	Biodiesel SoyD100	11.21	121.02	30.79	0.06	0.41	0.06	0.04	0.37	0.00	24.92	242.49	32.39

Vehicle Category	**Vehicle Type**	**Fuel Description**	**CO_2**			**CH_4**			**N_2O**			**CO_2e**		
			Vehicle Operation	**Fuel Production**	**Vehicle Material & Assembly**	**Vehicle Operation**	**Fuel Production**	**Vehicle Material & Assembly**	**Vehicle Operation**	**Fuel Production**	**Vehicle Material & Assembly**	**Vehicle Operation**	**Fuel Production**	**Vehicle Material & Assembly**
HDV	Biomass Fuels	Ethanol E100 (corn)	9.89	506.83	36.10	0.17	-0.42	0.07	0.04	0.66	0.00	26.58	694.21	38.02
HDV	Biomass Fuels	Ethanol E100 (wheat)	9.89	426.46	36.10	0.17	-0.35	0.07	0.04	0.63	0.00	26.58	604.64	38.02
HDV	Biomass Fuels	Mixed Alcohol MA100 (wood)	9.88	30.52	36.10	0.17	0.14	0.07	0.04	0.14	0.00	26.57	75.19	38.02
HDV	Biomass Fuel Cells	Methanol M100 LFG	-0.49	54.39	38.88	0.00	3.37	0.08	0.00	0.01	0.00	-0.49	142.88	41.16
LDV	**Internal Combustion Engines**	**Gasoline Oil**	**129.91**	**35.68**	**23.71**	**0.02**	**0.30**	**0.05**	**0.02**	**0.00**	**0.00**	**136.12**	**43.82**	**25.21**
LDV	Internal Combustion Engines	Methanol M85 NG100/C0	115.94	52.28	23.81	0.01	0.44	0.05	0.01	0.00	0.00	118.54	64.08	25.32
LDV	Internal Combustion Engines	Mixed Alcohol MA85 (NG)	119.13	46.40	23.81	0.03	0.47	0.05	0.01	0.00	0.00	122.16	58.72	25.32
LDV	Internal Combustion Engines	LPG NGL51/RF49	117.20	17.45	23.80	0.02	0.31	0.05	0.02	0.00	0.00	123.40	25.33	25.32
LDV	Fuel Cells	Fuel Cell M100 NG100/C0	90.05	42.59	29.98	0.02	0.36	0.05	0.00	0.00	0.00	90.43	52.29	31.87
LDV	Fuel Cells	Fuel Cell CH2 NG100	0.00	96.09	26.83	0.00	0.34	0.05	0.00	0.00	0.00	0.00	105.07	28.44
LDV	Fuel Cells	CH2 Fuel Cell Methanol	0.00	49.29	26.83	0.00	0.35	0.05	0.00	0.00	0.00	0.00	58.89	28.44
LDV	Fuel Cells	CH2 Fuel Cell LFG Methanol	0.00	19.63	26.83	0.00	0.44	0.05	0.00	0.00	0.00	0.00	31.32	28.44
LDV	Fuel Cells	CH2 Fuel Cell Gasoline	0.00	46.99	26.83	0.00	0.31	0.05	0.00	0.00	0.00	0.00	56.02	28.44
LDV	Biomass Fuels	Ethanol E10 (corn)	118.96	40.28	23.77	0.02	0.28	0.05	0.01	0.01	0.00	121.79	49.69	25.28

Vehicle Category	Vehicle Type	Fuel Description	CO_2			CH_4			N_2O			CO_2e		
			Vehicle Operation	**Fuel Production**	**Vehicle Material & Assembly**	**Vehicle Operation**	**Fuel Production**	**Vehicle Material & Assembly**	**Vehicle Operation**	**Fuel Production**	**Vehicle Material & Assembly**	**Vehicle Operation**	**Fuel Production**	**Vehicle Material & Assembly**
LDV	Biomass Fuels	Ethanol E10 (W0/G100)	118.96	36.99	23.77	0.02	0.30	0.05	0.01	0.00	0.00	121.79	45.63	25.28
LDV	Biomass Fuels	RNG Blend CNG	29.88	12.16	25.66	0.47	-0.07	0.05	0.01	0.00	0.00	43.39	10.99	27.29
LDV	Biomass Fuels	Mixed Alcohol MA85 (wood)	20.11	10.50	23.77	0.03	0.07	0.05	0.01	0.01	0.00	23.13	16.49	25.27
LDV	Biomass Fuel Cells	EtOH (corn) Fuel Cell	-0.05	50.37	29.95	0.00	-0.04	0.05	0.00	0.07	0.00	-0.05	69.00	31.83
LDV	Biomass Fuel Cells	E100 (W0/G100) Fuel Cell	-0.05	15.40	29.95	0.00	0.14	0.05	0.00	0.02	0.00	-0.05	25.80	31.83
LDV	EV	EV Recharging EV's	0.00	20.68	32.81	0.00	0.09	0.05	0.00	0.00	0.00	0.00	23.89	34.66
LDV	EV	EV Nat. Gas	0.00	88.23	32.81	0.00	0.26	0.05	0.00	0.00	0.00	0.00	95.76	34.66
LDV	PHEV	EV50/50km Recharging EV's	41.63	22.49	26.72	0.01	0.14	0.05	0.00	0.00	0.00	42.38	26.71	28.47
LDV	PHEV	EV50/50km Nat. Gas	41.63	56.27	26.72	0.01	0.22	0.05	0.00	0.00	0.00	42.38	62.65	28.47

NIR Mobile Combustion Emission Factor

The table below presents the fuel-based emission factors for different modes of transport that are retrieved from 2014 NIR Annex 6 Table A6.1-13. As discussed in the background section, fuel-based GHG quantification is more accurate comparing to distance-based calculation. However, the fuel consumption information for construction projects or MTO owned vehicles are not currently collected by the agency. For now, the fuel-based GHG reduction component in the transportation tab are more suitable to quantify for a smaller scale where the fuel data is available. Agency wide estimation could be obtained when the vehicle fuel consumptions are collected by the agency in the future.

Table E-12: Fuel-based GHG Emission Factor for Different Modes of Transport

Mode of Transport	**Vehicle and Fuel Type**	**Emission Factors (g/L fuel)**			
		CO_2	**CH_4**	**N_2O**	**CO_2e**
Road Transport	Gasoline Vehicles Tier2	2307	0.14	0.022	2317.056
Road Transport	Gasoline Vehicles Tier1	2307	0.23	0.47	2452.81
Road Transport	Gasoline Vehicles Tier0	2307	0.32	0.66	2511.68
Road Transport	Gasoline Vehicles Oxidation Catalyst	2307	0.52	0.2	2379.6
Road Transport	Gasoline Vehicles Non-catalytic Controlled	2307	0.46	0.028	2326.844
Road Transport	LDGT Tier2	2307	0.14	0.022	2317.056
Road Transport	LDGT Tier1	2307	0.24	0.58	2485.84
Road Transport	LDGT Tier0	2307	0.21	0.66	2508.93
Road Transport	LDGT Oxidation Catalyst	2307	0.43	0.2	2377.35
Road Transport	LDGT Non-catalytic Controlled	2307	0.56	0.028	2329.344
Road Transport	HDGV Three-way Catalyst	2307	0.068	0.2	2368.3
Road Transport	HDGV Non-catalytic Controlled	2307	0.29	0.047	2328.256
Road Transport	HDGV Uncontrolled	2307	0.49	0.084	2344.282
Road Transport	Motorcycles Non-catalytic Controlled	2307	0.77	0.041	2338.468
Road Transport	Motorcycles Uncontrolled	2307	2.3	0.048	2378.804

Mode of Transport	**Vehicle and Fuel Type**	**Emission Factors (g/L fuel)**			
		CO_2	**CH_4**	**N_2O**	**CO_2e**
Road Transport	LLDV Advanced Control	2681	0.051	0.22	2747.835
Road Transport	LLDV Moderate Control	2681	0.068	0.21	2745.28
Road Transport	LLDV Uncontrolled	2681	0.1	0.16	2731.18
Road Transport	LLDV Advanced Control	2681	0.068	0.22	2748.26
Road Transport	LLDV Moderate Control	2681	0.068	0.21	2745.28
Road Transport	LLDV Uncontrolled	2681	0.085	0.16	2730.805
Road Transport	HDDV Advanced Control	2681	0.11	0.151	2728.748
Road Transport	HDDV Moderate Control	2681	0.14	0.082	2708.936
Road Transport	HDDV Uncontrolled	2681	0.15	0.075	2707.1
Road Transport	Natural Gas Vehicles	2	0.009	0.00006	2.14288
Road Transport	Propane Vehicles	1515	0.64	0.028	1539.344
Off-road	Off-road Gasoline 2-stroke	2307	10.61	0.013	2576.124
Off-road	Off-road Gasoline 4-stroke	2307	5.08	0.064	2453.072
Off-road	Off-road Diesel<19kW	2681	0.073	0.022	2689.381
Off-road	Off-road Diesel>=19kW,Tier1-3	2681	0.073	0.022	2689.381
Off-road	Off-road Diesel>=19kW,Tier4	2681	0.073	0.227	2750.471
Off-road	Off-road Natural Gas	2	0.0088	0.00006	2.13788
Off-road	Off-road Propane	1515	0.64	0.087	1556.926
Railways	Railways Train	2681	0.15	1	2982.75
Marine	Marine Gasoline	2307	0.22	0.063	2331.274
Marine	Marine Diesel	2681	0.25	0.072	2708.706
Marine	Marine Light Fuel Oil	2753	753	0.073	21599.754
Marine	Marine Heavy Fuel Oil	3156	156	0.082	7080.436
Marine	Marine Kerosene	2	0.25	0.071	29.408
Aviation	Aviation Gasoline	2560	2.2	0.23	2683.54
Aviation	Aviation Turbo Fuel	2365	0.029	0.071	2386.883
Renewable Fuels	Renewable Fuels Ethanol	1508	0	0	1508
Renewable Fuels	Renewable Fuels Biodiesel	2472	0	0	2472

Sample IRI and Section Distance for Ontario Road

The IRI data were collected from Pavement Condition for Provincial Highway Database. The data used cover pavement condition from 2017 January 1st to 2017 December 31st. The roughness in terms of IRI was selected as a baseline of the "improved" road, which is a user input. The distance and the IRI of the Ontario road allows a general estimation of the effect of the road improvement. For the change of fuel consumption regarding IRI, the tool does not differentiate between asphalt pavement and concrete pavement.

Table E-13: Sample IRI Value for Ontario Road Section

Highway	DIR	From Distance	To-Distance	IRI	Pavement Type
QEW	E	0.23	4.658	1.22	AC
QEW	W	0.23	4.658	1.09	AC
QEW	E	4.658	13.227	1.12	AC
QEW	W	4.658	13.227	1.05	AC
QEW	N	13.227	22.091	1.13	AC
QEW	S	13.227	22.091	1	AC
QEW	N	22.091	29.528	0.91	AC
QEW	S	22.091	29.528	0.91	AC
QEW	N	29.528	34.084	1.04	AC
QEW	S	29.528	34.084	0.65	AC
QEW	N	34.084	36.544	0.94	AC
QEW	S	34.084	36.544	1.18	AC

Sample Diesel Engine Repower Emission Rates

The emission rates presented below are taken from the advanced diesel truck/engine technologies tool from the CMAQ Emissions Calculator. The CO2e emission rates are generated from the national-scale activity for project year from 1989 to 2019 through MOVES. The rates, in kg/km, were used with the estimated average traveling distance to calculate the annual emission of the selected vehicle type. The GHG reductions, calculated from comparing 2019 model results with the results for the specified year, represents the impact of the diesel engine retrofit for each vehicle type. The complete table can be found in the transportation tab of POETT.

Table E-14: Sample Emission Rates for Trucks for Engine Technology from 1989 to 2019

Source Type	Vehicle Type	Model Year	Emission Rate (kg/mile)	Emission Rate (kg/km)
62	Combination Long-Haul	2019	1.604696384	0.997114584
61	Combination Short-Haul	2019	1.576932118	0.979862626
53	Single Unit Long Haul	2019	0.843899812	0.524376336

Source Type	**Vehicle Type**	**Model Year**	**Emission Rate (kg/mile)**	**Emission Rate (kg/km)**
52	Single Unit Short Haul	2019	0.897429639	0.557638311
62	Combination Long-Haul	2018	1.604700472	0.997117124
61	Combination Short-Haul	2018	1.576931025	0.979861946
53	Single Unit Long Haul	2018	0.843896986	0.524374579
52	Single Unit Short Haul	2018	0.89742891	0.557637858
62	Combination Long-Haul	2017	1.604684572	0.997107244
61	Combination Short-Haul	2017	1.576929936	0.97986127
53	Single Unit Long Haul	2017	0.858677238	0.533558625
52	Single Unit Short Haul	2017	0.915990276	0.569171384

Glossary

Cold In-Place Recycling (CIR): a pavement rehabilitation process that typically used on the existing asphalt layer (usually less than 125mm). The process involves milling the existing pavement, crushing the recycled material, mixing the emulsion or other agents and additives into the recycled material, and paving the material back to the existing section. To ensure the pavement after the rehabilitation can support the expected traffic, a HMA layer is typical placed over the CIR material.

Cold In-Place Recycling With Expanded Asphalt Material (CIREAM): a pavement rehabilitation process that used on the existing asphalt layer. The process of CIREAM is similar to that of the cold-in-place recycling, but instead of using emulsified asphalt (emulsion), expanded asphalt mixture is used. The process typically have a shorter curing period comparing to cold in-place recycling.

Diameter at Breast Height (DBH) : a standard method of expressing the diameter of a tree. The value is commonly measured at 1.3m to 1.5m above ground, varying in practices among different countries, and can be used to estimate the biomass of the tree species.

Greenhouse Gas (GHG): gas that contributes to the greenhouse effect by absorbing infrared radiation. This calculator only count CO2, CH4, N2O, the most common contributors.

Emission Factor (EF): a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (EPA Website). EF in this calculator represent the greenhouse gas emission for per unit activity.

Full Depth Reclamation (FDR): A pavement rehabilitation that works on the full thickness of the asphalt pavement and a certain depth of the underlying base course. Because of the deeper treatment, the technique can address relatively shallow subgrade stability. The process involves pulverizing the pavement to a predetermined depth, using chemical or bituminous stabilization, and placing the treated material back to the road. A HMA layer could be added to further strengthen the pavement after the reclaimed area is cured.

Highway Costing System (HiCo): HiCo is the application for MTO to estimate the costs of building and maintaining roads and highways. The system contains the average of the lowest three bidder and helps with the agency to estimate the values of the work project. For the greenhouse gas tool particularly, HiCo system is one of the better sources that provide contract number, item unit, and quantity. HiCo quantity data can be retrieved from direct copy and pasting or by generating HiCo report, which shows all past quantities for one HiCo active item.

Hot In-Place Recycling (HIR):. A pavement rehabilitation method that addresses shallow surface distress (25mm to 50mm). Heater scarification, repaving, and remixing are three basic HIR construction process (pavement interactive). Each process generally involves removing or heating the pavement surface, mixing with rejuvenating agent, placing the recycled material, and then adding a thin HMA overlay for the structure. Hot In-Place Recycling is not common in Ontario due to equipment limitations.

Idle Reduction: Technologies and Practices that reduce the amount of an engine idles (US Department of Energy). In POETT, technologies covered are auxiliary power unit, fuel operated heater and engine off.

Supplementary Cementing Materials (SCMs): SCMs are commonly added to the concrete to reduce the material’s environmental footprint. For this study, blast furnace slag, steel slag, class C fly ash and Class F fly ash are considered. Using the SCMs individually or in combination allow the materials contribute to the concrete properties through hydraulic or pozzolanic activities