CARBON FOOTPRINT FOR HMA AND PCC PAVEMENTS

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16. Abstract

Motivated by the need to address challenges of global climate change, this study develops and implements a project based life cycle framework that can be used to estimate the carbon footprint for typical construction work-items found in reconstruction, rehabilitation and Capital Preventive Maintenance (CPM) projects. The framework builds on existing life cycle assessment methods and inventories. The proposed framework considers the life cycle emissions of products and processes involved in the raw material acquisition and manufacturing phase, and the pavement construction phase. It also accounts for emissions due to vehicular use and maintenance operations during the service life of the pavements. The framework also develops and implements a method to calculate project level construction emission metrics. Finally, the research provides a web-based tool, the Project Emission Estimator (PE-2) that can be used to benchmark the CO_2 footprint of highway construction projects. In conclusion, the research suggests ways of implementing the proposed framework within MDOT to help reduce the CO_2 footprint of highway construction projects.

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1. EXECUTIVE SUMMARY

Motivated by the need to address challenges of global climate change, this study develops and implements a project based life cycle framework that can be used to estimate the carbon footprint for typical construction work items found in reconstruction, rehabilitation and Capital Preventive Maintenance (CPM) projects. The framework applies existing life cycle assessment methods and inventories using data collected from 14 highway construction, rehabilitation and maintenance projects in the State of Michigan. Figure 1-1 conceptualizes the solution to the problem statement setting the scope of this report. The carbon footprint for each of the projects was calculated in terms of CO_2 equivalents of greenhouse gas (GHG) emissions. The primary emissions include life cycle emissions of products and processes involved in the raw material acquisition and manufacturing phase, and the pavement construction phase. The secondary emissions include emissions due to vehicular use and maintenance operations during the service life of the pavements. The vehicular use emissions were estimated using the MOVES simulator, and pavement maintenance schedules were estimated using sample pavement performance data. A method to calculate project level construction emission metrics was developed and illustrated using the observed projects. Finally, a web based tool, the Project Emission Estimator (PE-2), was developed based on the emissions calculated from the observed project. It includes an emission estimator tool that can be used to benchmark GHG life cycle emissions for highway reconstruction, rehabilitation and preventive maintenance projects. In conclusion, the research suggests ways of implementing the proposed framework within MDOT to help reduce the CO_2 footprint of highway construction projects.

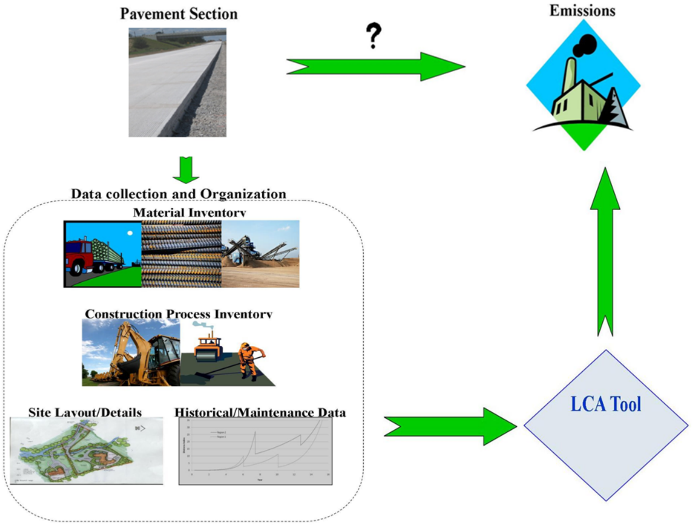

Figure 1-1: Conceptual Solution to Problem Statement

2. INTRODUCTION

The challenge of global climate change has motivated state transportation agencies involved in the construction and maintenance of transportation infrastructure to investigate strategies that reduce the life cycle greenhouse gas (GHG) emissions associated with the construction and rehabilitation of highway infrastructure [1]. In this study, we propose to measure the greenhouse gas (GHG) emissions for reconstruction and rehabilitation projects, including pertinent Capital Preventative Maintenance Program (CPM) treatments of pavements in the State of Michigan. The aim of this research is to calculate the carbon footprint, defined as a composite measure of all GHG emissions expressed as equivalents of carbon dioxide emissions, and to develop a tool that can be used to benchmark and estimate footprints to effectively reduce emissions in future projects. The underlying methodology uses a life cycle assessment (LCA) approach that accounts for emissions during the material acquisition and manufacturing, construction and use phases[1] of different pavements.

2.1. Goal and Objectives

The goal of this research is to develop a project-based LCA framework that will enable state and local agencies to support sustainable decision-making by investigating strategies that reduce GHG emissions associated with reconstruction, rehabilitation and CPM projects. The framework considers the product, process and service components of a pavement's life cycle. It includes a set of metrics and methods that can be applied to monitor and control GHG for all or some representative control sections through their life cycle. Decision-makers can use these metrics to develop strategies that reduce net environmental impacts and GHG emissions. The objectives of this research are as follows:

Theoretical Framework Development

Develop a project based LCA approach that accounts for the products and processes that support the construction of a highway project, and the services that the highway provides through its use life. The framework consists of the following components:

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[1] Please note that hence forth in this document the term 'use phase' of a pavement is used to mean the service life of the pavement.

1. A *site data collection and organization method* to account for emissions associated with all material and equipment *products* and construction *processes* used, in constructing and maintaining a highway section. Products include all material resources (measured by weight and/or volume), and equipment (quantity and hours of use) used on site. Processes include efficient construction schedules, site constraints, distances travelled to and on construction sites, and pavement maintenance schedules. The product and process data account for emissions through the materials mining and manufacturing, construction, and maintenance phases. As most of this data is to be collected directly from construction sites, the data collection method is based on current project documentation approaches to minimize the burden of implementation.
2. A *simulation-based approach* to estimate the vehicular emissions during the *service* life of a pavement.
3. Project life cycle *metrics* that can be used to assess and benchmark project emissions based on a comprehensive literature survey of LCA metrics and methods as applied to pavements.

Implementation

Implement the framework developed for 14 construction projects in Michigan.

Toolkit development

Based on the data gathered through the implementation of the framework develop:

1. A web-based inventory of all collected data – allowing remote access via a web-based interface.
2. A web-based toolkit and associated recommendations on how the established carbon footprints could be used to develop green construction standards for HMA and PCC pavements.

This report describes the supporting literature and theoretical foundations of the proposed project life cycle based framework. It explains the implementation of the methods described in the framework to collect and organize construction and rehabilitation data from 14 MDOT pavement re-construction, rehabilitation, and maintenance projects throughout the State of Michigan.

Further, it uses the observed data to estimate project GHG emissions and provides a web-based tool that can be used to benchmark and reduce emissions.

2.2. Significance

The significance of this research lies in the challenges resolved and the methodology developed, listed as follows:

1. **Project Life Cycle Based Approach:** Existing applications of LCA methods [2-7] to pavements, while significant, have advocated the comparison of concrete and HMA pavements. These studies have often had conflicting results because of an inconsistent definition of system boundaries (varying emphasis in each study on designs considered and phases involving materials installed, construction equipment used, and consideration of use); and use of functional units (such as emissions per lane mile) that may be misleading. This research effort does not use LCAs to compare alternative pavement materials. Instead, it extends LCA methods to develop and implement *project based* life cycle metrics and methodology to benchmark, monitor and reduce life cycle emissions for pavement construction projects. The project based approach addresses various problems with conflicting system boundaries and choice of appropriate functional units. It also supports decision-making aimed at reducing emissions on any given highway construction project, regardless of pavement type.
2. **Direct Site Observation:** It is difficult to arrive at exact metrics that can be reliably used to support decision-making because of the uncertain and non-prototypical nature of pavement construction processes, and the wide variation in site conditions and use patterns. Therefore, to be effective, the study used directly observed construction and maintenance data from 14 construction projects so that local and regional variations that influence pavement construction processes, long-term performance and maintenance needs, can be accounted for.
3. **Data Organization:** Given the large volume of construction and maintenance data that was collected, a comprehensive data inventory had to be created. A web-based interface was implemented so that the data can be easily viewed, analyzed and possibly shared by various stakeholders.

4. **Framework Development:** Finally, while the research was conducted using directly observed data, the trends and metrics were observed from a relatively small sample of 14 projects. Given the scope of the research project and the diversity of project types, it was difficult to collect datasets large enough to support statistically significant conclusions. Therefore, the emphasis of this research was on the development and implementation of a methodological framework that can be used to monitor, benchmark, and reduce GHG emissions. It is expected that if MDOT chooses to implement the recommended methods over a period, they will need to implement an ongoing data collection plan that will support recommendations for sustainable construction.

The long-term significance of this research is that it will enable decision-makers to ask and answer questions that are critical to identifying ways of improving construction operations, processes and design selection methods that reduce long term emissions and environmental impacts. A recent survey of pavement performance models [8] most highly recommended the models that accounted for heterogeneity, possibly arising from differences in environmental conditions. They also found that averaged behavior data was not representative partly because system behavior shows auto-correlation – emphasizing the need to base prediction models on actual historical performance. In keeping with their findings, we describe a method to collect and integrate historical and current construction and maintenance data of a highway network across different life cycle phases. It will enable researchers and decision-makers to analyze the behavior of alternative designs using historical data that reflects on-site conditions. The research takes advantage of existing methods of calculating GHG emissions, while furthering the goals of context sensitive performance analysis. This will further the integration between pavement performance, pavement life cycle cost analysis and environmental impact assessment.

2.3. Deliverables

1. Report construction inventories for 14 highway reconstruction, rehabilitation and CPM projects observed over a period of two summers
2. Report estimated emission factors for construction materials and equipment used
3. Report estimated emission factors for use phase of highways
4. Provide MDOT a tool to assess emissions through the different life cycle stages of a pavement

5. Provide recommendations for developing construction standards and specifications

The final deliverable has the following principal components:

- A framework to account for the product, process and service components of a pavement life cycle, including a comprehensive data collection and organization plan
- An inventory of carbon emissions of product and process components of 14 surveyed projects. The inventory will be developed by implementing the proposed framework. The carbon footprint information will be classified by life-cycle stages, by construction processes and by operation types
- An assessment of the life-cycle carbon footprint information along with the development of metrics that can be used to benchmark emissions for future projects
- A web-based tool than can be used to estimate and benchmark carbon emissions for highway construction projects towards identifying emission reduction strategies

The main result expected from this research is the development and limited implementation of a methodology to develop project inventories of highway construction and maintenance projects, and estimate GHG emissions classified by life-cycle stages, construction processes and operations.

3. BACKGROUND LITERATURE REVIEW

In this chapter, we provide an introduction to ideas in LCA and their applications to the field of pavements. In addition, we also list a set of available tools that address the question of making pavements more sustainable.

3.1. Life Cycle Assessment (LCA)

Life cycle assessment methodology is used to analyze the environmental impacts of a product through all its life cycle stages. An ideal life cycle assessment accounts for all life cycle phases of a product or process, including: raw material mining and extraction, material processing and manufacturing, use, maintenance and repair, and end of life/disposal. LCA is used to assess the environmental impacts of a product or process and has commonly been used as an assessment tool in the manufacturing sector. An LCA study involves the following steps: (i) development of goal and scope of the study, (ii) development of an exhaustive inventory of all energy and material inputs, and the environmental outputs and emissions associated with each life cycle phase, (iii) analysis of relative impacts of specific identified materials or processes, and (iv) development of an appropriate interpretation of the analysis to support policy and decision-making. This process ensures that all the environmental burdens associated with each of the life cycle phases are accounted for, and the most crucial impacts identified for mitigation.

The International Standards Organization (ISO) have developed the principles, framework, and guidelines necessary for conducting an LCA [9, 10]. These methods are part of the ISO 14000 series on Environmental Management, and are specifically discussed in ISO 14040:2006 and 14044:2006. When developing the goal and scope of an LCA, the guidelines require the establishment of a *system boundary* and appropriate *functional unit*. A system boundary defines all the processes directly or indirectly associated with a product that are to be included in the analysis. In defining the functional unit of a product or system being studied, its function must be established by keeping in mind the expected characteristics of its service and/or performance. Based on the function a unit is derived that can be used to normalize the associated inputs and outputs, providing a reference for comparison with similar products. It is important to note that when using an LCA to compare two products, units of each product must have equivalent function. Consider, for example, the application of LCA methods to differentiate between a plastic cup and a paper cup. The products are comparable as they have similar usage, and are not significantly impacted by the context in which they are used. Most importantly, the identity of the product and the functional unit for comparison does not change during the course of its lifetime. Similarly, when comparing the life cycle impacts of two different types of bulbs, it is important to compare bulbs that have the comparable life times and similar luminosity. In defining the system boundary and the functional units, various assumptions have to be made, which should be clearly outlined and explained.

3.2. Pavement LCA

Pavement LCA applications and methodologies have their roots in the application of traditional LCA methodologies that are typically product driven. Pavements, on the other hand, cannot be easily defined as products. In practice, it is difficult to assume a pavement section to be a well-defined product with a standard functional unit. Unlike typical products that have clearly defined functional lives, the functional lives of pavement control sections are less predictable. Even when two comparable pavement sections are constructed at the same time, they rarely undergo the same maintenance and rehabilitation during their functional lives. Often different parts of the same section tend to perform differently due to regional usage and environmental conditions (varying freeze thaw cycles). This results in incomparable functionality, service lives and impacts.

Most of the current research efforts in pavement LCAs emphasize prescriptive approaches that present general conclusions regarding the comparative impacts of pavement materials [11-14] based on estimated inventories and/or case studies. They have significantly furthered the field by illustrating the application of life cycle assessment methods. However, their conclusions are limited by explicit assumptions in the control sections selected for comparison, and implicit assumptions of uniform climate conditions, usage patterns and environmental contexts, such as access to raw materials and availability of local water resources. Regional and local variations are difficult to codify in these approaches, as they emphasize comparisons of alternative designs across assumed uniform conditions, rather than supporting context sensitive decisions that reduce long-term impacts. Often, there is limited consideration of construction process information, such as the type of equipment used and the impact of site location and layout when considering the total life cycle emissions.

There has also been some disagreement on an appropriate functional unit. While the measures per lane mile have been commonly used, they are not completely representative. As the size of projects scale, such measures are subject to statistical smoothening resulting in flawed results. This is partly because, as the number of lane miles increase, the material and equipment used for each additional lane mile do not scale linearly for a given project or uniformly across projects. As an alternative, a recent study [15] has used representative panels[2] of typical concrete and asphalt pavements to compare emissions of concrete and asphalt pavements. While not a perfect functional unit, this provides an approach to compare the emissions from a cluster of materials that are required to build a concrete panel and an asphalt panel respectively, and is arguably less sensitive to scale.

A lack of consensus on these underlying definitions has plagued the pavement LCA literature. A recent review of pavement LCAs, by the Portland Concrete Association (PCA) [16], have reported inconsistencies due to functional units, improper system boundaries, imbalanced data for asphalt and cement, use of limited inventory and impact assessment categories, and poor overall utility.

Efforts at developing decision-support frameworks, to inform agency and stakeholder decisions, also remain fragmented. Prescriptive LCA frameworks have been developed to support decision-making between broad pavement classes [17, 18]. However, the assumptions underlying such frameworks often make them unsuitable for supporting policies that aim to reduce long-term GHG. They often lead to inaccurate generalizations that cannot be used to support context sensitive policy. In addition, they leave limited room for monitoring, and/or rewarding continuous improvement in construction planning processes aimed at reducing GHG. Subjective point based systems, such as GreenRoads™ [19], have been considered for reducing construction emissions. While such systems are easier to implement, they lack appropriate verification. Hence, the current body of work exhibits methodological deficiencies and incompatibilities that serve as barriers to the widespread utilization of LCA by pavement engineers and policy makers [16].

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[2] Panels are specified lengths of pavement sections. For example, consider a 12’x15’x11” panel of a jointed plain concrete pavement.

In view of these limitations, the University of California Pavement Research Center (UCPRC) and the University of California Institute of Transportation Studies held a pavement life cycle assessment workshop to establish the common principles and framework that should be used in conducting a pavement life cycle assessment [20]. An important deliverable of this workshop was the Pavement LCA guidelines document [21]. It outlines the framework, system boundary assumptions, and assessment of data models and documentation requirements, along with a detailed pavement LCA checklist. The guidelines can be used in accordance to the ISO LCA standards and provide a project-level LCA perspective.

The research in this report builds on this pavement LCA framework and explicitly uses the checklist. The application of the checklist in this research is outlined in Appendix A: MDOT Pavement LCA Checklist. However, it avoids using LCAs to compare pavement materials; instead, it uses LCA methodology to calculate GHG emissions for particular projects. Therefore, the research uses a project based LCA approach to calculate GHG of highway construction products, processes and the service life. The approach takes advantage of existing methods of calculating GHG emissions, while emphasizing the collection of project data through the construction phase of the pavement life cycle. It particularly accounts for the emissions from (i) the mining, manufacturing and production of the material products (materials and equipment) used to construct the pavement, (ii) the processes involved during the construction and maintenance of the pavement, and (iii) the service life/use phase of the pavement. In doing so, the research builds on methods and metrics in the literature that apply LCA to different stages of the pavement's life.

3.3. Available Tools

This section reviews the available tools that can be used to assess GHG emissions pertaining to different life cycle phases of highway control sections. With industry facing pressures to market new innovations [22], Government-University-Industry partnerships and collaborations have played an important role in the development of many of these tools; fostering innovation and technology transfer between industry and academia [22]. Most of the tools surveyed have had limited implementation and their eventual success may depend on state and federal policies. However, with pending climate and energy legislation in the Unites States, they may be responsive to emergent policy requirements for agencies and contractors.

Table 3-1 highlights the current state of practice regarding tools that can be used to estimate GHG emissions and *can specifically be applied to highway sections*.

Table 3-1: Survey of GHG Impact Assessment Tools

Institution Type	GHG Impact Tools		
	Life Cycle Inventory/ Assessment	Emission Calculators	Rating/Point Systems
Government	NREL LCI	SGEC Tool	FHWA Self-Eval Tool
Academic/State	EIO-LCA PaLATE	Road Construction Emissions Model GreenDOT	Greenroads™ GreenLITES I-LAST
Industry	SimaPro AsPECT	CHANGER e-CALC AggRegain	Greenroads™

3.3.1. Governmental Tools

Impact tools provided by governmental organizations that can be used in assessing life cycle GHG impacts of highway controls sections include:

1. National Renewable Energy Laboratory (NREL) Life Cycle Inventory
    - Organization: U.S. Department of Energy
    - This Life Cycle Inventory database can be used by LCA practitioners to assess the environmental impacts of energy and material flows [7]. The database is useful when assessing emission metrics related to the materials and transportation impacts of highway control sections. However, data is limited when trying to quantify all materials that are commonly used in roadway sections and since carbon dioxide emissions are not a reporting requirement in the U.S., in some cases, materials are not assigned a CO_2 impact.
    - Application to Highway Life Cycle GHG Assessment
        - Material Acquisition/Extraction
        - Upstream manufacturing impacts of fuel combusted in equipment
        - On-Highway Transportation Impacts

2. Simplified GHG Emissions Calculator
    - Organization: U.S. Environmental Protection Agency
    - The simplified GHG emissions calculator is an MS Excel-based spreadsheet that aims to help organizations estimate their GHG emissions from stationary and mobile combustion sources, purchased electricity, refrigeration and air conditioning [23].
    - Application to Highway Life Cycle GHG Assessment
        - Off-Road Transportation and Equipment Impacts
        - On-Highway Transportation Impacts
        - On-Site Electricity Use
3. Sustainable Highways Self-Evaluation Tool
    - Organization: Federal Highway Administration (FHWA)
    - The Sustainable Highways Self-Evaluation Tool attempts to encompass sustainability aspects into highway and other roadway projects and programs using a self-evaluated scorecard [24]. The system is applied to the entire project from planning to operations, in which project score is awarded points for performing a LCA. Also points are awarded to projects that reduce GHG emission throughout construction, such as reducing fossil fuel use, having off-road equipment meeting Tier 4 standards, and encouraging the use of recycled materials.
    - With scoring systems, it is possible to account for all highway life cycle GHG emissions.
    - Recognizes approaches and strategies to assessing life cycle GHG emissions using; PaLATE, CHANGER, NREL, and EIO-LCA. All are discussed in this chapter.

3.3.2. Academic Tools

Impact tools provided by state agencies and/or academic organizations that can be used in assessing various life cycle GHG impacts of highway controls sections include:

4. Economic Input-Output Life-Cycle Assessment (EIO-LCA)
    - Organization: Carnegie Mellon University

  - The EIO-LCA model is an analysis model that defines the scope and number of environmental effects quantified in a LCA. It estimates the economic contribution, resource requirements and environmental emissions for a particular product, service, or activity based on economic transactions [25]. It is unable to estimate project specific processes such as on-site transportation impacts.
  - Application to Highway Life Cycle GHG Assessment
    - Material Acquisition/Extraction impacts
    - Upstream manufacturing impacts of fuel combusted in equipment
    - Upstream manufacturing impacts of the construction equipment
5. Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE)
   - Organization: Consortium of Green Design at the University of California, Berkeley
   - PaLATE is an excel-based LCA tool that uses life cycle costing metrics and environmental parameters from EIO-LCA to assess GHG emissions from pavement materials. It can also estimate GHG emissions from construction and hauling equipment used on the project [26].
   - Application to Highway Life Cycle GHG Assessment
     - Material Acquisition/Extraction Impacts
     - Off-Road Transportation and Equipment Impacts
     - Batch Plant and Secondary Material Processing Impacts
6. Road Construction Emissions Model
   - Organization: Sacramento Metropolitan Air Quality Management District
   - The Road Construction Emission Model is an excel-based emission calculator that estimates air emission due to road construction activities based on construction period, hauling emissions, commuter emissions, and off-road equipment emissions [27].
   - Application to Highway Life Cycle GHG Assessment
     - Off-Road Transportation and Equipment Impacts
7. GreenDOT
   - Organization: National Cooperative Highway Research Program (NCHRP)

- GreenDOT is an excel-based emission calculator designed for state DOTs to assess emissions from highway construction, and maintenance activities. It attempts to estimate the carbon dioxide emissions from electricity use, on-road fleets, off-road equipment and materials used [15]. The product was developed as part of NCHRP Report 25-25 Task 58.
- Application to Highway Life Cycle GHG Assessment
    - Material Acquisition/Extraction impacts
    - Electricity Use
    - On-Road Transportation Impacts
    - Off-Road Transportation Impacts

8. Greenroads™
    - Organization: University of Washington
    - Greenroads™ is a highway sustainability rating system that applies to the design and construction of highways [28]. The system works with a repository of "best practices" and assigns them a point value when implemented on the project design and construction. Regarding GHG emissions in the construction process, the system gives credit if a LCA is conducted, and also gives credits to projects that reduce GHG emission throughout construction. For example, reducing fossil fuel use, having off-road equipment meeting tier 4 standards, and encouraging the use of recycled materials.
    - With rating systems it is possible to account for all highway life cycle GHG emissions
9. GreenLITES
    - Organization: New York Department of Transportation (NYDOT)
    - GreenLITES is a certification program used internally by NYDOT. It certifies their transportation project design and operations are incorporating sustainable practices by assessing them certified, silver, gold, and evergreen certifications [29]. In addressing GHG emissions from construction and rehabilitation operations, the program encourages the reuse and recycling of materials that are preferably obtained locally. The program also encourages the reduction of the

    department’s carbon footprint along with reducing petroleum and energy use on the project.
    - With rating systems, it is possible to account for all highway life cycle GHG emissions

10. Illinois - Livable and Sustainable Transportation Rating System (I-LAST)
    - Organization: Illinois Department of Transportation
    - I-LAST is a sustainability performance metric system designed to incorporate sustainable and livable concepts in Illinois highway projects [30]. Using a comprehensive list of best practices and methods, projects are rated using the programs scorecard. The program assesses GHG emissions by promoting mass transit in the community planning stages, using locally produced materials, recycled and secondary materials used in design and construction, and encourages non-motorized travel use.
    - With rating systems, it is possible to account for all highway life cycle GHG emissions

3.3.3. Industry Tools

Impact tools provided by industry that can be used in assessing various life cycle GHG impacts of highway controls sections include:

11. SimaPro
    - Organization: Pre’ Consultants
    - SimaPro is a process-based LCA software tool that assesses the environmental impact of products and/or processes [6]. It uses a life cycle approach to assess environmental impacts. Materials and processes are assessed using the software’s various life cycle inventory databases. Specific interactions relating to the chain of processes that comprise the final material and/or process must be itemized separately to build the overall life cycle.
    - Application to Highway Life Cycle GHG Assessment
        - Material Acquisition/Extraction impacts
        - Electricity Use
        - Upstream manufacturing impacts of fuel combusted in equipment

12. Asphalt Pavement Embodied Carbon Tool (AsPECT)
    - Organization: UK's Transport Research Laboratory (TRL)
    - AsPECT is a LCA used in the United Kingdom to assess embodied energy and emissions from asphalt used in highways [31]. In can assess asphalt pavement material production emissions, emissions from placing the material, and batch plant emissions associated with producing the asphalt mixture.
    - Application to Highway Life Cycle GHG Assessment
        - Asphalt Batch Plant Emissions
        - Material Production Emissions (Asphalt materials)
        - Compacting and laying emissions
13. Calculator for Harmonized Assessment and Normalization of GHG Emissions for Roads (CHANGER)
    - Organization: International Road Federation
    - CHANGER is a tool that estimates the GHG emissions from pavement materials, transportation of materials, electricity use, and construction equipment [32]. This is a commercial product and must be purchased.
    - Application to Highway Life Cycle GHG Assessment
        - Electricity Use
        - Fuel Use
        - Material Production Emissions
        - Transportation Impacts
        - Off-Road Equipment Use
14. e-CALC
    - e-CALC is an excel-based program that estimates GHG emissions from 4 types of construction methods; underground utility construction, horizontal directional drilling, pipe bursting, open-cut with excavators or backhoes and open-cut by trenching[33]. It estimates on-site equipment and hauling emissions associated with construction projects.
    - Although these may not specifically apply to highway construction, the information modeling capabilities are useful for application to highway life cycle GHG assessment in the following ways:

        - On-Site Construction Equipment Impacts
        - On-Site Hauling Impacts

15. AggRegain CO_2 Tool
    - Organization: Waste & Resources Action Program (WRAP)
    - The AggRegain CO_2 Tool is CO_2 calculator utilized through excel in which emissions can be assessed by investigating the use of recycled and secondary materials in bitumen bound, concrete, hydraulically bound, unbound construction applications [34]. It outputs savings by selecting these various products to be used in the construction project.
    - Application to Highway Life Cycle GHG Assessment
        - Material Production
        - Transportation Impacts
        - Secondary (Composite) Material Production

3.4. Assessment of Tools

The tools highlighted above represent three areas defining tools related to pavement sustainability: Life Cycle Inventory, Impact (GHG) Calculators, and Rating/Point Systems. Each of these is used to support a pavement LCA in different ways. For example, Life Cycle Inventory tools are used to quantify the inputs into the system, Impact calculators establish the magnitude of outputs investigated, and finally, Rating/Point Systems can illustrate and document sustainable approaches exemplified in the life cycle. A review of the tools available illustrate that different approaches can be used to account for the different phases of the construction project. However, as outlined, each tool lacks the ability to account for all phases of the highway construction phase. Therefore, it may be necessary to use a combination of these tools to address the entire construction phase. In addition, there is a shortage of construction project inventories. The research described here attempts to integrate project-level construction data with a combination of economic and process LCA based emission factors to estimate GHG emissions. The approach taken here is to account for the project phase using a combination of these tools with data obtained directly from construction and rehabilitation projects to estimate the GHG emissions. **This also provides the first step in developing emission reduction strategies to influence sustainable decision-making.**

4. PROJECT BASED LCA FRAMEWORK

The most important contribution of this research is the development of the project based LCA framework. In this chapter, the underlying theory and methods supporting the framework are discussed. The next chapter describes its implementation.

4.1. System Definition

The goal of the proposed framework is as follows:

1. Calculate project GHG emissions
2. Develop an inventory of construction processes and product footprints that can be used to benchmark project emissions
3. Provide a tool that can estimate emissions for future projects
4. Serve as a platform for identifying emission reduction best practices

The stakeholders of this study are state agencies such as the Michigan Department of Transportation (MDOT) and construction contractors. It is expected that an implementation of this framework will allow the stakeholders to calculate project emissions, and identify ways of reducing project GHG emissions. Agencies can use the framework to get a life cycle perspective of emissions from specific highway sections, including observed emissions from construction, maintenance, rehabilitation projects, and an estimate of emissions during the use phase. Contractors can use it to estimate GHG emissions for specific construction operations – particularly with the goal of identifying alternative materials or improvements in construction processes to reduce their emissions.

Based on the objectives of the proposed framework, the boundaries of the system being studied in this framework are:

1. Product components: This considers the impact of the pavement product itself – specifically accounting for all pavement materials and equipment that contribute to the construction of the highway section. All materials listed in project pay items as per MDOT specifications, are accounted for except materials that are associated with bridge construction. For each of the materials, emissions for the mining and manufacturing

phase are accounted for. In addition, the emissions of transporting the materials to the construction site are included. Both virgin materials, and where reported recycled materials, are accounted for. For example, recycled aggregate is considered explicitly. All equipment used during the construction and maintenance operations is accounted for as well. For each equipment type, total energy use (gallons of fuel) on the construction site (as a function of total hours of usage) is accounted for. In addition, a fraction of the emissions from manufacturing of the equipment, proportional to the number of hours of use on a particular project is included. The product components are limited to involve only materials and equipment directly associated with the stakeholder's decision-making processes.

2. Process components: The process includes two components – the processes on site that are directly involved in the highway construction and maintenance operations, e.g., construction schedule and operation design; and the processes that directly influence decisions of long-term pavement behavior, e.g., determination of maintenance schedules. The process components are limited to involve only processes that directly involve the stakeholder decision-making processes.
3. Service life components: Service life components of pavements can be quite difficult to determine and even more difficult to estimate. Therefore, a traffic simulation environment MOVES [35] was used to estimate use phase emissions due to on-road vehicular traffic. Excess emissions due to traffic delays, and reduced speeds in construction zones, were also considered. While this is a very limited consideration of the service life of pavements, it provides agency stakeholders a reasonable baseline to benchmarking projects.

The product and process data will be directly observed from project sites, while the service phase data is estimated using traffic simulations. The pavement life cycle phases that this framework involves are:

1. Material Acquisition/Extraction Impacts (Product)
2. Upstream Manufacturing Impacts of Fuel Combusted in Equipment (Product)
3. Upstream Manufacturing Impacts of the Construction Equipment (Product)
4. On-Highway Transportation Impacts (Process)

5. Off-Road Transportation Impacts (Process)
6. Off-Road Equipment Impacts (Process)
7. Batch Plant and Secondary Material Processing Impacts (Process)
8. Construction Schedule (Process)
9. On-Road Vehicular Emissions (Service)
10. Long Term Pavement Maintenance Schedules and Performance (Service)

For each of these datasets, the framework includes a comprehensive data collection plan – to be discussed in a later section.

4.2. Hybrid LCA Methodology

Applying LCA to study the environmental effects of products or processes requires systematic accounting for the different stages through the life cycle. The life cycle phases considered are the materials extraction phase, manufacturing/production stage, the use phase and the ultimate end-of-life/ disposal and recycling phase. All inputs and outputs into a product or process are accounted for, and the environmental impacts of each are directly calculated to determine the total life cycle environmental impacts. This report focuses on using this method to calculate the GHG emissions – one component of all environmental impacts calculated by an LCA.

There are two ways to conduct an LCA - using an input-output based LCA, or a process based LCA. Economic input-output based LCAs are based on economic transactions and resource interactions between an exhaustive set of economic sectors. The system wide use of resources, as measured by economic input and output across all related sectors, is used as an indicator of emissions from industries in that sector. Input-output models identify emissions that are immediately related to the product and/or process at hand, as well as emissions from related economic activity across sectors. Process-based LCA practitioners on the other hand, isolate processes using well-defined system boundaries and calculate direct emissions of all activities within the defined boundary. The inputs (materials and energy), along with the outputs (emissions) from each step in the product or process life cycle are itemized and accounted for. A critical difference between these two methods is that input-output LCAs take into account multiple economy-wide interactions, attempting to provide a comprehensive assessment, while process LCAs tend to be detailed assessments of specific industrial processes that can be easily identified and isolated. All interactions defining the chain of specific processes that comprise the material extraction and production phase are difficult to account for. For example, the transportation impacts from raw material extraction sites to the manufacturing/production facility may fall beyond the system boundary of the process LCA and be excluded, and difficult to estimate. In such cases, sector wide input-output LCAs are better suited for estimating average emissions associated with such system wide interactions.

A choice between one or the other LCA often involves trade-offs between accuracy and scope, and is sometimes dictated by availability and measurability of data sources. The advantages and disadvantages of these two methods are outlined in previous work [36] and reproduced in Table 4-1.

In this research effort, a hybrid LCA method was adopted. Hybrid LCAs have been previously considered for application to construction processes [4]. The method takes advantage of the structure of a process LCA to define the system boundaries of a construction process, and identify and inventory the associated resource (materials and equipment) inputs, and emission outputs. In order to estimate the GHG for all materials and equipment inputs, an input-output and/or process LCA tool is used to take advantage of the most recent emission factors that have been reported in the process LCA literature, when applicable, as well as maximize the advantages of an input-output LCA. In effect, we use integrated hybrid LCA models to represent the life cycle impacts of the construction projects. In the model, the GHG emissions are quantified as a function of the construction and vehicle operations in terms of material/fuel usage.

Table 4-1: Advantages and Disadvantages of IO and Process-based LCA Models[37]

	Process-Based LCA	**EIO-LCA**
Advantages:	results are detailed, process specific	results are economy-wide, comprehensive assessments
	allows for specific product comparisons	allows for systems-level comparisons
	identifies areas for process improvements, weak point analysis	uses publicly available, reproducible results
	provides for future product development assessments	provides for future product development assessments
		provides information on every commodity in the economy
Disadvantages :	setting system boundary is subjective	availability of data for complete environmental effects
	tend to be time intensive and costly	product assessments contain aggregate data
	difficult to apply to new process design	process assessments difficult
	use proprietary data	must link monetary values with physical units
	cannot be replicated if confidential data are used	imports treated as products created within economic boundaries
	uncertainty in data	difficult to apply to an open economy (with substantial non-comparable impor
		uncertainty in data

The emission factors used in this study are from process LCAs reported in literature. They have been taken primarily from the Stripple [38], Athena [39] and NREL [7] inventories. These emission factors are usually expressed as Tons of CO_2 equivalents per unit weight or volume. Therefore, given a bulk volume or weight of a material use on a particular project, the emissions can be calculated by using the emission factors. (Appendix B: Emission Factors itemizes all the emission factors used in this study and their respective sources.)

The Economic Input Output-Life Cycle Assessment (EIO-LCA) is also used in the hybrid model. It is a model that defines the scope and number of environmental effects quantified in a LCA. Developed at Carnegie Mellon University [37], it estimates the economic contribution, resource requirements and environmental emissions for a particular product, service, or activity. The model attempts to capture all the requirements to produce a product, service, or activity, for the life cycle stages of extraction/mining, transportation, and manufacturing. Construction activity, operation and maintenance activities, and end-of-life/disposal impacts of products are not accounted for in the EIO-LCA model, and have to be determined independently. EIO-LCA has been used for conducting LCAs to assess the sustainability of different kinds of pavements. For this study, EIO-LCA was used to account for manufacturing of the materials used in each project, along with the manufacturing impacts of the fuel and equipment to be used in the construction project.

The usefulness of the EIO-LCA model is dependent on the accuracy of the material and equipment inventories developed for each pavement design and construction operation type. In addition, the outputs are reliant on the economic input of the identified materials and equipment in US Dollar and based on the 2002 US economy. Average cost for each material or item varies by region and the costs reported in the contracts are agency costs (cost to the DOT rather than cost of material production), which are inapplicable to EIO-LCA studies. Therefore, material prices must be isolated from agency's cost. It is important to use material prices (rather than estimated cost to the agency) that were reflected in the project to obtain the most accurate results in EIO-LCA. This can be used to investigate the impact of variability in pricing due to availability of regional materials on life cycle emissions. For this study, national average material prices were obtained through RS Means data (2009) [40] and then converted to 2002 dollar using applicable cost indexes. (Cost indices were calculated using a base of 100 in 1913, as per Engineering News Record data, e.g. 2010 cost index is 183.5).

4.3. Inventory Development: Data Collection Methodology

This section describes the method used to collect highway construction data for the development of inventories of material and equipment associated with a project's product process and service components. Product and process data was collected directly from construction sites, while service data was simulated using highway characteristics and traffic data.

Construction product and process data collection led to the development of material and equipment inventories, which represent the construction and rehabilitation process. New construction, re-construction and different maintenance operations were considered. The primary challenge in collecting this data was eliciting co-operation and collaboration from project engineers, contractors and sub-contractors on site. Hence, it was imperative to take advantage of existing reporting methods, thus minimizing the burden of reporting. In addition, data was collected through direct field observation by researchers. For the service component, the Motor Vehicle Emission Simulator (MOVES) simulation was used to estimate on-highway vehicle emissions throughout the service life of the pavement. Results from the simulation were also used to investigate additional emissions due to construction work zone delays. The MOVES simulator was developed by United States Environmental Protection Agency (U.S. EPA) [35].

MDOT requires the use of software called FieldManager™, a construction management and reporting software created by InfoTech Inc. [41] on all their construction and rehabilitation contracts. The software maintains electronic reports of MDOT Inspector's Daily Records (IDR). Inspectors (on behalf of MDOT) use FieldManager™ to record, on a daily basis, information regarding general site conditions, contractor personnel and equipment on site, and quantities of different material installed on site. FieldManager™ was chosen for this research to take advantage of MDOT's existing process for tracking and monitoring all their construction and rehabilitation contracts. Hence, this method takes advantage of current field expertise, and reporting practices to support the data collection procedure. The IDRs were directly collected from the FieldManager^{TM} database and used to accurately account for the product and process data collected for each of the projects surveyed.

In the next sub-sections, each data category is explained in detail.

4.3.1. Product Data

Materials used on the construction sites were recorded using the IDR, tracking progress made on each pay item as specified in the construction contract. The location, station information and quantities of materials associated with each item installed were stored. The data was used to maintain an as-built record of procured and installed material. The collected data is considered highly accurate, as the contractors were paid based on these records. Using as-built quantities in the calculation of life cycle impacts and emissions is significantly more representative of project impacts compared to similar calculations done with estimated quantities.

Product data allowing for the estimation of impacts associated with the manufacturing of construction equipment was also collected. First, the purchasing price of general categories of construction equipment being used on the project was determined. The total impact for producing the machinery was then determined using three types of data pertaining to the equipment:

- Purchasing value of equipment (from online equipment vendors)
- Useful life of equipment [42, 43]
- Hours used on specific project (from FieldManager^{TM})

Using this information, the impacts were estimated for each individual piece of machinery, and then broken down further by applying the portion of the machinery's life that was reflected in the actual project. This was done using the number of hours used/total useful life ratio. For example, if the expected life of equipment is 10,000 hours, and the number of usage hours on a particular project is 1,200 hours, then only three twenty-fifths of the manufacturing impact of that equipment is considered for the project.

The development of this inventory was crucial to this project. It also has long-term implications. When available to other researchers, it can support the investigation of questions beyond the scope of this study but particularly relevant to the topic. It is expected in the long-run, MDOT will continue to use this method to collect data across various construction projects. The data collected across similar and different construction projects can then be analyzed by cross classifying across pavement designs, construction operations and site-specific conditions to highlight sensitivity of impacts and emissions to local and regional variables.

The emissions from these material inventories were estimated from methods described in the section titled Materials Emissions.

4.3.2. Process Data

The contractor equipment inputs in the IDR were critical to quantifying project construction equipment emissions. Recent studies have shown that energy use and emissions of construction processes are primarily due to construction equipment use, which can account for 50% of most types of emissions. Also, equipment larger than 175 Hp made prior to 1996 tend to have higher emissions than more recent models [17]. Therefore, data was collected to account for the use of equipment on construction operations. While, the type and quality of construction equipment influence project emissions, the design of the operations – in particular travel distances on site – also influence project emissions. In this report, the emphasis has been on studying the processes that define the construction operations – with the goal of encouraging emission reduction through increased efficiency on construction sites.

In taking full advantage of fields specified in the IDR, inspectors were requested to identify equipment present on-site, how long the equipment worked, and the operation the equipment was performing. Inspectors recorded: (i) equipment characteristics such as model year, gross vehicle weight and mileage on the vehicle (henceforth all this information is referred to as equipment type for brevity); and (ii) activity characteristics such as number of trips, one way distance, and return distance. Due to a lack of complete cooperation from the inspectors, the data collected through the inspector reports was incomplete. Appropriate assumptions, explained later in the report, were made to account for the missing data. For more accurate assessment, there may be a need to standardize the reporting procedure for Inspectors when using FieldManager™. Information collected though FieldManager™ was also supplemented with information collected in collaboration with contractors. This included information regarding equipment specifics needed to calculate equipment emissions such as the equipment model, year, make, type of fuel used (sulfur content) and engine type. In some cases, contractors were already tracking their equipment usage to monitor efficiency, and were willing to share the information. This information is highlighted in the Project Emissions Estimator (PE-2). Information collected from the contractor was used to support any assumptions made and the information recorded in FieldManager™ IDR when applicable. In the future, if equipment emissions are to be monitored by MDOT, reporting standards for all inspectors must be developed for uniform reporting of on-site equipment use. In addition, it is expected that collaboration between agencies and contractors will increase so that relevant data can be correctly and exhaustively reported.

On-site travel distance data is an indicator of construction operation design efficiency. For example, inefficient design can result in longer operation cycle times as well as longer travel distances from batch plant location. Some of this data was obtained directly from on-site observation. In addition, material-testing orders provided by MDOT were used to calculate the distances travelled in transporting materials to the construction site. Researchers were able to map the site layout with respect to material stockpiles, batch plants, suppliers, etc.

The following outlines the data types collected to accurately account for on-site travel from hauling equipment:

1. Equipment descriptions are categorized into generalized construction equipment categories. (i.e. dozer, excavator, etc.)
2. Generalized equipment categories are assigned a fuel consumption rate and an hours per day operating rate
3. Quantify fuel used/combusted in equipment

This process data also includes travel distances and number of trips for the hauling equipment. This data was obtained from on-site observation material testing orders. To account for combustion process emissions, carbon content of diesel fuel was used and obtained from the U.S. EPA [44].

The data obtained from material testing orders was used to estimate emissions from hauling equipment traveling to and from material stockpiles and pits that provide the materials which make up the pavement designs. This data included the travel distances from the suppliers to site, from stockpiles and batch plants to site, and from stockpiles/suppliers to batch plants. The testing orders provided addresses of material suppliers along with limited descriptions of material stockpiles. Locations of these stockpiles were also obtained through correspondence with the contractors.

The following outlines data types collected to account for to-site travel from hauling equipment:

1. Site layout maps to estimate distances from material suppliers to site or batch plant locations
2. Number of trips taken from suppliers or stock pit
3. Total travel distances on-site

Emissions from equipment activity and to site transport are estimated using the methodology outlined in Equipment Emissions.

Additionally, the construction schedule process data was collected to investigate net increased emissions due to schedule delays. Particularly, two schedules were analyzed in performing this analysis; as-planned and as-built. Original progress schedules (MDOT Form 1130) were used to outline the as-planned schedule. The resource allocation for the as-planned schedule – particularly important for calculation of as-planned production rates - was calculated from the project proposal's estimate. The progress schedule outlines construction activities along with proposed starting and end dates for each activity. FieldManager™ was used to develop the as-built resource loaded schedule, by allocating pay items to activities outlined in the progress schedule and assessing the actual productivity (material and equipment usage) depicted in FieldManager™.

4.3.3. Service Data

Life cycle performance of highway sections plays a critical role in reducing GHG emissions. Long life pavements that require little or no major rehabilitation promise to lower the overall life cycle GHG emissions. Pavements with minimal rehabilitation and maintenance can lower the overall life cycle GHG emissions. As part of this study, pavement condition and historical maintenance data are used to estimate maintenance schedules and overall pavement life cycle definitions.

In addition, emissions associated with the service provided by the pavement – referred to as the use phase emissions, must also be accounted for. The system boundary for the use phase is difficult to define. For this research, the scope was limited to emissions due to on-road vehicular traffic use of the pavement.

Therefore, the data collected for this component is:

- Maintenance and rehabilitation records for the highway section investigated
- Pavement condition data such as Distress or International Roughness Index measurements before and after maintenance
- Quantity of material and equipment used for rehabilitating the roadway – this simply accounts for the product and process emissions of the maintenance and rehabilitation operations and are considered as a gross number in this phase
- Highway traffic characteristics
- Emissions due to work zone delays

It is important to note that, although not considered in this study, pavement-vehicle interaction will also influence life cycle GHG emissions. For example, increased fuel efficiency of rigid pavements reduces life GHG emissions [45].

Service data collection lead to limited traffic scenarios that could adequately represent the highway sections investigated. In-use service data associated with highway section is used to estimate on-road vehicle emissions resulting from the service phase of the pavement section. As mentioned earlier, U.S. EPA MOVES Model was used for this analysis. Types of service data used in this study are, but not limited to, the following:

- Fuel Composition data
- Climate data
- Vehicle Characteristics
- Traffic Class Distribution

It is with these types of service data, the service component of the pavement LCA was assessed.

4.4. GHG Calculation Using Project Based LCA Methodology

Analyzing the three types of data described earlier allowed the researchers to estimate GHG emissions resulting from the construction and rehabilitation projects investigated. The following methods were used to estimate GHG emissions:

4.4.1. Product Component GHG Emissions

To estimate the GHG emissions from the product components using the hybrid LCA approach, researchers used various emission factors. For material acquisition/extraction emission of driving materials, emission factors were obtained from published process LCA data. For example, cement, binder, and aggregates are all represented using emission factors published in literature, and commonly used as representative emission factors for these materials. These factors were converted to represent units used by MDOT. The calculation is based on the amount of carbon dioxide emissions per unit of material used. Where published emissions could not be accessed, EIO-LCA was used to develop emission factors based on emissions associated with the industry sector that the product was classified under. An example calculation for using EIO-LCA is as follows:

- Material: Pavement Marking Waterborne Paint (Gallon)
- EIO-LCA sector and model used: 325510 Paint and Coating Manufacturing represented in the US 2002 National Producer Price Model
- Using $1000 as a baseline to estimate the material's Global Warming Potential (GWP) impact, the Metric Tons of CO_2 Eq Emissions per $1000 purchased is 0.988.
- The unit price for 2009 for a gallon was $83.33. This is converted to a 2002 price using the factor 0.7146 (= cost index 2002/cost index 2009 = 128.7/180.1).
- Therefore, if the project is using 500 gallons of pavement marking paint the estimated GHG emissions from producing the material is found to be (500 x 83.33 x 0.7146 x [0.988/1000] =) 29.476 MT CO_2 Eq.

EIO-LCA was also used to determine impacts from manufacturing the fuel combusted in the construction equipment on site, and impacts associated with manufacturing the machinery utilized on the project. The former was quantified from construction equipment use reports generated from FieldManager™. The latter was estimated by first determining the purchasing price of generalized construction equipment being used on the project, obtained from equipment vendor's websites. Once the price for the equipment representing the projects was determined, those prices were then converted to 2002 prices using the following formula.

$$EC_{2002} = EC_{2009} \text{ x } [1 + r]^n / [1 + i]^n$$

Where EC is the equipment cost, n=6 years, r is the discount rate assumed to be 5%, and i is the inflation rate assumed to be 3%.

The total impact for producing the machinery that was used on the projects was then determined using EIO-LCA. EIO-LCA is only capable of estimating the entire machine's impact. Therefore, using the information from EIO-LCA, the impact was broken down for each individual piece of machinery, and then broken down further by applying the portion of the machinery's life reflected in the actual project. This was done using the number of hours used/total useful life ratio. For example, if the expected life of equipment is 10,000 hours, and the number of usage hours on a particular project is 1,200 hours, then only three twenty-fifths of the manufacturing impact of that equipment is considered for the project.

4.4.2. Process Component GHG Emissions

A combination of methods and tools were used to estimate the GHG emissions from process components of the hybrid LCA. It consisted of emissions from transporting materials to site, emissions from distances travelled on site during construction, batch plant emissions and increased emissions associated with delays in construction schedules.

On-Highway transportation impacts were considered by accounting for impacts due to hauling materials from the supplier to site. Information on supplier locations was obtained from material testing orders procured through MDOT. The locations and distances were mapped using Google Maps. The mode of transportation was assumed as on-highway combination diesel transport truck fully loaded at 30 Metric Tons. The corresponding emissions were found to be 0.386 MT CO_2/Mile. (Refer to *factors.xslx*)

The emissions resulting from off-road transport and construction equipment usage was estimated using EPA approved methodologies. The equipment was generalized based on the following premises:

- Equipment type categories, horsepower (HP), and load factors (% of HP used) classifications were obtained from the California Environmental Quality Act (CEQA) tool for assessing emission for road construction projects [46].
- Load factors were estimated considering average operation level as a percentage of the engine manufacturer's maximum horsepower rating [47].
- The same horsepower and load factor classifications were assigned to the equipment types used in the case studies.

Variability in year, make, and model are excluded from this analysis due to lack of adequate current data. The data set classifies the equipment into use types. On-site construction equipment is considered "stationary." Hauling equipment, transporting materials on and off site from stockpiles, batch plants, etc. are considered "hauling". All miscellaneous equipment such as the foreman's pick-up is considered "other". In some cases, division and section identification numbers classify the equipment. These represent the type of work being performed by the equipment. The identification numbers directly relate to division and sections of work outlined in MDOT's Standard Specifications for Construction [48]. Analyzing this parameter allows researcher to assess productivity and GHG emissions based on work type.

Estimated diesel fuel emissions from the equipment were based on fuel consumption. Recent studies have shown that fuel use emission factors have less variability than time-based emission rates [49]. Therefore, gallons of fuel consumed were estimated using the following formula:

$$Fuel\ Rate\ (Gal/hr) = LF \times TF \times FF \times HP$$

Where: LF is load factor and TF is the time factor which was assumed to be 50min/hour in this study. FF is Fuel factor (diesel) and assumed to be 0.04gal/(hp-hr) [50]. HP is the average horsepower used for each equipment type. Based on the determination of fuel consumption, three GHG emissions were estimated (Carbon Dioxide CO_2, Nitrous Oxide N_2O, and Methane CH_4) using the following equations:

Carbon Dioxide:

$$Emissions\ (MT) = \Sigma^{n}_{i=1} Fuel_i \times HC_i \times C_i \times FO_i \times [CO_2/C]\ [44]$$

Where: Fuel_i = Volume of Fuel Type i Combusted, HC_i = Heat Content of Fuel Type i, CC_i = Carbon Content Coefficient of Fuel Type i, FO_i = Fraction Oxidized of Fuel Type i, CO_2 (m.w.) = Molecular weight of CO_2, C (m.w.) = Molecular Weight of Carbon.

The following values were used in the calculation of CO_2 emissions and obtained from U.S. Environmental Protection Agency's guide on calculating GHG emissions from mobile sources [44]:

- HC_i= 5.825 mmBtu/Barrel
- C_i= 19.95 kg C/mmBtu
- FO_i= 1.0
- CO_2 (m.w.)= 44.01
- C(m.w.)= 12.01

Nitrous Oxide & Methane

$$Emissions\ (g) = Fuel_i \times EF_p$$

Where: $Fuel_i$ = Volume of Fuel Type i Combusted, EF_p = Emission Factor per pollutant type (N_2O or CH_4)

The following values were used in the calculation of N_2O and CH_4 emissions and obtained from U.S. Environmental Protection Agency's guide on calculating GHG emissions from mobile sources [44]:

EF_{N2O}= 0.26 g/gal

EF_{CH4}= 0.58 g/gal

After determining the various GHG emissions from equipment types estimated from the case studies, a total carbon dioxide equivalent was calculated using the following Global Warming Potential (GWP) multipliers [51]:

GWP_{N2O} = 296

GWP_{CH4} = 23

This methodology is used to estimate carbon dioxide emissions from off-road transport and construction equipment usage for each observed project.

An alternative method to calculating on-site transportation emissions is to directly calculate the travel distances and number of trips for the hauling equipment using the site-specific location data directly observed from site. The number of trips is determined from the total amount of material placed on-site (from FieldManager^{TM}), and the capacity of the hauling equipment and the design of the construction operation. Given the cycle times for driving operations (such as mainline paving), the volume and the number of trucks in use, the distances travelled to and from the batch plant, and the kind of hauling equipment used, the impacts associated with the equipment use during the operation can be calculated. This is strictly a function of the site design and operation logistics. Hot Mix Asphalt (HMA) hauling trucks were assumed to have a hauling capacity of 28 Tons of HMA, and concrete hauling trucks were assumed to have a hauling capacity of 10 cubic yards of concrete.

The following formula establishes the method used to calculate the total distances travelled on-site for a particular scenario in which the batch plant location is placed at the Point of Beginning (POB) of the pavement section, and trucks hauled the concrete back and forth to the points at which it was placed. If the batch plant is located off-site, the additional distance to the POB of pavement section must be added. Assuming there was only one truck equivalent in the placement operation, the length of each truck trip was incremented by the distance that was paved by the volume of concrete carried in the truck. The calculation formulates to an arithmetic progression as follows:

$$D = [x \text{ x } n \text{ x } (n + 1)]/5280$$

Where D is the distance travelled on site in miles, x is the distance paved per truck trip in feet and n is the total number of truck trips. The assumption of using a single truck to calculate the number of truck trips is entirely reasonable, as we are not concerned about the duration of the operation and are only interested in the distance travelled. The total distance travelled can be used to estimate emissions using one of the various emission calculators described in this report. Batch plant emissions were estimated using emission factors published in literature. The source of the emission factors used can be found in the emission factors table (*factors.xslx*). Based on the total tonnage of composite material manufactured in the batch plant, emissions were estimated. Alternative technologies such as warm-mix asphalt (WMA) were not investigated in this study.

The final process component to be analyzed is construction schedules. The motivation behind analyzing construction schedules is to recognize that inefficiencies in the activity scheduling process directly relate to increased construction site emissions. Inappropriate planning can result in delays and rework that in turn increases equipment and material use, thus increasing the total project emissions. Therefore, the as-planned schedule for a particular project that suffered significant delays was compared to the as-built schedule, using information in FieldManager™, to identify the impact of construction delays on construction emissions.

Equipment usage was estimated based on the number of working days and the assumption of a 10-hour working day. A combination of emission factors in the literature based, in process LCAs and the Economic Input Output-Life Cycle Assessment (EIO-LCA), was used to estimate the impacts of materials through the life cycle stages of extraction/mining, transportation, and manufacturing (see list of all factors in *factors.xlsx*). When using EIO-LCA, material costs were obtained through RS Means data [40] and then converted to 2002 dollar using applicable cost indexes. When using SimaPro, the direct weight of the materials used was considered as inputs.

When assessing equipment emissions, the working days from both as-planned and as-built schedules were identified to establish extra equipment use. The make, model, type, and Horsepower characteristics of each type of equipment were identified using fleet information provided from the contractor. Using the following equation, the emissions were estimated for each activity's controlling equipment type.

$$Emissions = O_t \text{ x } HP \text{ x } C_F \text{ x } \varepsilon$$

- Where O_t = Operating time factor, HP =Rated Horespower, C_F = Fuel Consumption Rate (Gal/(HP*hr), and ε = emission rate (lbs CO_2/Gal)
- The following assumptions were made:
- Opertaing Time Factor was assumed to be 45 minutes/hr (0.75)
- Working Day = 10 hours
- Fuel Consumtion Rate = 0.04 Gal/(Hp*hr) (Peurifoy and Oberlender 2002)
- Emission Rate = 22lbs CO_2/Gallon [52]

4.4.3. Service Component GHG Emissions

Service component emissions were estimated in two ways:

- Assessment of pavement performance data to estimate the actual pavement maintenance schedules, that define the service life of the pavement
- Estimation of vehicle emissions by simulating and modeling vehicle-use scenarios using EPA MOVES model

In the performance based approach, the pavement use phase is defined by outlining the various preventative maintenance strategies that are implemented throughout the life of the highway section. Rehabilitation options are highlighted in MDOTs capital preventative maintenance (CPM) manual [53], however, the time at which these options occur is not explicitly stated. In order to maintain the project-based perspective of this LCA application and account for regional variations in pavement performance, it is suggested that maintenance schedules be based on historical performance of the pavement sections. This involves investigating historical pavement condition data to determine when rehabilitation strategies are being carried out. MDOT uses the Distress Index (DI) parameter to assess a pavement section's condition. It is a measure of the cracking distresses influencing the pavement's condition. This analysis can prove to be very beneficial in developing regional maintenance schedules that can be used as a guide to assess the environmental impacts of the maintenance phase of the LCA. Additionally, analysis like this can provide the essential timelines needed to define life cycle periods used in LCA. Performance based approaches like these, promise to further the investigation of context sensitivity regarding the GHG emissions of highway construction and maintenance operations.

The use phase of the project consists of estimating the CO_2 equivalent emissions associated with different on-road vehicular traffic on the highway sections. This is done using the EPA's current official model for estimating air pollution emissions from motor vehicles under different traffic scenarios, MOVES2010a (Motor Vehicle Emission Simulator) [35]. This tool replaces the previous EPA official estimator, MOBILE6. MOVES is used for estimating emissions from motor vehicles at the national, county, and project scale. For this study, MOVES is used to estimate CO_2 equivalent at the project scale. The project parameters are based on actual MDOT project information. The project scale allows for more detailed input parameters to be analyzed, which consequently creates a more accurate emission estimation of the particular roadway. The parameters used are specific sections of highway with unique attributes such as road type, length, speed, average daily traffic (ADT), and meteorology. At the project level, all of these specific parameters are inputs into the MOVES database.

Two projects were evaluated using MOVES. The first project was US-41, which is a two lane major collector road located in Northern Michigan in Marquette County. This road type is classified in MOVES as a type 3 road, which is a rural unrestricted access roadway. The second project was I-69, which is an expressway located in southeast Lower Michigan in both Genesee and Lapeer County. This road type is classified as a type 2 road, which is a rural restricted access roadway. These projects were both actual MDOT road construction projects. The inputs for the project level analysis were very specific. They describe the unique project parameters. The inputs are fuel supply and fuel formulation, local meteorology, including temperature and relative humidity, vehicle/source type fraction for vehicle miles travelled (VMT), vehicle population fraction, traffic speed, project length, road grade, ADT, and the driving schedule (traffic maintenance schedules during a maintenance scenario).

The fuel supply and formulation data was a default input generated from the MOVES database. This data includes very specific information regarding the physical makeup and market share of gasoline and diesel fuel, explanation of which goes beyond the scope of this study.

The climate data includes the temperature and relative humidity for a typical day in a month incremented by one hour. Each of these one-hour meteorology snapshots is specific to the county that is selected in the MOVES graphical user interface (GUI). MOVES also provides this detailed data within its database. Therefore the default data was used.

The vehicle type fraction data is the fraction of VMT that each vehicle type can be assigned. The user is required to assign fractions to each MOVES-specific vehicle type using the particular roadway. These fractions can be defined monthly, type of day or hourly. For this study an average fraction was assumed for each of the two road types. MOVES allows vehicle type fraction information to be imported from Highway Performance Monitoring System (HPMS). HPMS is a national level database maintained by FHWA detailing information about "*the extent, condition, performance, use and operating characteristics of the nation's highway*" (http://www.fhwa.dot.gov/policyinformation/hpms.cfm). The information for HPMS vehicle class fraction was found at the Office of Transportation Data for the Georgia Department of

Transportation, for vehicle classes 1, 2, and 3, for each specific road type [54]. For the heavy truck classes 4 through 13, the default traffic fractions from the (Mechanistic-Empirical Pavement Design Guide) ME-PDG program were used. The choice of ME-PDG is based on its wide acceptance and general reliability as a pavement design tool. These fractions were combined using the assumed fraction that 15% of the total traffic is heavy trucks. These fractions had to be reclassified in order to conform to the MOVES required source type. The HPMS vehicle classes were grouped into the MOVES source types. Some were matched directly, like motorcycles, while some MOVES source types contained multiple HPMS vehicle classes such as combination long haul trucks. The HPMS classes were fractioned and added up according to the MOVES source type they mapped on to. Table 4-2 outlines the vehicle type fraction data that was used from HPMS and input into MOVES to characterize the traffic in the simulation.

Table 4-2: Source Type Fraction Methodology

sourceTypeID	sourceTypeName	HPMS Vehicle Class	HPMSVtypeID	HPMSVtypeName
11	Motorcycle	1	10	Motorcycles
21	Passenger Car	2	20	Passenger Cars
31	Passenger Truck	3	30	Other 2 axle-4 tire vehicles
32	Light Commercial Truck	3	30	Other 2 axle-4 tire vehicles
41	Intercity Bus	4	40	Buses
42	Transit Bus	4	40	Buses
43	School Bus	4	40	Buses
51	Refuse Truck	6	50	Single Unit Trucks
52	Single Unit Short-haul Truck	5,6,7	50	Single Unit Trucks
53	Single Unit Long-haul Truck	5,6,7	50	Single Unit Trucks
54	Motor Home	5	50	Single Unit Trucks
61	Combination Short-haul	8,9,10,11,12,13	60	Combination Trucks

HPMS Class	Source Types	Variable for fraction	Source Type	Equation
1	11	x1	11=	x1
2	21	x2	21=	x2
3	31,32	x3	31=	x3/2
4	41,42,43	x4	32=	x3/2
5	52,53,54	x5	41=	not used in rural
6	51,52,53	x6	42=	not used in rural
7	52,53	x7	43=	x4
8	61,62	x8	51=	x6/3
9	61,63	x9	52=	x5/3+x6/3+x7/2
10	61,64	x10	53=	x5/3+x6/3+x7/2
11	61,65	x11	54=	x5/3
12	61,66	x12	61=	(x8+x9+x10+x11+x12+x13)/2
13	61,67	x13	62=	(x8+x9+x10+x11+x12+x13)/2

MOVES inputs must sum to 1

The variable fractions are uniformly distributed. For example, *x4* indicates the fraction of traffic that belongs to HPMS class 4, which consists of vehicle source types 41, 42 and 43. As vehicle types 41 and 42 are not considered for rural scenarios, their representation in *x4* is null. Hence, the fraction *x4* is representative only of vehicle source type 43. Similarly, the vehicle source types 31 and 32 are represented equally in the fraction *x3*, which represents HPMS vehicle type 3. Therefore, the representative variable for 31 and 32 is *x3/2*. Intercity and transit busses were not factored into MOVES because they were assumed to not drive on rural roads or rural highways.

The vehicle age distribution is the fraction of vehicles on the road by how old they are for each of the MOVES source types. MOVES ranges from 0 to 30, new to 30+ years old respectively. This information was found at the EPA website as a default input [55]. The data was modified slightly to reflect the fraction of cars by age, which is a required input in MOVES, rather than the total number of cars by age.

The most crucial input into MOVES is the link input. This describes the project specifics, like road length, average speed, ADT, and percent grade. The length (in miles from POB to POE) of the projects were determined from project descriptions from MDOT, this is in miles from beginning to end. The average speed was assumed to be the permanent speed limit set on the road. The ADT was found at the MDOT website and is specific to each section of road [56]. This data was averaged if there were more than one ADT given on a single section of road. The ADT was broken down by the hour. For simplicity, the ADT was fractioned equally between all 24 hours of the day. This becomes the average hourly traffic. The percent grade of the road for a particular project was calculated from a website that uses the elevation of two user-chosen points on a map [57]. The points used for these projects were the start and end of the particular project.

When determining the emissions from daily traffic during a construction or maintenance scenario, additional driving schedule information was used. The driving schedule reflects traffic management in a construction work zone, particularly the change in traffic speed as vehicles enter and exit a work zone. It was assumed that for the unrestricted road type a typical vehicle will come to a stop from 55 mph, and remain stopped for 10 minutes, (600 seconds - maximum allowable by MDOT), then speed up to the reduced speed through the construction zone (assumed to be 45 mph), and finally accelerate to a normal driving speed of 55 mph. A maintenance period driving schedule for a restricted road consists of all vehicles slowing down from 70 mph to 60 mph. For simplicity, the acceleration and deceleration of traffic was assumed constant. The second by second data was calculated using the following formulae for constant acceleration (based on time and distance respectively).

$$a = [v_f - v_i] / t \ \ \& \ a = [v_f - v_i]\,[v_f - v_i] / [2 \times d]$$

Where a = acceleration, v_f= final velocity, v_i = initial velocity, d = distance, and t = time. Each section where there is a change in driving pattern (due to the work zone) is considered to be a new "link" in the roadway. These had to be input as separate links in the link table as well. Each link had to be given a new average speed based on the acceleration, and a new length, which was calculated from the acceleration formula to solve for distance. The following table is an example of the driving schedule table and link table.

Table 4-3: Driving Schedule Table

linkID	secondID	speed	grade
1	1	55.00	0
1	2	50.97	0
1	3	46.93	0
1	4	42.90	0
1	5	38.87	0
1	6	34.83	0
1	7	30.80	0
1	8	26.77	0
1	9	22.73	0
1	10	18.70	0
1	11	14.67	0
1	12	10.63	0
1	13	6.60	0
1	14	2.57	0
1	15	0.00	0
2	1	0.00	0
2	600	0.00	0
3	1	0.00	0
3	2	3.75	0
3	3	7.50	0
3	4	11.25	0
3	5	15.00	0
3	6	18.75	0
3	7	22.50	0
3	8	26.25	0
3	9	30.00	0
3	10	33.75	0
3	11	37.50	0
3	12	41.25	0
3	13	45.00	0
5	1	45.00	0
5	2	47.00	0
5	3	49.00	0
5	4	51.00	0
5	5	53.00	0
5	6	55.00	0

Table 4-4: Link Table

linkID	countyID	zoneID	roadTypeID	linkLength	linkVolume	linkAvgSpeed	linkDescription	linkAvgGrade
1	26103	261030	3	0.10417	125	26.86	55-0	0%
2	26103	261030	3	0.00000	125	0	stopped	0%
3	26103	261030	3	0.07500	125	22.5	0-45	0%
4	26103	261030	3	2.77139	125	45	drive through project	0%
5	26103	261030	3	0.06944	125	50	45-55	0%

MDOT's project plans specify the distance before the work zone where a speed reduction sign is located. This distance *D*, was used to account for the deceleration of the vehicle as it approached the work zone [58]. This distance varied with the speed limit of the road. The time values, when used, were estimated based on driving experience.

Once the data was estimated using MOVES, it was put together into a spreadsheet to be analyzed and made useful. All the hours in a month were summed to form a typical days worth of CO_2 equivalent emission. Then each of these typical days in a month were multiplied by the number of days in the particular month and summed to estimate a typical year (typical Jan day*31+typical Feb day*28.25+…+typical Dec day*31). This total represents the total CO_2 emissions on a specific section of highway for one year. To calculate emissions for an average day, the total was divided by the number of days in a year, 365.25. This total annual emission can then be represented as a metric by fractioning the average emissions per day by the length of the project and the ADT of the project. The units for this emission metric are Metric Tons of CO_2e/day/mile/1000 vehicles. This provides a functional unit for considering the emissions during the service life of pavements with equivalent functionality, as defined by traffic volume.

Throughout the life cycle of the road, the total emissions were estimated using a 1% growth in ADT each year [58]. This growth factor for ADT directly correlates to the emission output and was backed up by a sample MOVES run at the national scale over a period of 20 years. The trend in the yearly data of this set was growing at slightly over 1.07%. This result justified the assumption of 1% growth in emissions per year.

4.5. Functional Units and Metrics

The functional unit '*emissions per lane mile'* has been used widely in the literature. However, this unit has various limitations – most importantly, it does not scale in any uniform fashion as the number of lane miles increase. One reason is that the length of shoulder does not increase in the same way as the number of lane miles increase. In addition, there is an impact of statistical smoothening as the denominator increases. Therefore, for the sake of this study, it is not suitable as the *only* functional unit, as the proposed framework accounts for multiple pavement functionalities. The functionalities include:

1. Product performance, e.g. differences in emissions of alternative and/or recycled materials compared to virgin materials
2. Process performance, e.g. savings in emissions through appropriate construction site layout, schedule and operation design.
3. Services performance, e.g. increased emissions due to construction zone delays, and emissions for different maintenance schedules and pavement life cycles.

In addition, it is important to note that while this framework is inspired by LCA approaches, its aim is not to compare products and processes – but to instead provide decision-support to strategically reduce GHG emissions for each of these functionalities. Hence, most of the units discussed in this section are intended to be decision metrics rather than pure functional units. Therefore, the choice of an appropriate functional unit/metric depends on the decision being considered. Broadly, the following functional units were considered:

1. Product Component: Project level perspective
    a. Average CO_2 equivalents per 100 MT of concretic and asphaltic materials (see explanation later)
    b. Average overall CO_2 equivalents per MDOT material specifications as defined in Division 9, reported per lane mile
    c. Average overall CO_2 equivalents per construction category (e.g. drainage, earthwork) per lane mile
    d. Equipment manufacturing and upstream fuel production emissions per lane mile
    e. Transportation emissions of raw materials to site per lane mile
2. Process Component: All emissions expressed per working day of project – Construction activity/schedule level perspective
    a. Composite materials production on site (e.g. batch plant emissions)
    b. Secondary materials processing on site (e.g. RCA, RAP)
    c. Emissions due to delays in construction schedule

   d. Emissions related to construction operation design
3. Service Component: Project/Network level
   a. CO_2 equivalent emissions expressed in units of vehicle emissions per day per mile, where one unit of vehicle emissions per day per mile, is the daily emission (in MT) associated with a mile length of a highway section with Average Annual Daily Traffic of 1000. The emissions for a given highway section over a period can be derived by multiplying the metric, by the Average Annual Daily Traffic and period being considered.
   b. Integrative life cycle emissions of a highway section per lane mile considering all the components and phases.

It is important to note that all the units discussed above are incomplete and must be taken as a whole. Strictly speaking, they ***should not*** be used to compare processes and materials. Rather, they should be used as metrics to establish benchmarks for representative project types and highway sections. In turn, these can be used as baselines to support decision-making and continuously reduce GHG emissions and increase efficiency.

Of the above metrics, the ones that were specifically investigated and developed were 1a, 3a and 3b. In both these cases, a calculated metric was derived as discussed next.

4.5.1. Average CO_2 Equivalents per 100 MT of Concretic and Asphaltic Materials

This metric has been derived from a measure developed by ICF International Inc., as part of a recent study investigating GHG mitigation measures in Transportation Construction [15]. It expresses the material emissions per 100 MT of concretic or asphaltic materials. The definition of concretic and asphaltic materials is as follows. Concretic Material Emissions are defined as the emissions from the concretic materials - cement, aggregate, fly ash, sand, steel, and curing compound - that go into a 15ft. long by 12ft. wide by 11in. deep concrete panel that has 10 dowel bars spaced 12in. on center, and 6 tie bars spaced 30in. on center (As illustrated in Figure 4-1). The concrete unit weight mix design and the weight of materials for such a panel are illustrated in Table 4-5 and Table 4-7. The emissions from this panel were calculated to be 1.5417 MT of CO2 equivalents per panel or 13.88 MT of CO_2 per 100 MT of concretic materials. This compares with GreenDOT's metric of 15.484 MT of CO_2 per 100 MT of concretic materials. Asphaltic Material Emissions are defined as the emissions from asphaltic materials – binder, aggregate, sand, RAP, and bond coat – that go into a 15ft. long by 12ft. wide by 12in. deep asphalt panel (As illustrated in Figure 4-2). The HMA unit weight mix design and the weight of materials for such a panel is illustrated in Table 4-6 and Table 4-8. The emissions from this panel were calculated to be 0.1532 MT of CO_2 equivalents per panel or 1.294 MT of CO_2 per 100 MT of asphaltic materials. This does not compare with GreenDOT's metric of 7.325 MT of CO_2 per 100 MT of asphaltic materials.

It is important to note that the terms 'concretic' and 'asphaltic' are being used on purpose and are not to be confused with 'concrete' and 'asphalt'. The terms represent a conglomerate of materials based on the definition of the standard pavement panels. Therefore, they are representative of emissions associated with 100 MT of such a panel. The pavement material bulk is then expressed as a function of such panels. For example a project with 500 MT of asphaltic materials could be compared to five 100 MT of a typical asphaltic panels as described. It is important to note that most major projects (and this is evident in a later section) can be expressed as a combination of asphaltic and concretic panels. The choice of this unit is to develop a standard reference that all project materials can be expressed as – *thus providing the ability to compare the emissions of different projects, rather than compare the emissions of different pavement types.*

Table 4-5: Concrete Unit Weight Mix Design

Concrete Unit Weight Mix Design/Cyd of Concrete	*Unit/Cyd of Concrete	% of Mix by Weight	Emission Factor	Unit
Cement *(Ton)	0.240	12.037	8.42E-01	MT/Ton
Aggregate *(Ton)	0.951	47.758	6.16E-03	MT/Ton
Sand *(Cyd)	0.376	30.554	1.08E-04	MT/Cyd
Fly Ash *(Ton)	0.042	2.124	1.78E-02	MT/Ton
Water *(Ton)	0.150	7.527	NA	
(0.45 W/C Ratio) (Unit Weight: 1.9914 Tons Concrete/Cyd Concrete)				
Overall Emissions (MT CO_2)/ Cyd of Concrete	**2.08E-01**			

Table 4-6: HMA Unit Weight Mix Design

HMA Unit Weight Mix Design/ Ton of HMA	*Unit/Ton of HMA	% of Mix by Weight	Emission Factor	Unit
Binder *(Ton)	0.053	5.32	1.57E-01	MT/Ton
Aggregate *(Ton)	0.331	33.14	6.16E-03	MT/Ton
Sand *(Cyd)	0.292	47.34	1.08E-04	MT/Cyd
RAP *(Ton)	0.142	14.20	4.92E-03	MT/Ton
Overall Emissions (MT CO_2)/ Ton of HMA	**1.11E-02**			

Table 4-7: Concrete Panel Mix Design

Concrete Panel Mix Design				
Component	Weight/Volume	Unit	Emission Factor	Unit
Cement	1.722	Tons	8.42E-01	MT/Ton
Course Agg	5.806	Tons	6.16E-03	MT/Ton
Fine Agg	2.293	Cyds	1.08E-04	MT/Cyd
Steel	0.085	Tons	5.20E-01	MT/Ton
Curing Compound	0.720	Gallons ($18.30/Gal)	0.96	MT/$1000
Equivalent to 6.105 Cyds and Approximately 12.242 Tons (11.105 MT) *Sand = 120 pcf				
Overall Emissions (MT CO_2)/Panel	**1.5417**			
Overall Emissions (MT CO_2)/100MT	**13.880**			

Table 4-8: HMA Panel Mix Design

HMA Panel Mix Design				
Component	Weight/Volume	Unit	Emission Factor	Unit
Binder	0.694	Tons	1.57E-01	MT/Ton
Aggregate	4.325	Tons	6.16E-03	MT/Ton
Sand	3.814	Cyds	1.08E-04	MT/Cyd
RAP	1.853	Tons	4.92E-03	MT/Ton
Bond Coat	0.800	Gallons ($6.90/Gal)	1.45	MT/$1000
Equivalent to 13.05 Tons (11.838 MT) HMA *Sand = 120 pcf				
Overall Emissions (MT CO_2)/Panel	**0.1532**			
Overall Emissions (MT CO_2)/100MT	**1.294**			

The Society of Environmental Toxicology and Chemistry (SETAC) guidelines for conducting a LCA, states that if the material comprises less than 1% of the total product, it can be neglected in the LCA [59]. Therefore, concrete admixtures such as air entrainer and set modifier, along with HMA additives, have been omitted from this calculation.

These emissions are estimated from the panel designs and can be compared to the metrics provided in a recent National Cooperative Highway Research Program (NCHRP – GreenDOT) study [15]. The metric for the concretic materials is comparable. However, the discrepancies in the metric for asphaltic materials are due to choices of emission metrics used as described below:

1. Aggregate Factor:
    a. Used in this research: 0.00616 MT CO_2/MT
    b. Used in NCHRP Study: 0.012 MT CO_2/MT
2. Binder factor:
    a. Used in this research: 0.157 MT CO_2/MT
    b. Used in NCHRP Study: 1.237 MT CO_2/MT

These emissions factors were used because there is precedence of their use in other credible LCA studies [38, 39].

4.5.2. CO_2 Equivalent Emissions of On-Road Vehicular Traffic

CO_2 emission equivalents were estimated using a metric derived in the vehicle use scenarios modeled in MOVES. The metric used was MT of CO_2 emissions/day/mile/1000 vehicles – its calculation has been explained in a previous section.

4.5.3. Life Cycle CO_2 Equivalent Emissions

Life cycle GHG emissions can be estimated by summing all product, process, and service components described earlier in this section. The life cycle components for an analysis period of *N* can be summarized as follows:

1. Construction emissions (includes product and process emissions plus the emissions due to traffic delays).
2. Maintenance emissions (includes product and process emissions plus the emissions due to traffic delays). Total number of maintenance emissions is equal to the number of interventions over the analysis period. The number and timing of the maintenance operations can be estimated from the highway historical performance.

3. Total service phase emissions (includes the emissions resulting from on-road vehicular traffic) as estimated using the MOVES simulator.

Sum of each of the above components provides the gross emissions, *E* for the pavement section over the entire time horizon of *N* years. The relevant metric is the equivalent uniform annualized emissions expressed the same way as the equivalent uniform annualized cost is in a lifecycle cost analysis.

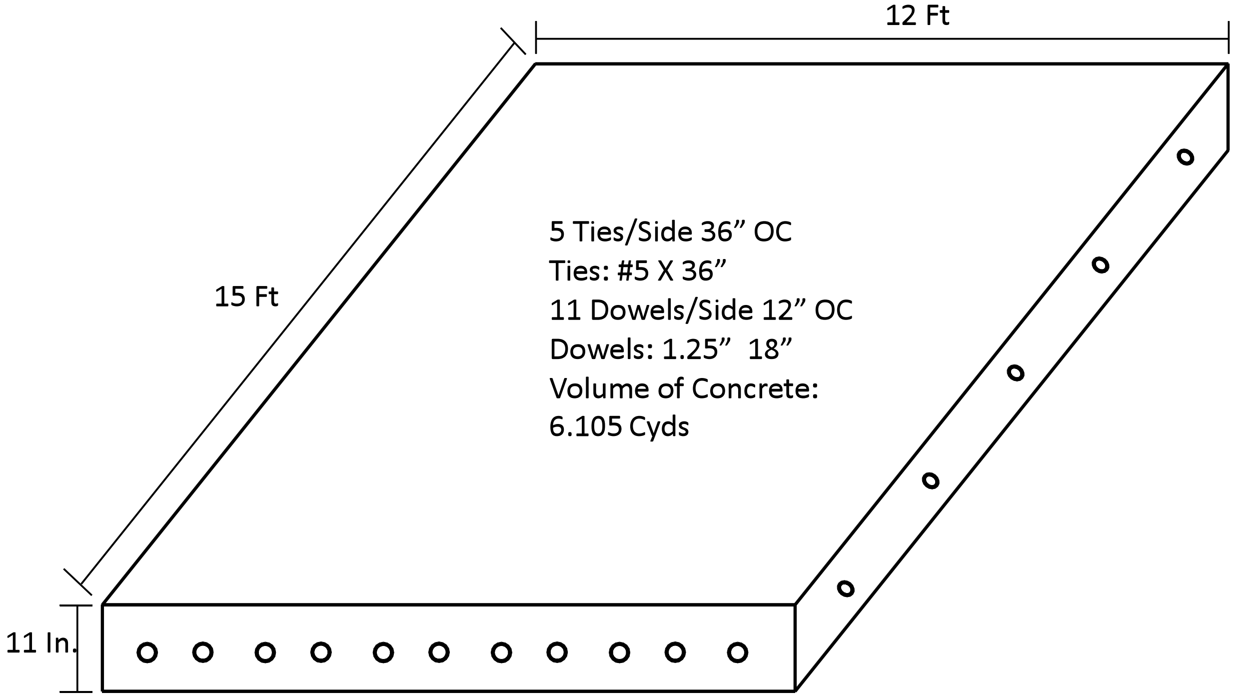


Figure 4-1: Concrete Panel Design

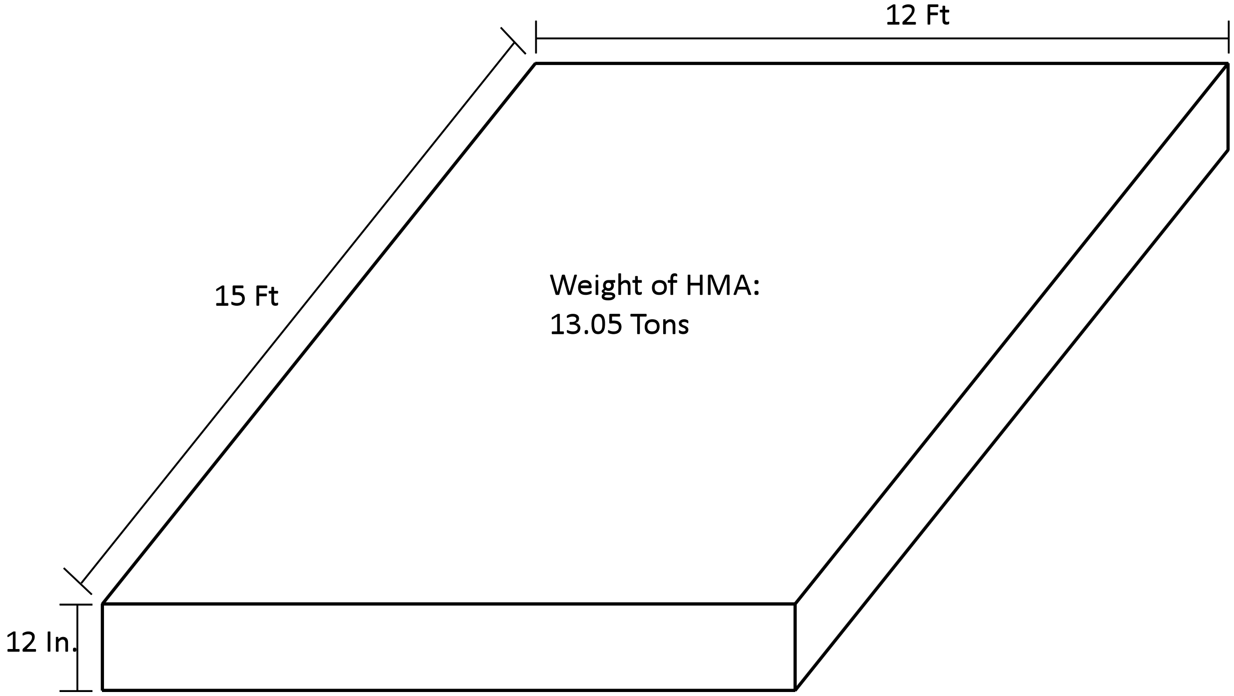


Figure 4-2: HMA Panel Design

5. FRAMEWORK IMPLEMENTATION

This chapter illustrates the implementation of the project based LCA framework involving the following steps for each project surveyed:

1. Visits to assess project location and collect information such as position of batch plant
2. Meeting with contractors, project managers and MDOT inspectors to communicate the purpose of the project and solicit help with recording equipment use information

For all the projects the following steps were conducted:

1. Product and process data as described in Chapter 4 were remotely accessed from InfoTech's database and organized into a working schema on the Michigan Tech University server
2. Material and equipment use inventories (record of all equipment and material usage and relevant construction site data) were developed
3. The emission factors as explained and documented in Chapter 4 were used to calculate the emissions for product and process components for each of the projects
4. The functional metrics as defined in Chapter 4 were calculated for each project

This chapter describes the data collection, and organization process, followed by an explanation of the tool called Project Emission Estimator or PE-2 that can be used as a decision-support system for benchmarking future projects.

Each of the projects was classified into four categories: New construction/ major construction (R1), Reconstruction (R2), Major rehabilitation (M1), Rehabilitation (M2); based on size and type of the project. The projects that were investigated in this study are [60]:

1. Project number 11056-50757 (R1): 3.27 mi of road reconstruction, ramps, culverts and permanent traffic recorders on US-31 northbound and southbound from the Michigan state line northerly to US-12, Berrien County. Alternate 1 is hot mix asphalt road reconstruction and related items and Alternate 2 is concrete road reconstruction and related items. The State DOT invited bids for the reconstruction on two alternative pavement designs: one using

HMA and the other using concrete. The project was awarded to a bid that had the lowest life cycle cost, which in the competitive bidding process was the HMA design.

2. Project number 03033-75215 (R2): 6.94 mi of concrete overlay rehabilitation, pavement removal, concrete pavement reconstruction, culvert replacements, signing, pavement markings, median cable barrier installation, rest area demolition and construction, landscaping, concrete deck overlay, and railing replacement on I-196 from 71st Street northerly to 118th Avenue and on I-196 over 71st Street, Allegan County.
3. Project number 44043-79776 (R1): 10.14 mi of concrete pavement and shoulder reconstruction, guardrail and drainage improvements, and bridge rehabilitation of 12 bridges on I-69 from east of M-15 easterly to east of M-24, Genesee and Lapeer Counties.
4. Project number 05071-79647 (R2): 3.00 mi of crack relief, asphalt crack relief layer, reconstruction, crushing and shaping with hot mix asphalt widening, miscellaneous drainage, safety improvements, decorative sidewalk, decorative lights, and tree planting on US-131 from Elder Road northerly to M-66 and from north of Dale Avenue to south of Division Street in the village of Mancelona, Antrim County.
5. Project number 52041-80145 (R1): 3.02 mi of roadway reconstruction and realignment, drainage improvements, guardrail upgrading, and pavement markings on US-41/M-28 from Brown Road westerly to the Marquette/Baraga County line, Marquette County.
6. Project number 55011-84193 (R1): 2.02 mi of street reconstruction including excavation, hot mix asphalt pavement, concrete curb and gutter, sidewalk, storm sewer, sanitary sewer, water main, traffic signals, permanent signing, pavement marking, and restoration on US-41 from 20th Avenue northerly to 48th Avenue in the city of Menominee, Menominee County. (Data collected from Yr 1 of 2)
7. Project number 56021-105611 (M1): 4.16 mi of hot mix asphalt cold milling and overlay, joint repairs, shoulder upgrades behind the existing curb and gutter, sidewalk ramp upgrades, and other miscellaneous work on M-20 from west of Meridian Road easterly to east of Vance Road, Midland County.
8. Project number 41031-105479 (M1): 0.81 mi of full depth concrete pavement joint and crack repairs on M-37 (Broadmoor Avenue) from north of 60th Street northwesterly to south of 52nd Street, in the city of Kentwood, Kent County.

9. Project number 51021-106248 (M1): 6.83 mi of hot mix asphalt cold milling and resurfacing on M-55 from west of Udell Hills Road to west of Cooley Bridge, Manistee County.
10. Project number 02041-106939 (M1): 4.63 mi of concrete pavement repairs, hot mix asphalt cold milling and resurfacing, drainage structure repairs and sidewalk ramps on M-28 from east of Center Street easterly to west of the Anna River bridge, in city of Munising, Alger County.
11. Project number 51012-106238 (M2): 4.35 mi of overband crack filling, micro surfacing, centerline and shoulder corrugations, and pavement markings on US-31 from north of US-10 to south of Hansen Road and from north of M-55 to south of M-22, Mason and Manistee Counties.
12. Project number 11112-106504 (M2): 8.63 mi of transverse and longitudinal joint resealing with isolated transverse crack sealing on US-31 northbound and southbound from M-139 to Napier Avenue, Berrien County.
13. Project number 37014-106474 (M2): 12.76 mi of crack treatment and single course micro surfacing on US-127 from River Road northerly to the Isabella/Clare County line, Isabella County.
14. Project number 83033-106529 (M2): 7.10 mi of overband crack filling and single course micro surfacing on US-131 northbound and southbound from south of Boon Road northerly to south of Old US-131, Wexford County.

For each of the projects the data was collected for product and process components as described in Chapter 4 and organized in a database server that is hosted on a web server at Michigan Tech University. A web-based tool the PE-2 was developed to provide an interface to querying the data and directly accessing all the calculated metrics.

5.1. Project Emissions Estimator (PE-2)

PE-2 is an interactive web-based service that was developed primarily using PHP: Hypertext Preprocessor (PHP) – a general purpose scripting language that is interpreted by a web server and used to dynamically generate web pages. PE-2 also uses Ajax technology - a combination of Javascript, CSS and HTML that create interactive web pages - to support a user-friendly interface primarily designed for contractors and agency decision-makers.

The PE-2 tool can be accessed at http://www.construction.mtu.edu:8000/cass_reports/webpage/. The goal of the PE-2 tool is two-fold:

1. Inventory Reporting: The PHP code queries the data server and calculates the GHG emissions using the methodology described in Chapter 4. Hence, the user can choose a project, the PE-2 tool queries all relevant product and process data that was collected and dynamically creates a report for the particular project. The functional metrics are reported for each project as well.
2. Benchmarking & Estimating: The PE-2 web service provides an interactive web interface for decision-makers and contractors to aid them in benchmarking their projects. It uses the same methods used in calculating the emissions for the projects studied, as explained in Chapter 4. However, it allows the user to provide the input through an easy to use interface. The input consists of materials and respective quantities, and the type, number and hours of estimated equipment usage (product and process). To make the interface easy to use, the user can choose the materials and equipment from a predefined list. In addition, the material list in the drop-down menu is classified by MDOT pay-item specifications to allow for easy navigation. The estimator tool also allows users to benchmark equivalent annualized emissions for a project by providing traffic characteristics and an expected maintenance schedule. It uses benchmark values for emissions of construction, reconstruction and maintenance operations based on the surveyed 14 projects and the estimated emission metrics for the project section given the simulated trends from the MOVES simulator.

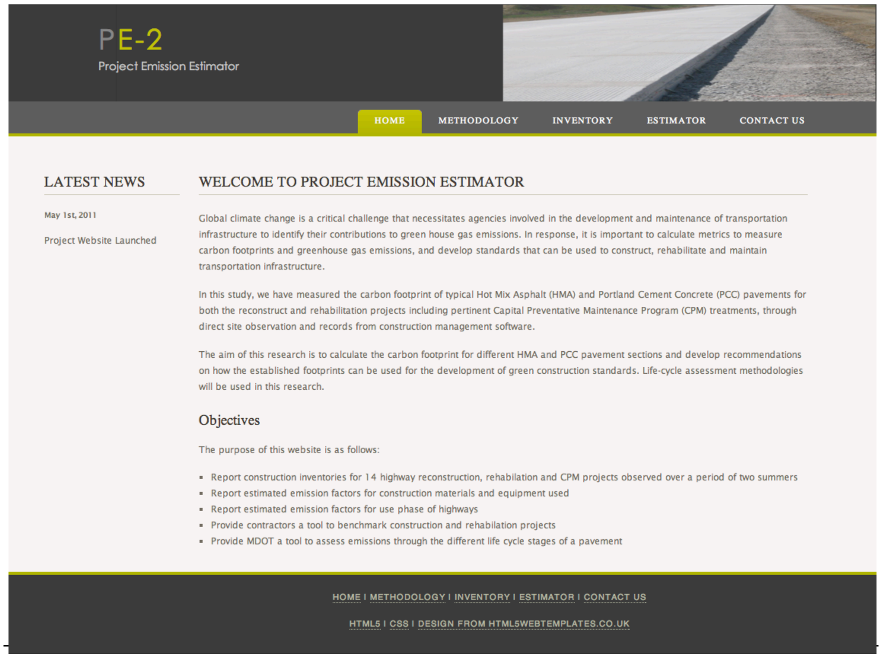
The PE-2 interface has four main tabs with the following functionalities:

1. Home: Introduction to the project and the purpose of the tool (See Figure 5-1).
2. Methodology: Introduction to the underlying methodology.
3. Inventory: This is the inventory reporting interface. It provides a summary of the product and process emissions calculated. For each project a report is generated (See Figure 5-2).
4. Estimator: This is the estimator interface and has three components to it:
    a. The materials estimator: Figure 5-3 illustrates the interface that allows users to add materials to a list by choosing the material from a list of items classified by pay-item divisions specified by MDOT. As the list builds, the summation button

at the bottom of the page sums up the total emissions and the page can be printed off as a report.

b. The equipment estimator: Figure 5-4 illustrates the interface that allows users to add number of equipment and number of hours of estimated usage, to a list by choosing the equipment from a list of classified by the activities that typically the items are associated with. As the list builds, the summation button at the bottom of the page sums up the total emissions and the page can be printed off as a report.

c. The life cycle estimator: Figure 5-4 illustrates the interface that allows users to input project traffic characteristics and progressively build a construction and maintenance schedule to estimate the expected life cycle emissions. An example has been illustrated later in the chapter.



LATEST NEWS

May 1st, 2011

Project Website Launched

WELCOME TO PROJECT EMISSION ESTIMATOR

Global climate change is a critical challenge that necessitates agencies involved in the development and maintenance of transportation infrastructure to identify their contributions to green house gas emissions. In response, it is important to calculate metrics to measure carbon footprints and greenhouse gas emissions, and develop standards that can be used to construct, rehabilitate and maintain transportation infrastructure.

In this study, we have measured the carbon footprint of typical Hot Mix Asphalt (HMA) and Portland Cement Concrete (PCC) pavements for both the reconstruct and rehabilitation projects including pertinent Capital Preventative Maintenance Program (CPM) treatments, through direct site observation and records from construction management software.

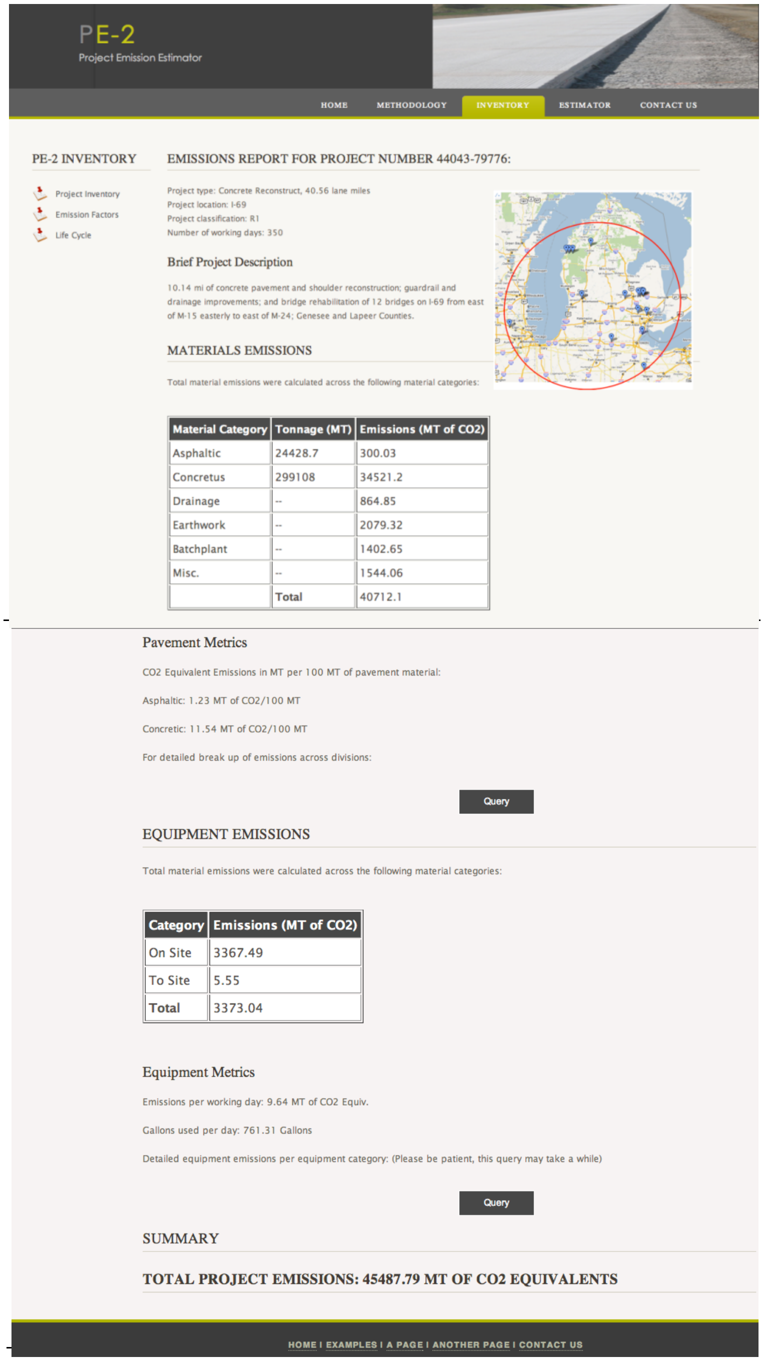
The aim of this research is to calculate the carbon footprint for different HMA and PCC pavement sections and develop recommendations on how the established footprints can be used for the development of green construction standards. Life-cycle assessment methodologies will be used in this research.

Objectives

The purpose of this website is as follows:

- Report construction inventories for 14 highway reconstruction, rehabilation and CPM projects observed over a period of two summers
- Report estimated emission factors for construction materials and equipment used
- Report estimated emission factors for use phase of highways
- Provide contractors a tool to benchmark construction and rehabilation projects
- Provide MDOT a tool to assess emissions through the different life cycle stages of a pavement

Figure 5-1: PE-2 Homepage



PE-2 INVENTORY

EMISSIONS REPORT FOR PROJECT NUMBER 44043-79776:

Project type: Concrete Reconstruct, 40.56 lane miles
Project location: I-69
Project classification: R1
Number of working days: 350

Brief Project Description

10.14 mi of concrete pavement and shoulder reconstruction; guardrail and drainage improvements; and bridge rehabilitation of 12 bridges on I-69 from east of M-15 easterly to east of M-24; Genesee and Lapeer Counties.

MATERIALS EMISSIONS

Total material emissions were calculated across the following material categories:

Material Category	Tonnage (MT)	Emissions (MT of CO2)
Asphaltic	24428.7	300.03
Concretus	299108	34521.2
Drainage	--	864.85
Earthwork	--	2079.32
Batchplant	--	1402.65
Misc.	--	1544.06
	Total	40712.1

Pavement Metrics

CO2 Equivalent Emissions in MT per 100 MT of pavement material:

Asphaltic: 1.23 MT of CO2/100 MT

Concretic: 11.54 MT of CO2/100 MT

For detailed break up of emissions across divisions:

EQUIPMENT EMISSIONS

Total material emissions were calculated across the following material categories:

Category	Emissions (MT of CO2)
On Site	3367.49
To Site	5.55
Total	3373.04

Equipment Metrics

Emissions per working day: 9.64 MT of CO2 Equiv.

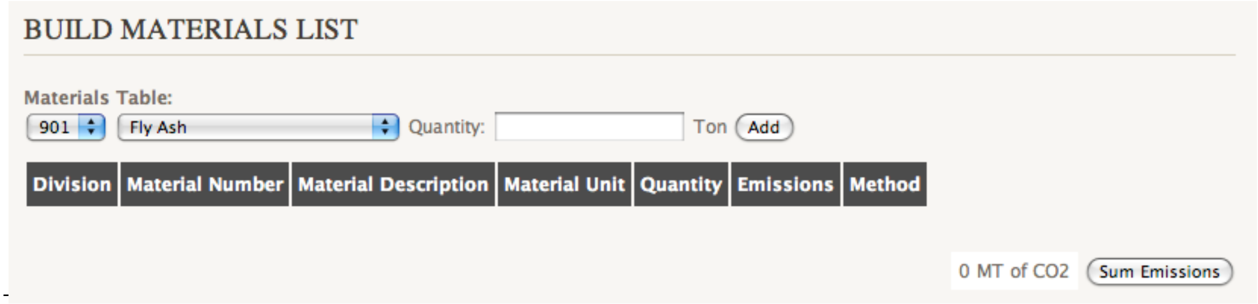
Gallons used per day: 761.31 Gallons

Detailed equipment emissions per equipment category: (Please be patient, this query may take a while)

SUMMARY

TOTAL PROJECT EMISSIONS: 45487.79 MT OF CO2 EQUIVALENTS

Figure 5-2: Project Inventory Report



BUILD MATERIALS LIST

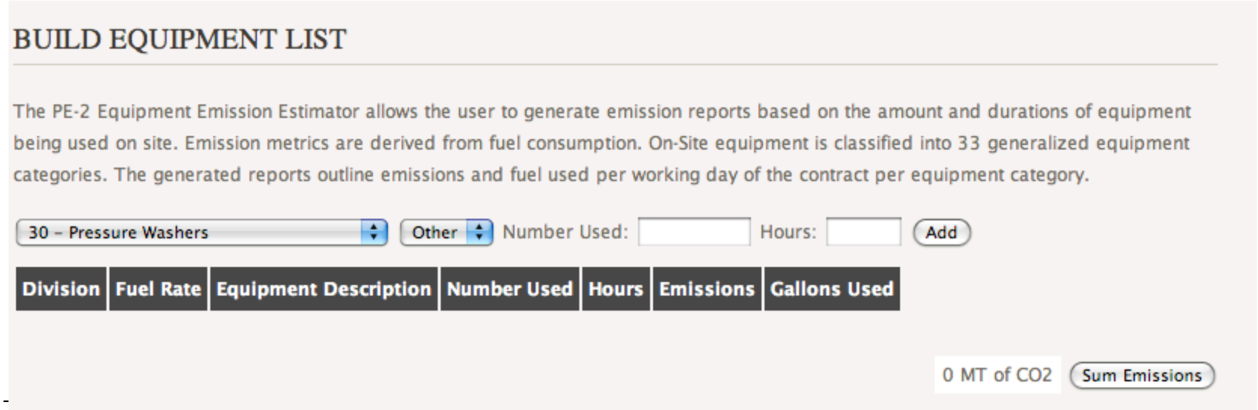
Materials Table: 901 Fly Ash

Quantity: Ton

Division	Material Number	Material Description	Material Unit	Quantity	Emissions	Method

0 MT of CO2

Figure 5-3: Material Impact Estimator



BUILD EQUIPMENT LIST

The PE-2 Equipment Emission Estimator allows the user to generate emission reports based on the amount and durations of equipment being used on site. Emission metrics are derived from fuel consumption. On-Site equipment is classified into 33 generalized equipment categories. The generated reports outline emissions and fuel used per working day of the contract per equipment category.

30 – Pressure Washers Other

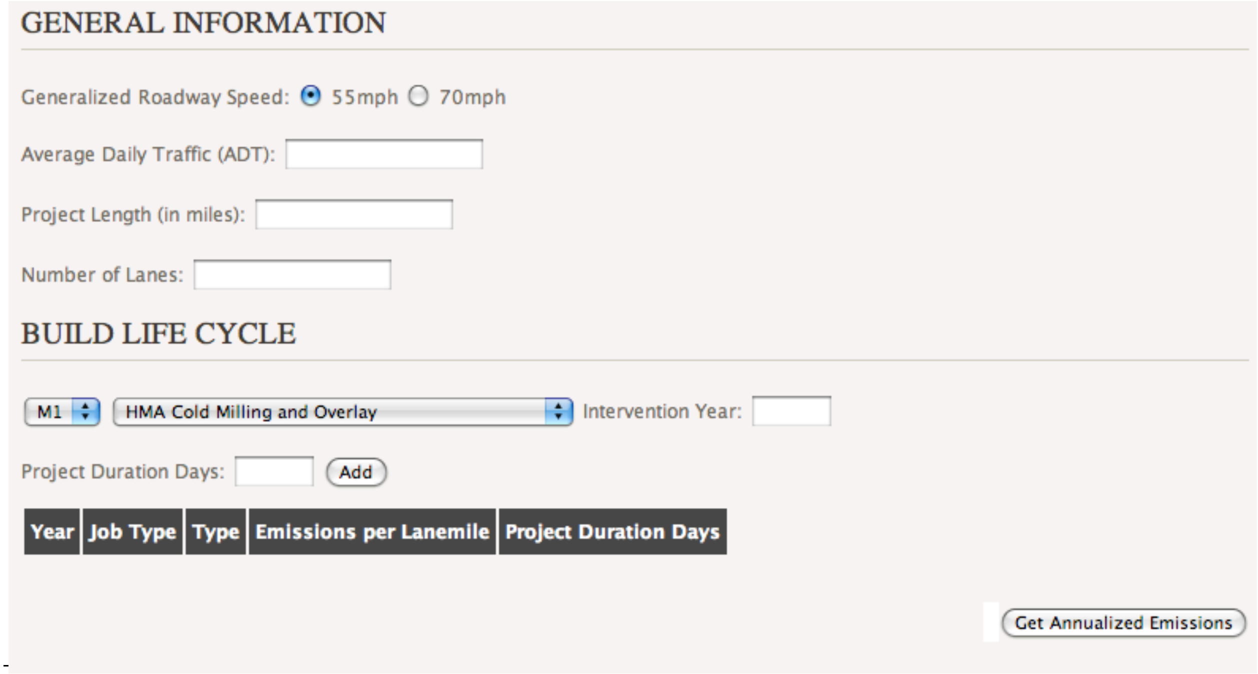
Number Used:

Hours:

Division	Fuel Rate	Equipment Description	Number Used	Hours	Emissions	Gallons Used

0 MT of CO2

Figure 5-4: Equipment Impact Estimator



GENERAL INFORMATION

Generalized Roadway Speed: ● 55mph ○ 70mph

Average Daily Traffic (ADT):

Project Length (in miles):

Number of Lanes:

BUILD LIFE CYCLE

M1 HMA Cold Milling and Overlay

Intervention Year:

Project Duration Days:

Year	Job Type	Type	Emissions per Lanemile	Project Duration Days

Figure 5-5: Life Cycle Impact Estimator

5.2. Inventory Assessment

This section outlines the general results that were observed from an assessment of the project emissions data. This section investigates the metrics described in Chapter 4 under the following categories:

- Product Emissions: Primarily focusing on materials used in construction projects.
- Process Emissions: Primarily focusing on construction operations common to most highway projects.
- Service Emissions: Primarily focusing on emissions during the service life of the pavement dependent on maintenance scheduling and vehicular traffic emissions.

5.2.1. Product Emissions

The product emissions can be classified into the following categories:

- The concretic material tonnage was calculated by summing all the material used for work in MDOT sections 901, 903, 905, 914, 915 and total tonnage of concrete in any other section (this is usually extremely small). The emissions observed for this material cluster was divided by the total tonnage for the cluster and multiplied by 100 to produce the observed emissions per 100 MT of concretic material, and compared with the theoretical value calculated in section 4.5.1, u_{conc} = 13.88 MT per 100 MT.
- The asphaltic material tonnage was calculated by summing all the material used for work in MDOT section 904 and all volumes of HMA. The emissions observed for this material cluster was divided by the total tonnage for the cluster and multiplied by 100 to produce the observed emissions per 100 MT of asphaltic material, and compared with the theoretical value calculated in section 4.5.1, u_{asp} = 1.294 MT per 100 MT.
- The earthwork emissions were calculated by summing emissions from the material used for work in MDOT sections 902, 910, 916 and 917.
- The drainage emissions were calculated by summing emissions from the material used for work in MDOT sections 909 and 913.
- Materials in all other sections in division 9 were classified as miscellaneous.

The purpose of breaking up total project emissions into these categories is to create a metric that can be used to benchmark material emissions, instead of comparing one material/pavement type to another. Hence, major concrete pavement reconstruction projects had HMA use and vice versa. For all the observed projects the values were calculated as follows:

Table 5-1: Total Emissions in MT of CO_2 Equivalents

Type	Job	Concretic	Asphaltic	Earthwork	Drainage	Misc	Total	Lane Miles
M1	Concrete Patch Repairs and HMA Resurfacing	302.62	11.5	0	0	31.91	346.02	9.26
M1	Full Depth Concrete Pavt Joint and Crack Repairs	186.24	0	0	0	72.7	258.94	3.24
M1	HMA Cold Milling and Resurfacing	0	141.11	8.41	0	103.23	252.76	13.66
M1	HMA Cold Milling and Overlay	36.81	208.12	66.36	0.36	38.63	350.28	16.64
M2	Transverse and Long. Joint Cutting and Resealing (Conc.)	72.21	0	0	0	53.01	125.22	34.52
M2	Microsurface	38.31	2592.9	69.5	93.22	174.27	2968.2	51.04
M2	Overband Crack filling and Micro surface	25.64	227.2	7.71	0	34.68	295.23	8.7
M2	Overband Crack Seal and Microsurface	11.84	296.35	9.09	0	50.14	367.41	28.4
R1	HMA Reconstruct	97.86	1163.95	214.93	404.01	587.64	2467.57	13.08
R1	Concrete Reconstruct	32812.81	300.03	2066.04	864.85	1544.06	37587.79	40.56
R1	HMA Reconstruct and Roadway Realignment	36.21	251.71	283.92	374.16	275.78	1221.78	6.04
R1	Road Reconstruction HMA and Concrete	571.75	171.07	121.82	1139.36	59.58	2063.59	4.4
R2	Unbonded Concrete Overlay	18634.75	685.49	850.67	1089.18	1936.14	23196.24	27.76
R2	Asphalt Crack Relief Layer; Reconstruction; Crush and Shape	331.16	308.92	143.38	198.29	46.85	1028.58	6

The values presented in Table 5-1, show that for construction and reconstruction projects (R1 and R2) all the different material categories are well represented. For the maintenance projects, (M1 ad M2) the type of project influenced the distribution of emissions in each of the categories. *It is important to reiterate that the emissions for concretic and asphaltic materials categories are representative of a particular collection of materials and should not be confused as a comparison between with concrete and asphalt pavements.* The metric that showed the most significant trend was a measure of the emissions per 100 MT of concretic materials and asphaltic materials as defined in section 4.5.1. Specifically, an important trend was noticed, in the emissions per 100 MT of concretic material and asphaltic materials, across all the R1 and R2 projects, leading to the following notion:

The factors u'_{conc} *and* u'_{asp}*, calculated from the observed data represents a consistent metric across all projects, comparable to the theoretical estimates of* u_{conc} *and* u_{asp}*. Where* E_{conc} *and* E_{asp} *are the emissions associated with concrete and asphalt materials (as calculated from observed site data), and* M_{conc} *and* M_{asp} *are the weights in MT of all the concretic and asphaltic materials (as observed from site data), and*

$$E_{conc} \text{ x } (1/\ M_{conc}) = u'_{conc}\ ;\ E_{asp} \text{ x } (1/\ M_{asp}) = u'_{asp}$$

This notion could gain credibility if, the product of E_{conc} and $(1/M_{conc})$ is constant across all observed projects. The constant then would be equal to u'_{conc}. Similarly, across all observed projects, the product of E_{asp} and $(1/M_{asp})$ would be a constant and equal to u'_{asp}.

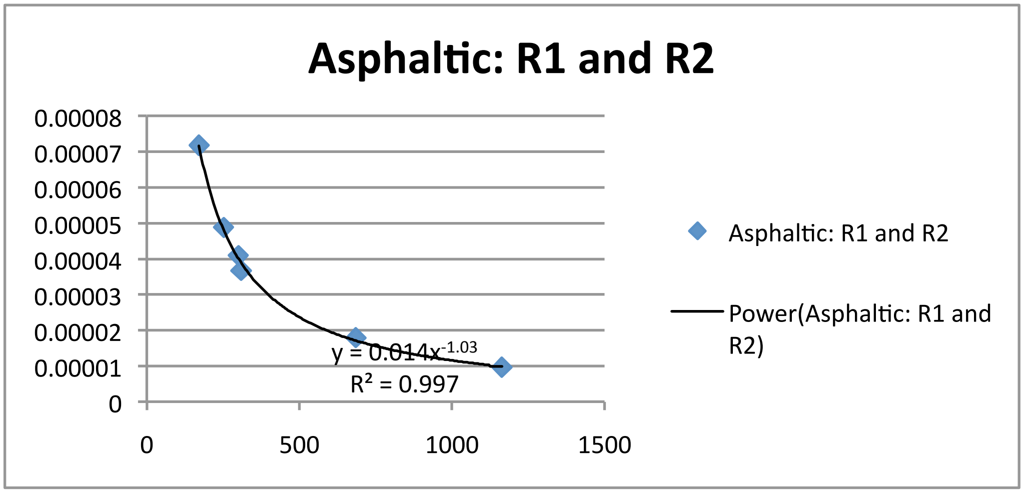


Figure 5-6: 1/M_{asp} (y-axis) vs. E_{asp} (x-axis) for R1 and R2 projects

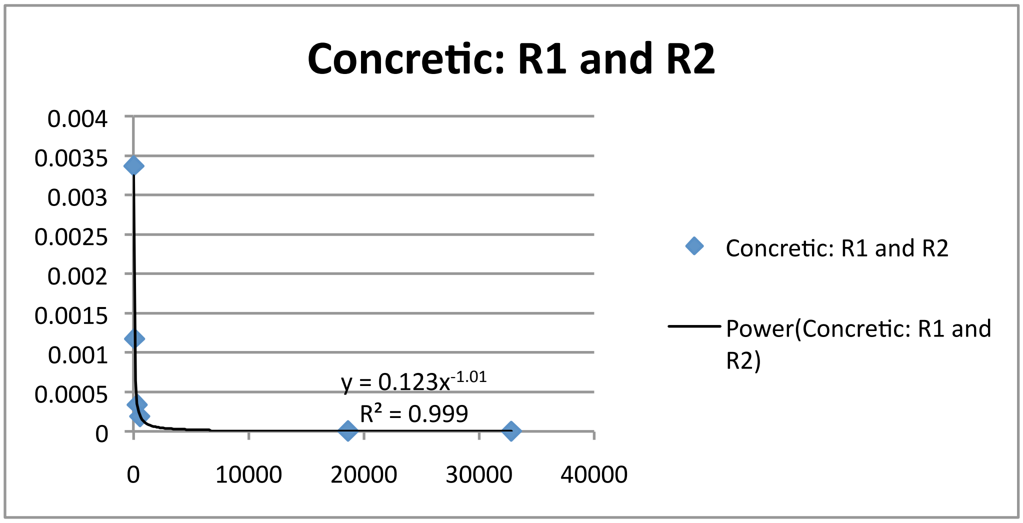


Figure 5-7: 1/M_{conc} (y-axis) vs. E_{conc} (x-axis) for R1 and R2 projects

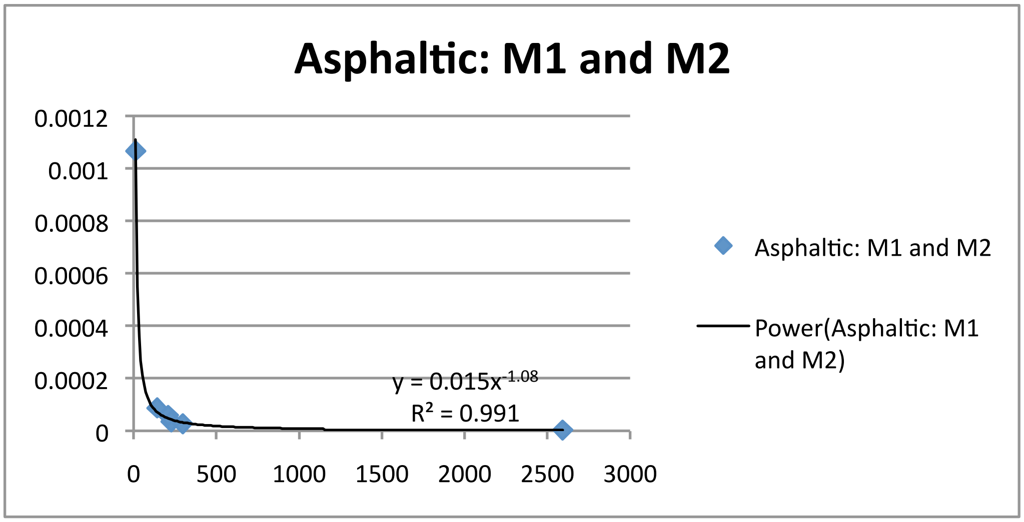


Figure 5-8: 1/M_{asp} (y-axis) vs. E_{asp} (x-axis) for M1 and M2 projects

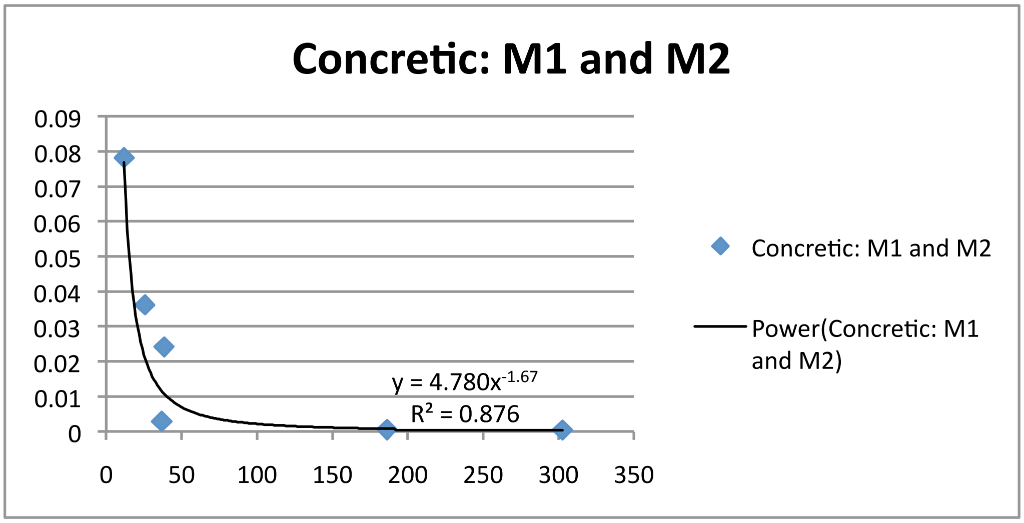


Figure 5-9: 1/M_{conc} (y-axis) vs. E_{conc} (x-axis) for M1 and M2 projects

Figures 5-1 through 5-4 illustrate the plots of 1/M_x versus E_x (x= concretic or asphaltic materials), for the different project classifications (R1 and R2, and M1 and M2). As can be seen from the regression models illustrated in Table 5-2, the observed metric validates the notion described above. In addition, it is similar to the calculated metric thus further adding credibility to the observation. This is a step towards establishing a metric to benchmark emissions for future projects.

The exception is the case representing M1 and M2 projects involving concretic materials. This may be possibly explained by the fact that the observed M1 and M2 projects were primarily asphalt pavements and had very limited use of concretic materials. In general the reliable metrics are the observed and calculated values for concretic and asphaltic materials for R1 and R2 project types.

Table 5-2: Emission Regression Models (metrics expressed in MT of CO_2 emissions/100 MT of material weight)

Project Type	Material Type	Regression Equation	R^2	Observed Metrics	Calculated Metrics
R1 and R2	Concretic material	$E_{conc}^{1.008} x (1/M_{conc}) = 0.1233$	0.99989	$u'_{conc} = 12.33$	$u_{conc} = 13.88$
	Asphaltic material	$E_{asp}^{1.034} x (1/M_{asp}) = 0.0146$	0.99743	$u'_{asp} = 1.46$	$u_{asp} = 1.296$
M1 and M2	Concretic material	$E_{conc}^{1.59} x (1/M_{conc}) = 4.7805$	0.87658	$u'_{conc} = 478.05$	$u_{conc} = 13.88$
	Asphaltic material	$E_{asp}^{1.089} x (1/M_{asp}) = 0.0159$	0.99145	$u'_{asp} = 1.59$	$u_{asp} = 1.296$

It is important to reiterate that the purpose of this metric is not to compare asphalt and concrete materials. The definitions of asphaltic and concretic materials are based on a clustering of specific material sections in division 9 that contribute to asphalt and concrete pavement construction respectively. The significance of the metric is that it can be used to estimate emissions for new projects based on a material estimate. It is also very important to note that this metric represents only emissions of materials in the pavement (product component) – and therefore is a reflection of only part of the pavement life cycle emissions. It strictly accounts for the cradle-to-gate emissions. The performance of a project and/or pavement accounts for emissions from the process and service components as well.

5.2.2. *Process Emissions*

This section investigates the emission from construction operations and schedule delays on construction sites. A particular project was studied in depth to illustrate how inefficiencies in project planning and scheduling can increase project emissions. This analysis builds on the method to collect and analyze construction project emissions data, and calculates the associated GHG emissions by comparing the as-planned and as-built schedules. The purpose of this analysis is to identify the impact of construction delays on project emissions. The delays often result from unexpected circumstances that unfold during the project construction, that were not or could not have been anticipated during the project planning process. It is expected that reduction in such delays and rework can reduce additional resource usage – as compared to the as-planned resource usage – thus increasing total project emissions. The following analysis investigates this notion by comparing the emissions associated with the as-planned resource loaded schedule and the as-built resource loaded schedule.

Data collected from FieldManager™ was used to develop the as-built observed schedule. The as-planned schedule was developed using the progress schedule (MDOT Form 1130) that is submitted by the contractors to MDOT project delivery engineers, before the construction start date. Also used to develop the as-planned schedule was the project proposal's engineering estimate (bid tab). The progress schedule outlines construction activities along with proposed starting and end dates for each activity. Driving activities, defining the actual construction of the roadway were identified and used. Henceforth they are referred to as primary activities. These activities were assigned a division of work and section number as defined in the Michigan Department of Transportation's (MDOT) Standard Specifications for Construction[48]. In addition, a controlling pay item was identified to represent each activity. These primary activities and controlling items were used to characterize the parameters in the schedule analysis.

It was necessary to identify primary activities and controlling items when assessing differences in schedule performance because the scope of this analysis is to investigate GHG emissions associated with the highway construction process in particular. The activities were chosen so that they are representative of typical highway construction projects. Therefore, mainline paving activities are considered as primary activities as they are common to all projects and variation in them due to site conditions can be compared across projects. However, traffic control activities were excluded, as there is limited data to support their inclusion.

The information from FieldManager™ was organized by tabulating the resources associated with each controlling item installed for each of the primary activities for each day of the project. The controlling item identification number (Pay Item #) identified in the as-planned schedule was also used generate as-built information from FieldManager™. Information representing daily activity and productivity information was analyzed. The controlling items were allocated to working dates, an identification number, quantities installed and equipment used. The importance of this data organization and classification is that it can be utilized to generate as-built schedules automatically from FieldManager™ data.

The data collected through FieldManager™ and outlined in the progress schedule and engineer's estimate was used to develop material and fuel inventories for the as-planned and as-built schedules, which in turn can be used to calculate emissions from materials and equipment used throughout the schedules. Using methodologies described in 4.4.1 & 4.4.2, emissions were estimated comparing as-built and as-planned material consumption and equipment usage.

5.2.3. Process Emissions Case Study

The case study involved in this analysis was a ten mile concrete pavement re-construction project (JN79776). Along the ten mile length of the job, pavement removal, earthwork and paving operations were performed in sequence. The schedule analysis was conducted at the level of primary activities – activities that are most critical to the construction project. For each of these activities, a controlling work item was chosen – items that had the most impact. The primary activities and associated controlling items is the major share of the project and therefore indicative of the overall project performance. The primary activities and associated controlling items identified were:

- Primary Activity: Remove Concrete Pavement
    - Controlling Item: Pavement Removal
- Primary Activity: Grade Subbase
    - Controlling Item: Station Grading
- Primary Activity: Install Drainage
    - Controlling Item: Underdrain Pipe
- Primary Activity: Place Base Material
    - Controlling Item: Geotextile Separator
- Primary Activity: Pave Mainline
    - Controlling Item: Non-reinforced Concrete

Figure 5-10 shows the as-planned schedule and as-built schedule production rates. The X-axis represents the time and the Y-axis representing the cumulative completion percentages of each activity. The analysis was done for only the eastbound mainline lanes of the project. When calculating the as-planned resource loaded schedule the bid tab quantities were used. However, the original bid tab quantities represent the entire project, not just mainline. Therefore, a ratio of as-built mainline quantities to that of the total quantities (as calculated from FieldManager^{TM} records) was calculated and applied to the bid tab quantities to calculate the as-planned quantities.

For each activity, controlling equipment was identified. Controlling equipment is the equipment that is crucial to the completion of the activity and likely to be the most important emitter. Each activity was assigned controlling equipment, as follows:

- Remove Concrete Pavement: Pavement Breaker
- Grade Subbase: Grader
- Install Drainage: Trencher
- There was no equipment related to the primary activity of placing base material as the related controlling item only required manual labor (4-man crew to place the geotextile separator)
- Pave Mainline: Concrete Pave

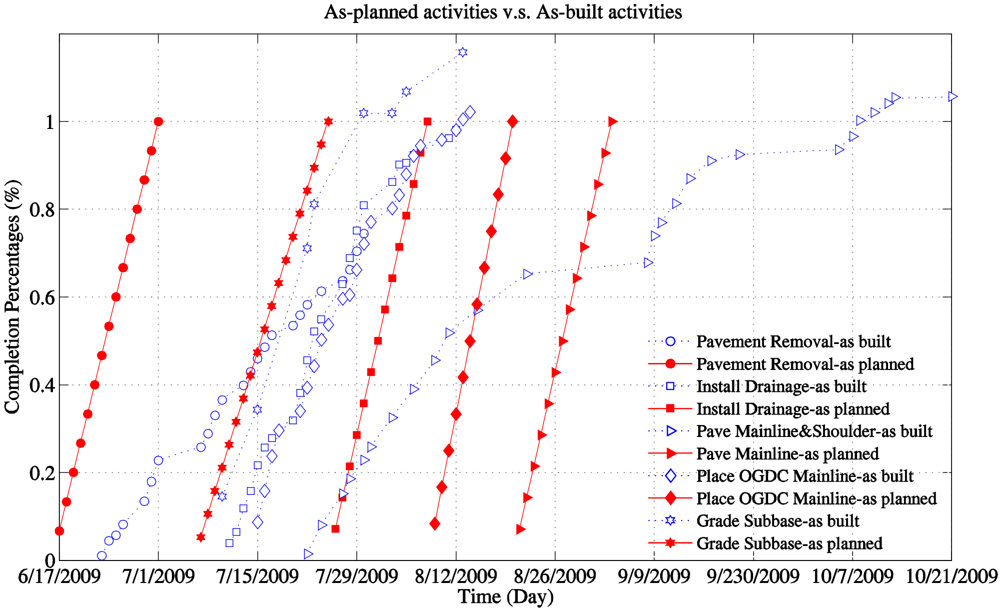


Figure 5-10: As-Planned vs. As-Built Schedule

During the pavement removal operation, the agitation of the soil and the presence of heavy equipment on site enhanced the capillary effect and caused ground water to flood the subgrade. In addition, seasonal rains added to the flooding on site and impeded all operations. After the site conditions were re-assessed, an undercut was excavated so that a geo-grid barrier could be placed and the sub-grade reconstructed to avoid future incidents of flooding. This resulted in a change order, involving the extra operations needed because of the unforeseen moisture problem (as shown in Figure 5-10). In most cases, it is estimated that there is a 5-10% increase in project costs [61] as result of most change orders - depending on work type, operations, and time. Greater accuracy of preliminary design and estimation methods can reduce the impacts of change orders. In this example, the unfortunate coincidence of the soil condition, and the consequences of heavy equipment on unprepared ground, led to significant project delays as was reflected in schedule delays and thus additional GHG emissions.

The investigation of how material consumption, equipment usage, and productivity of each activity affects the overall project GHG emissions can lead to recommendations for the design and management of the project. Table 5-3, Table 5-4, and Table 5-5 illustrate the differences between as-planned and as-built quantities and emissions from controlling materials and equipment. Figure 5-11, Figure 5-12, Figure 5-13, Figure 5-14, and Figure 5-15 compare the as-planned and as-built emissions for each of the primary activities due to the differences in use of the controlling pay-items and equipment.

Table 5-3: Quantity Comparison

Virgin Material Consumption based on Controlling Item (Quantities)					
Primary Activity	Controlling Item	Unit	AsPlanned	AsBuilt	% Change
			Qty	Qty	
Remove Concrete Pavement	Pavment Removal	Syd	249065.99	185431.46	-25.55
Grade Subbase	Station Grading	Syd	448.67	519.32	15.75
Install Drainage	Underdrain Pipe	Ft	110007.45	107945.00	-1.87
Place Base Material	Geotextile Separator	Syd	213236.10	217750.15	2.12
Pave Mainline & Shoulder	Non-reinforced Concrete	Syd	217358.96	229876.19	5.76

Table 5-4: Controlling Item Emissions

Virgin Material Consumption based on Controlling Item (Emissions)					
Primary Activity	Controlling Item	Unit	AsPlanned	AsBuilt	% Change
			GHG Emissions (MTCO$_2$eq)	GHG Emissions (MTCO$_2$eq)	
Remove Concrete Pavement	Pavment Removal	Syd	[1]NA		
Grade Subbase	Station Grading	Syd	[1]NA		
Install Drainage	Underdrain Pipe	Ft	45.0	44.1	-2.00
Place Base Material	Geotextile Separator	Syd	379	387	2.11
Pave Mainline & Shoulder	Non-reinforced Concrete	Syd	13600	14400	5.88
[1]No consumption of virgin materials					

Table 5-5: Controlling Equipment Emissions

Mainline Equipment Operations and Emissions based on Controlling Item								
Primary Activity	Equip	Item	Unit	As Planned	As Built	As Planned	As Built	% Diff
				# of days	# of days	GHG (MT)	GHG (MT)	
Remove Concrete Pavement	Pavement Breaker	Pavment Removal	Syd	15	24	5.66	9.06	60.00
Grade Subbase	Grader	Station Grading	Syd	19	8	14.87	6.26	-57.89
Install Drainage	Trencher	Under-drain Pipe	Ft	14	22	5.29	8.31	57.14
Place Base Material	[1]NA	Geo-textile Separator	Syd	[1]NA				
Pave Mainline & Shoulder	Concrete Paver	Non-reinforced Concrete	Syd	14	26	11.63	21.60	85.71
[1]Geotextile Seperator placed by manual labor (4-man crew)								

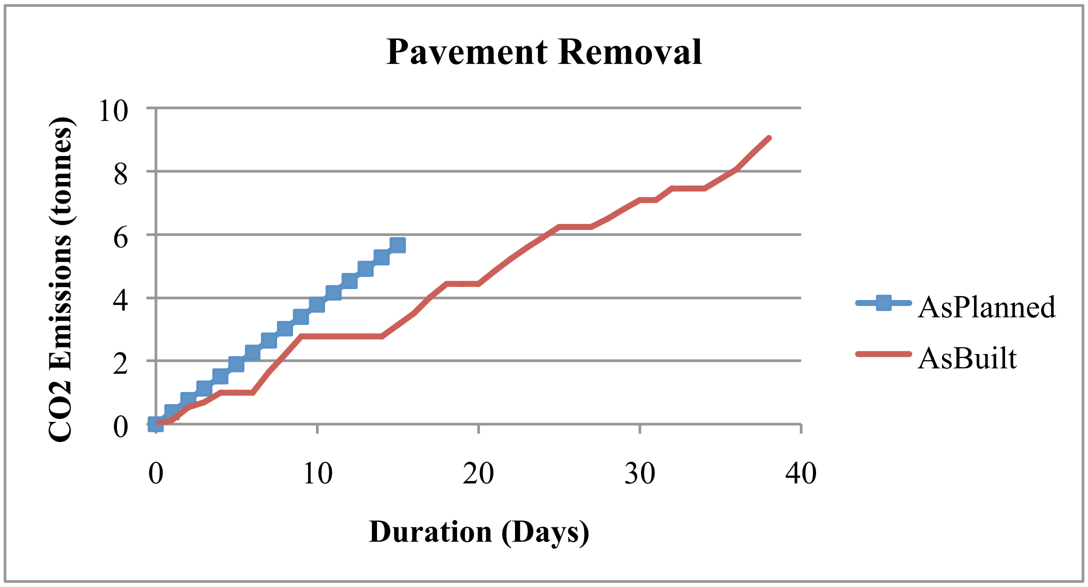


Figure 5-11: Pavement Removal Emissions

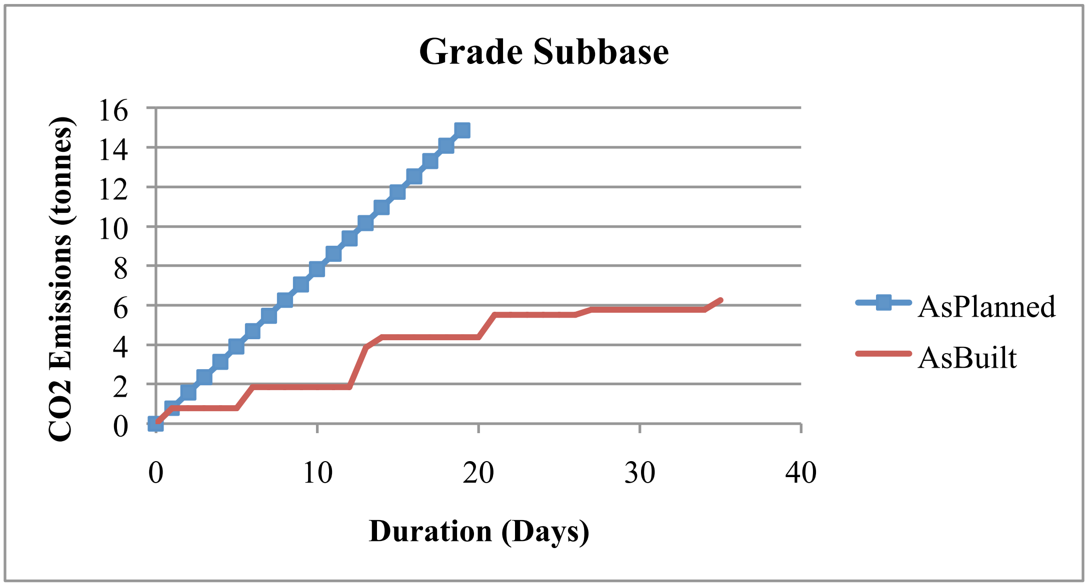


Figure 5-12: Grade Subbase Emissions

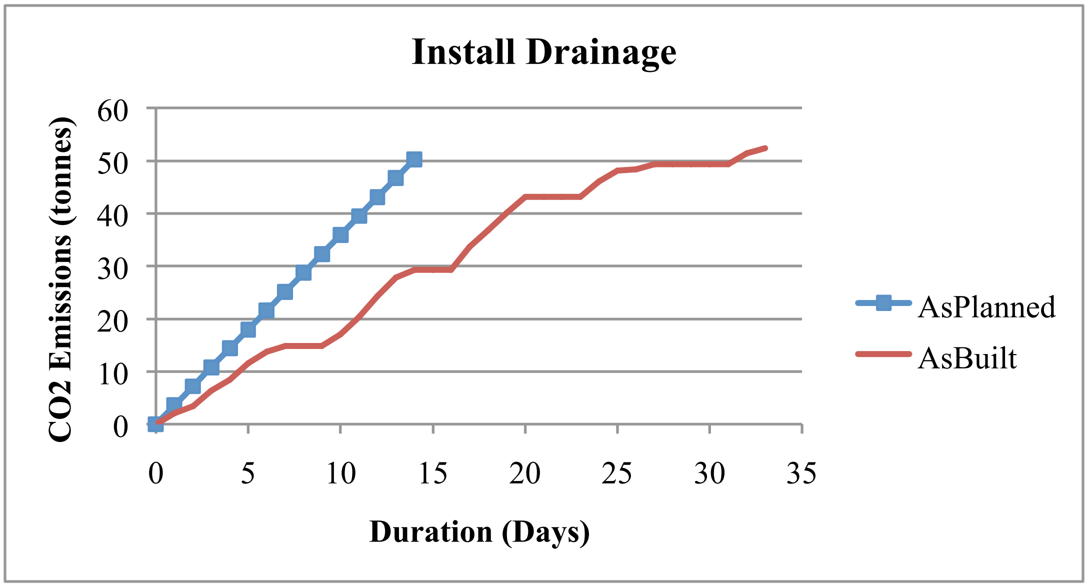


Figure 5-13: Install Drainage Emissions

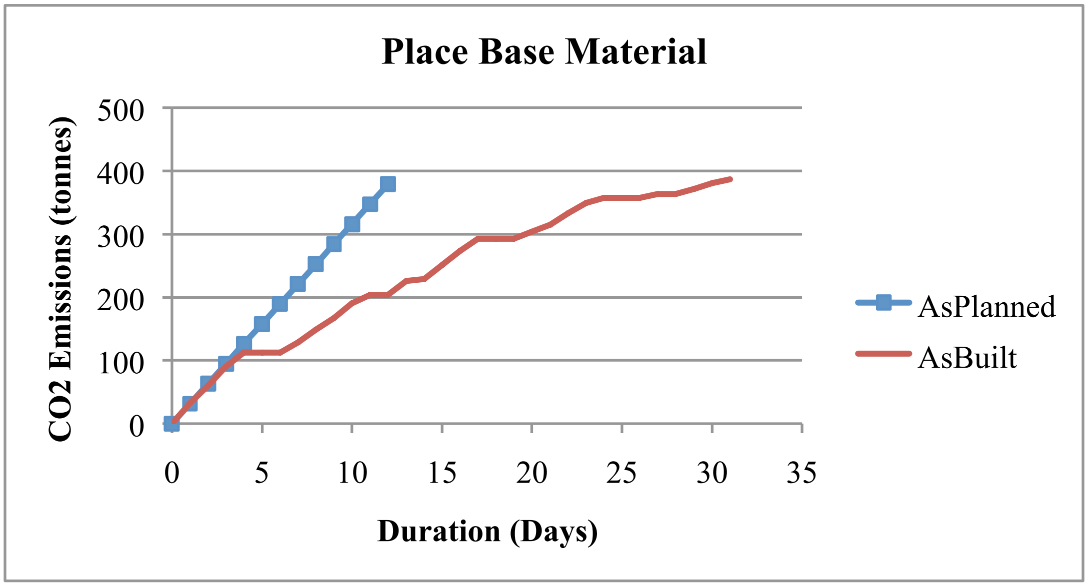


Figure 5-14: Place Base Material Emissions

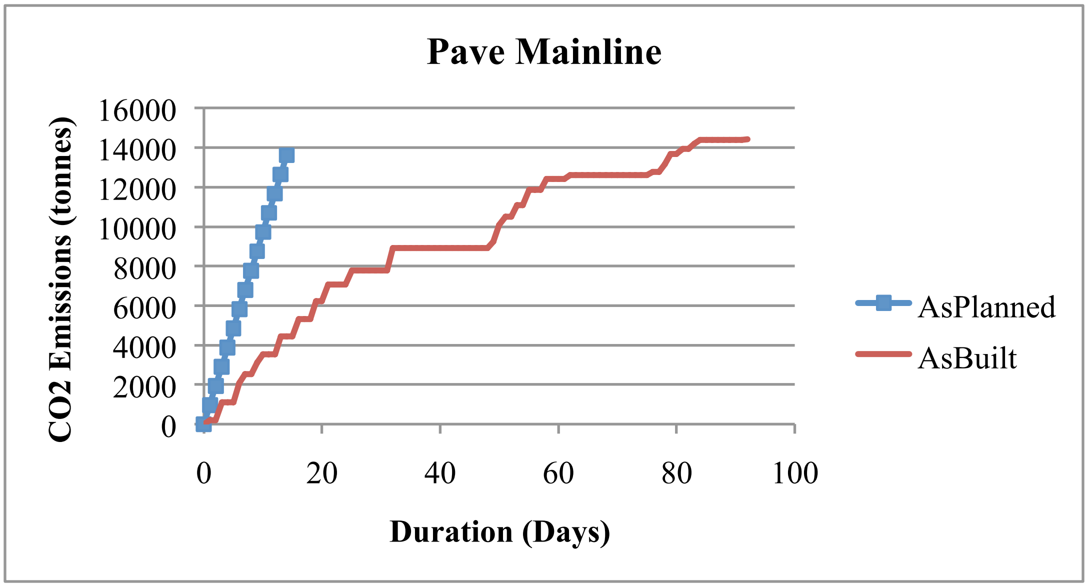


Figure 5-15: Pave Mainline Emissions

For this particular case study, a comparison of the as-planned and as-built schedules shows a significant increase in equipment use on site, resulting in 7.8 MT of extra CO_2 emissions. The impact of the extra materials used, as measured from their manufacturing phase, was approximately 807 MT of CO_2 emissions. The moisture problem encountered on site during the pavement removal operation, along with the re-construction of the sub-grade and installation of the geo-grid barrier, was largely responsible for the excess emissions. It is important to recognize that the increased emission can be directly ascribed to the oversight during the planning phase. Indeed, if the as-planned schedule had been realized, the extra emission could have been avoided. It also indicates that efficient schedules with shorter durations and robust contingency planning can go a long way in reducing project emissions without any monetary investment on behalf of the contractor. Besides, it also highlights that increasing efficiency and reducing GHG emissions of a highway construction project are aligned goals and beneficial to the contractor.

In order to estimate the value of reduction in emissions due to efficient planning, the following analogy can be considered. The emissions due to extra equipment use on site, 7.8 MT of CO_2 emissions, is equivalent to the emissions produced in generating electricity to power an entire household for one year, or the emissions from 325 propane cylinders used for home barbeques [62]. The emissions due to extra materials installed due to rework, 807 MT of CO_2 emissions, is equivalent to providing electricity to 100 homes for an entire year or the emissions from 33,000 propane cylinders used for home barbeques [62].

The result of this investigation shows that schedule delays and rework resulting from unexpected change orders during the construction process can lead to more than expected emissions on construction sites. Therefore, appropriate management of construction schedules and optimal use of materials and equipment on site during construction can significantly help in lowering emissions during highway construction. When considered for multiple construction projects across the nation, a focus on reducing emissions through better management of construction projects can result in significant savings. Management best practices developed in areas of lean construction and lessons learned from construction operation simulations and planning can be transferred and applied very successfully to achieve these goals. This analysis presents a first step towards more detailed future research.

The pertinent question raised is: how much should contractors and owners explicitly budget into their operation planning and management budget to avoid these delays and extra emissions, and more critically, at what point is the return on investment worth the savings in emissions? This leads to a multi-objective trade-off problem that is very similar to the time-cost trade-off problem. Alternatively, with appropriate benchmarking of emissions for typical highway construction projects, DOTs could consider incentive contracts that provide contractors incentives to reduce emissions during construction. While this is a very attractive idea, it also requires a reliable and easy method that can be used to measure construction site emissions. The methods presented in this section are a first step in developing such methods.

Future research work can lead to exact recommendations regarding specific construction operations. For example, what spatial and schedule constraints need to be explicitly considered when staging the paving operation and locating the batch plant, to minimize construction site travel distances. This research is in line with the development of point-based systems for reducing the emissions from highway construction, such as GreenRoads™ [19], which provide top-down prescriptive recommendations to practitioners. Results from more detailed analysis of construction schedules and operations will lead to bottom-up corroboration of such principles.

5.2.4. Service Emissions

Improved life cycle performance of highway sections plays a critical role in reducing GHG emissions. Long life pavements that require little or no major rehabilitation throughout its life promises to lower the overall life cycle GHG emissions. With this in mind, designing long-term pavements considering durability and longevity will change the way highway sections are constructed. Long-life pavements can lead to lower overall life cycle GHG emissions. One study showed that 40-year designs compared to 20-year designs results in shorter return on environmental investment [58]. However, long-term pavement performance studies are often limited due to limited regional availability of pavement construction performance data. Assessment of performance is critical to assess the long-term effectiveness of alternative materials (industrial by-products) and construction processes that promise to reduce the energy and greenhouse gas emissions [11]. A FHWA Long Term Pavement Performance (LTPP) study identified some early trends that indicate the dependence of long-term pavement performance on design and site conditions [63]. Ultimately, longer lasting pavements with reduced levels of maintenance can and will reduce life cycle GHG emissions. In this chapter, intervals of maintenance operation were investigated based on pavement condition to define a life cycle of flexible pavements in two regions of Michigan.

To define the overall pavement LCA, a life cycle period must be characterized outlining the various preventative maintenance strategies that will be implemented throughout the life of the highway section. Rehabilitation options are highlighted in MDOTs Capital Preventative Maintenance Manual [53], however, the time at which these options occur is not explicitly stated. Therefore, this research suggests deriving maintenance schedules based on historical performance of the pavement sections. This involves investigating historical pavement condition (Distress Index) data to determine when rehabilitation strategies are being carried out. Distress Index (DI) is a parameter used by MDOT to assess a pavement section's condition. It is a measure of the cracking distresses influencing the pavement's condition. A limited sub-set of data was used to investigate the performance of flexible pavements. For this analysis, regional variability was investigated. Distress index values were assessed over a 15-year period in two regions of Michigan and then compared to illustrate regional variability. The results of this analysis are outlined in Table 5-6. The third maintenance cycle was assumed to approach a DI of 35 before intervention.

From this limited performance/maintenance history analysis, the pavements in region 2 reach a higher DI before maintenance operations are executed. In addition, the age at which the intervention occurs varies. The maintenance cycles occur in region 2, on average, 1.44 years later than in region 1. This could be a result of climate conditions in each region, local preferences, or other indicators such as International Roughness Index (IRI) or rutting depth influencing when operations may occur.

Table 5-6: Regional Performance and Maintenance

Region 1			
Maintenance Operations			
	Cycle 1	*Cycle 2*	*Cycle 3*
Age (yrs)	6.04	10.13	15.3
Distress Index (Before/After)			
Value	10.01/2.55	11.4/2.2	35/0
Region 2			
Maintenance Operations			
	Cycle 1	*Cycle 2*	*Cycle 3*
Age (yrs)	7.44	12.75	15
Distress Index (Before/After)			
Value	27.3/11.4	24.7/17.5	35/0

This analysis can prove to be very beneficial in developing regional maintenance schedules that can be used as a guide to assess the environmental impacts of the maintenance phase of the LCA. Additionally, analysis like this can provide the essential timelines needed to define life cycle periods used in LCA. Performance based approaches like these promises to further the investigation of context sensitivity regarding the environmental impact of highway construction and maintenance operations.

5.3. Project Life Cycle Emission Estimation

A pavement's life cycle emissions are illustrated using the PE-2 estimator tool along with data from the observed MDOT projects. Figure 5-16 outlines a *conceptual plot* of the cumulative emissions associated with typical roadway’s life cycle. It illustrates the sub-components of the service life of a pavement, namely initial construction, followed by vehicle use phases punctuated by maintenance operations and concluded by a final reconstruction. It is important to recognize that the life cycle illustrated here as well as the maintenance schedule is purely to illustrate the underlying method used. Indeed the PE-2 estimation tool allows users to test the life cycle emissions for life cycles and treatments of their own choice. The associated emission calculation components can be broken down as follows:

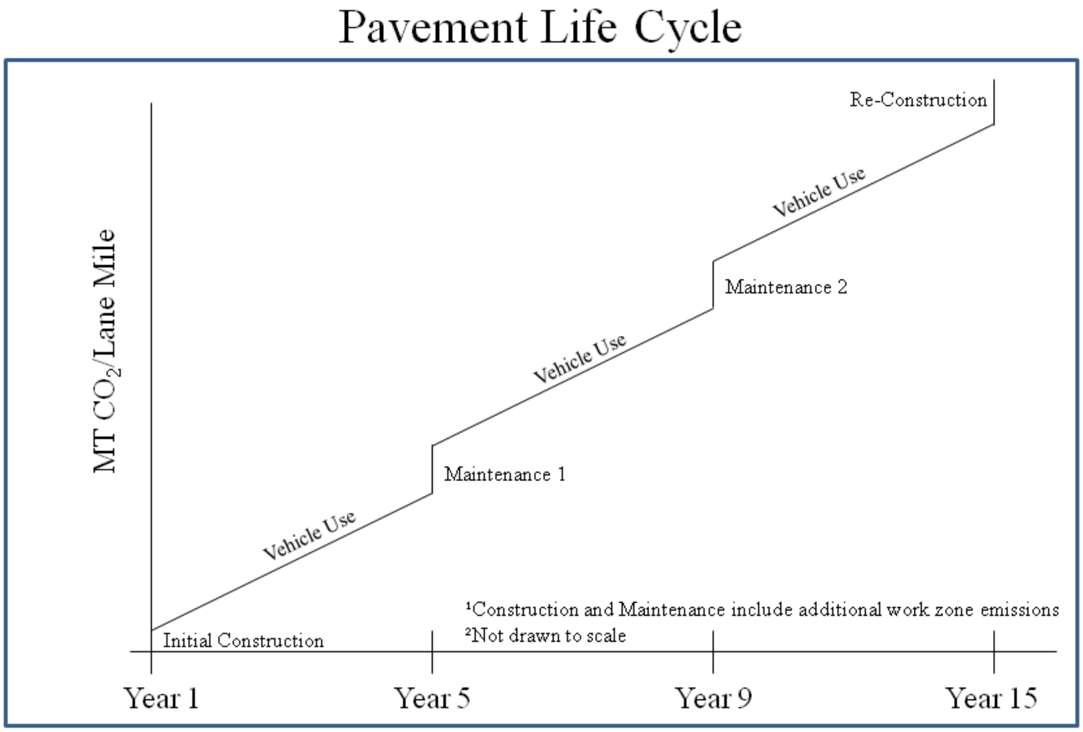


Figure 5-16: Conceptual Illustration of Pavement Life Cycle

- Emissions from construction operations during reconstruction and successive maintenance and rehabilitation operations:
  - Emissions from the manufacturing and processing of virgin and recycled materials
  - Emissions from on-site construction equipment
  - Emissions from hauling equipment hauling materials to and from the project site
  - Upstream impacts for the manufacturing of the fuel combusted in the construction and hauling equipment
  - Upstream impacts from the manufacturing of equipment being used on site
- Work Zone Emissions during construction and maintenance operations
  - Emissions associated with traffic delay throughout work zone durations
- Use Phase Emissions

- Emissions associated with vehicle use of the roadway

To illustrate the information outlined in Figure 5-16 Conceptual Illustration of Pavement Life Cycle the following example was modeled using the PE2 Life Cycle Tool and the following results were obtained:

General Project Information:

- Roadway Speed = 70mph
- Average Daily Traffic = 8800 vehicles/day
- Project Length = 10 miles
- Number of lanes = 4 (Results in 40 lane miles)

First intervention strategy:

- Emissions from US-31 HMA Reconstruct (PN50757) were used to account for year 1 initial construction and work zone emissions.
- The duration of the project was determined to be 197 days

Second intervention strategy:

- Emissions from US-31 Over band Crack seal and Micro surface (PN106529) were used to represent the first maintenance.
- Defined at year 5, project duration determined to be 22 days

Third intervention strategy:

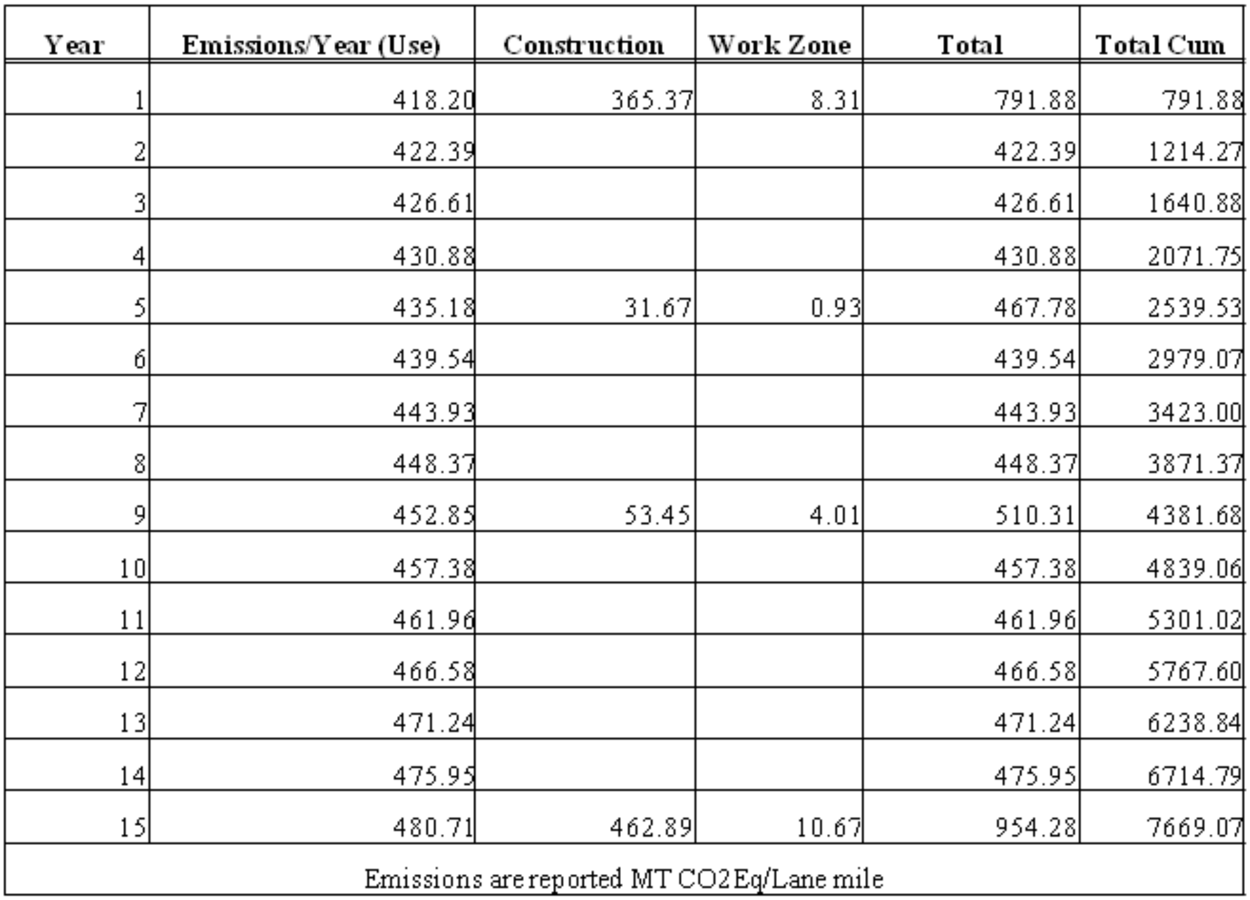
- Emissions from M-20 HMA Cold milling and Overlay (PN105611) were used to represent the second maintenance.
- Defined at year 9, project duration determined to be 95 days

Final intervention strategy:

- Emissions from US-41 HMA Reconstruct and Realignment (PN80145) were used to represent the end-of-life.
- Defined at year 15, project duration determined to be 283 days

Results from the life cycle illustration are outlined in Table 5-7 and Figure 5-17. Emissions associated with construction, maintenance and work zones are diminutive compared to emissions associated with vehicle use. Overall, annualized emissions per lane mile are approximately 511.27 MT CO_2 Eq/Year. In general, emissions from the use phase can represent 85-95% of the pavement life cycle.

Table 5-7: Life Cycle Emissions



Year	Emissions/Year (Use)	Construction	Work Zone	Total	Total Cum
1	418.20	365.37	8.31	791.88	791.88
2	422.39			422.39	1214.27
3	426.61			426.61	1640.88
4	430.88			430.88	2071.75
5	435.18	31.67	0.93	467.78	2539.53
6	439.54			439.54	2979.07
7	443.93			443.93	3423.00
8	448.37			448.37	3871.37
9	452.85	53.45	4.01	510.31	4381.68
10	457.38			457.38	4839.06
11	461.96			461.96	5301.02
12	466.58			466.58	5767.60
13	471.24			471.24	6238.84
14	475.95			475.95	6714.79
15	480.71	462.89	10.67	954.28	7669.07
Emissions are reported MT CO2 Eq/Lane mile					

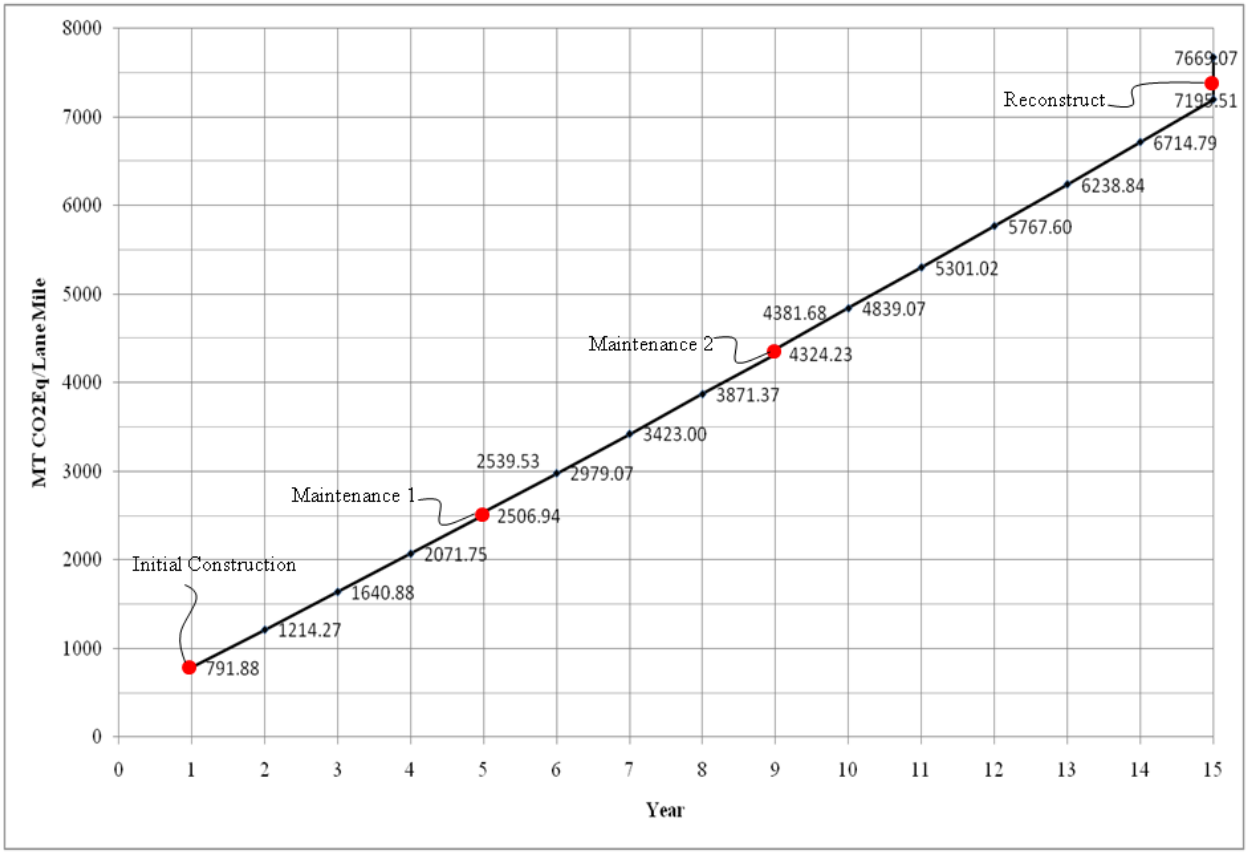


Figure 5-17: Life Cycle Emissions

6. RECOMMENDATIONS

This chapter outlines the primary recommendations that are being made to MDOT based on this research. The premises of the recommendations are that MDOT intends to reduce GHG emissions associated with the design, construction, maintenance, rehabilitation and use of HMA and PCC pavements. The main recommendations are as follows:

6.1. Data Reporting and Organization

It is critical for MDOT to recognize that development of GHG emission strategies is a dynamic process, requiring continuous monitoring of project performance. The strategies have to be updated to reflect improvements in construction technologies, such as equipment with improved fuel standards, are introduced in practice, and advances are made in sustainable material production processes and design. Continuous reporting and monitoring of material and equipment use on highway construction sites is going to play a crucial role in informing strategies. It is recommended that MDOT implement the data collection framework described in this report.

In order to minimally impact the reporting burden of the contractor and the inspectors on site, the following steps are recommended:

1. Currently equipment use reporting is not mandatory, and when contractors do report equipment usage, they use text fields to describe equipment type. This often results in different descriptions (spellings, reporting styles, etc.) of the same equipment. It is recommended that MDOT update the FieldManager^{TM} reporting interface in collaboration with Info Tech to reflect different equipment categories (see example implementation in PE-2 tool) in drop down menus to enable consistent and easy reporting of equipment types and quantity being used.
2. MDOT should encourage contractors to report batch plant usage data and provide estimates of distances travelled in transporting raw materials to construction sites. If voluntary reporting is not successful, MDOT can motivate contractors by requiring the information during the bid qualification process. Further monetary incentives can also be

introduced in the contracting process, particularly if contractors have an emission reduction plan in place.

3. In collaboration with InfoTech, implement a procedure by which the data collected through FieldManager^{TM} gets automatically transmitted to a database supporting tools like PE-2. This will ensure that a emissions report page can be automatically generated for each project without any direct intervention. In conducting this project, the data collected through FieldManager^{TM} was accessed by remotely accessing the InfoTech. The data was then transferred into the MTU database after a few steps of processing. This process can be automated in collaboration with InfoTech to ensure that actual emissions for all future projects can be monitored using the PE-2 tool.
4. Implement a system to gather vehicular emissions data for representative pavement sections across the State of Michigan. This will help monitor and develop accurate estimates for traffic emissions during the service life of pavements.
5. The PE-2 tool can generate emissions reports using as-built project data. It can also develop estimates for a new project given an estimate of materials and equipment use. However, the reliability of these estimates is strongly dependent on the underlying emission factors in the PE-2 database. At this time, the database reflects emission factors that are current and consistent with advances in published literature. However, it is crucial that MDOT revise and update the PE-2 emission factors data base from time to time, as new technologies are introduced – especially technologies that reduce emissions during the material production phase, or as new materials are introduced. For example, the emission factor for cement may need to be updated as improvements are made in the cement manufacturing and production phases. It is important to ensure that the databases are updated using peer-reviewed, reliable data sources – preferably data that has been published in industry and academic journals. In the long-run, this will ensure the reliability of the tool while nudging the industry towards transparent standards.

6.2. Estimation and Benchmarking

It is strongly recommended that MDOT use the PE-2 tool to monitor GHG emissions from construction projects, and to benchmark emissions for future projects. The PE-2 tool should be used at the project and the network levels. Specifically the recommendations are as follows:

1. At the project level, use the PE-2 tool on all future projects to estimate and benchmark emissions. The first step would be to use the bill of materials and estimated material use to benchmark expected project emissions before the project starts. At the end of the project, use PE-2 to generate an emissions report using the actual data collected (see data collection recommendations). MDOT should encourage contractors (through direct economic or equivalent incentive) to reduce the actual project emissions when compared to the benchmark for the project.
2. Develop an incentive plan that would recognize contractor's efforts at reducing GHG emissions during the project construction process. This could be through more efficient project site design and schedule planning or using alternative materials during the construction process.
3. At the network level for all (or a sample of) state highway control sections, maintain a record of emissions from construction and maintenance projects, and use the service phase emission metrics defined in this report – or directly through PE-2 – to maintain a running record of project life cycle emissions for representative corridors.
4. When considering emission reduction strategies, it is very crucial that MDOT recognize that emission reduction is part of a broader goal of building more sustainable pavements. Therefore, all measures must consider the long-term socioeconomic outcomes as well. For example, an easy way of reducing equipment emissions would be to mandate the use of new and more expensive equipment that have reduced emission footprints. However, this would bias the playing field in favor of larger national contractors, crowding out smaller regional contractors who have fewer financial resources to purchase new equipment. Such socioeconomic impacts should be carefully considered. Reduction strategies should emphasize incentive based individual adoption based on win-win premises for all stakeholders, rather than top-down enforced standards that may disproportionately disadvantage certain stakeholders.

6.3. Future Research Directions

A critical outcome of this research is that it has developed a comprehensive data infrastructure and developed an inventory using 14 representative projects. It is strongly recommended that the current database and the PE-2 system be made available to researchers as a resource. In addition, steps should be taken so that the database is continuously updated with new project data. This sections further outlines the resources needed to guide this research effort to a complete fruitful field application.

Immediate research needs will include funding at the level of a Tier-II project focusing on an extensive field implementation of the proposed methodology in collaboration with InfoTech, participating contractors and material suppliers. This study should be conducted over one to two years with time for *two summers of fieldwork* investigating:

- (i) The technology necessary to support the automatic collection and integration of project site data into the PE-2 backend database
- (ii) Usability of the new FieldManager^{TM} interface and devising ways of reducing barriers for contractors and inspectors in reporting daily resource use information.

It will ensure the implementation of a continuous data recording and monitoring system capable of generating daily project inventories as the project is being completed. The goal of this research will be to develop the following procedures for MDOT:

- (i) A method that will use PE-2 to benchmark carbon emissions of construction projects using resource estimates before start of construction, and compare it to actual emissions based on data collected during construction.
- (ii) A method to identify appropriate incentives that can be awarded to contractors if actual emissions are less than or equal to estimated benchmark emissions.

In future, as the datasets grow in size and diversity, research should be funded at the Tier-I/II level to investigate questions of pavement sustainability – which can in turn inform important questions of pavement design and management. Some of the future research directions are:

1. Investigation of long-term statistically significant relationships between pavement life-cycle parameters such as cost, performance and other sustainability indicators, including but not limited to emissions, for different kinds of pavements at the project and network levels using ***actual observed data***, instead of depending on estimates and/or anecdotal project experiences.
2. Consideration of the influence of context and project specific parameters such as climate, service loads, geography on the performance of a pavement through its life cycle.

3. Development of recommendations for sustainable construction practices that account for economy, emissions and long-term pavement performance. Such recommendations would be based on significant trends in observed project and pavement performance data.

All three of the above will support MDOT decision-makers justify their decisions and support policy that will encourage contractors, suppliers and local agencies coordinate efforts to reduce pavement life cycle emissions while improving pavement performance. It is very important to recognize that this research presents a first stepping-stone in that direction.

7. APPENDIX A: MDOT PAVEMENT LCA CHECKLIST

Michigan Department of Transportation: Carbon Footprint for HMA and PCC pavements (checklist)

Prepared for the Michigan Department of Transportation using template from Pavement LCA Workshop, developed by Pavement LCA Group at UC Davis [21]

A checklist is provided below for the Michigan Department of Transportation (MDOT) outlining steps, assumptions, data sources, and research gaps for, "Carbon Footprint for Hot Mix Asphalt and Portland Cement Concrete Pavements"

1. System Definition

This study aims to establish a carbon footprint for Hot Mix Asphalt (HMA) and Portland Cement Concrete (PCC) Pavements for reconstruction, rehabilitation and Capital Preventive Maintenance (CPM) projects. The study will consider emissions of GHGs due to energy consumption and material wastage during the material acquisition and manufacturing and construction phases (primary impacts) as well as those due to maintenance during the serviceable life of the assets (secondary impacts). Carbon dioxide emissions for different design types will be determined and categorized for application to various reconstruction, rehabilitation and preventive maintenance projects.

The system boundary for this research project attempts to capture the total quantity of Carbon Dioxide emissions expressed as an equivalence (CO_2 eq) taking into account the Nitrous Oxide, Methane, and where applicable other trace GHGs.

The system is defined by:

- Driving materials to be used in the construction and maintenance of the roadway (Virgin and/or Recycled)
- Energy resources consumed (Fossil Fuels, Renewable, Electricity etc.)
- Processing Materials (Concrete, HMA, Secondary Materials)

- Construction and Hauling Equipment employed throughout construction and maintenance (Non-Road Vehicles)
- On Road Vehicles including transportation, maintenance, and passenger vehicles
- Vehicle use throughout construction zones

1.1. Functional Unit

See discussion in section 4.5 Functional Units and Metrics

1.1.1. ***Physical dimension***

See discussion in section 4.5.1 Average CO_2 Equivalents per 100 MT of Concretic and Asphaltic Materials

1.1.2. ***Performance requirements***

See discussion in section 4.3.3 Service Data

1.2. ***Analysis Period***

Three methods were considered to determine the analysis period* to be used for each of the alternative pavement designs:

*Note: Life Cycle Analysis period is assumed the same as functional design life. Annualized/Amortizing was be implemented.

1. As outlined in MDOT's Pavement Design and Selection Manual [53] and based off pavement fix type, analysis periods were determined from the following table:

Table 7-1: Design Life based on Pavement Fix [53]

Pavement Fix	Design Life and Length of Accumulated ESALs (Years)
New/Reconstructed Rigid and Flexible Pavements	20
HMA over Rubblized Concrete	20
Unbonded Concrete Overlay over Repaired Concrete	20
HMA on Aggregate Grade Lift	15 to 20
HMA over Crush & Shaped Base	10 to 15

Mill & HMA Resurface on a Flexible Pavement	10 to 15
Repair and HMA Resurface on a Flexible Pavement	10 to 15
Repair and HMA Resurface on Composite or Concrete	10 to 12
Mill and HMA Resurface on Composite or Concrete	10 to 12

2. Using archived sample MDOT Historical Maintenance and performance data, researchers developed a method to estimate the design period of alternative pavement types based on this data. On average how long before pavement was reconstructed. Compare with strategies outlined in Pavement Design and Selection Manual.
3. Actual Pavement Design and Selection packages were obtained for 4 of the 5 original pavement designs investigated, analysis periods were obtained from those reports. Packages contain traffic info such as ESALs, AADT, Growth rate, etc. Limits Life Cycle analysis of only five types. (Original Projects combined with maintenance activities that apply to these original five pavement types) Possible to compare equivalent designs outlined in selection packages.

1.3. Life Cycle Inventory

1.3.1. Primary energy: Not reported

1.3.2. GHG emissions

For this study, researchers at MTU considered GHG emission from the construction and rehabilitation, use, and maintenance of various roadways in Michigan. Gases considered were:

- Carbon Dioxide
- Nitrous Oxide*
- Methane*

*These gases were converted to a carbon dioxide equivalent using appropriate methodologies.

1.3.3. Material flows

Material flows were tracked and recorded using construction management software provided by MDOT. Quantities of materials were analyzed for their corresponding GHG emissions.

1.4. Life Cycle Phases and Their System Boundary

1.4.1. Pavement design (for each system)

Pavement designs considered in this study were limited to the designs implemented in the projects investigated. Material quantities were derived from as-built construction usage rather than that of estimated design quantities.

Material analyzed was constrained to materials used to make up the actual roadway. (i.e. Base, Drainage, and Pavement materials). These are the driving materials that were determined to be analyzed in the study.

1.4.2. Material Production

1.4.2.1. Raw Material

Feedstock energy: Feedstock energy was not considered in this study as the emphasis was on estimating GHG emissions. Primary energy used to produce raw materials was considered.

1.4.2.2. Engineered Material

Transport of materials to site:

The impacts from the transport of materials to the site were considered in this study. Testing orders obtained from MDOT outlining material supplier locations allowed for this analysis.

Engineered material

Mixing in plant (HMA or PCC):

Both HMA and Concrete batch plant emissions were considered and estimated using published emission factors and based on tonnage of material placed throughout construction.

Transport from/to plant:

Transport from/to plant is not explicitly estimated in the project emission estimator. It is accounted for in FieldManager^{TM} Equipment usage reports obtained from MDOT inspectors. However, researchers have derived a formula to predict the total distance travelled to/from the plants using an arithmetic progression. Impact can be estimated using this technique. See To-Site impacts.

Transport of recycled material:

Transporting of recycle material is assumed to be accounted for in FieldManager^{TM} Equipment usage reports obtained from MDOT inspectors.

1.4.3. Construction

Equipment usage:

Equipment usage is estimated from FieldManager^{TM} Equipment usage reports obtained from MDOT inspectors.

Water use:

Water use was not estimated in this study.

Work zone traffic congestion:

Considered using MOVES simulation based estimation.

Vehicle technology change:

Not considered

Traffic growth:

Traffic growth throughout construction was not considered

Lighting energy, if at night:

Not considered

Movement of equipment:

Mobilization of equipment was not considered

Equipment manufacturing:

Upstream impacts from equipment manufacturing were considered in this study.

Factory or plant construction:

Not Considered

1.4.4. Use

1.4.4.1. Vehicle operation

Impact to fuel economy from roughness:

Not Considered

Damage to freight:

Not Considered

Damage to vehicle:

Not Considered

Vehicle tire wear:

Not Considered

Traffic growth:

Traffic Growth was assumed to be 1% compounded annually

Change in vehicle technology:

Not Considered

Sensitivity analysis:

Not Considered

1.4.4.2. Heat island:

Not Considered

1.4.4.3. Non-GHG climate change mechanism:

Not Considered

1.4.4.4. Water pollution from runoff:

Not Considered

1.4.4.5. Roadway lighting:

Not Considered

1.4.4.6. Carbonation:

Not Considered

1.4.5. End of Life

1.4.5.1. Recycling

End-of-Life Impacts were assumed to be accounted for as recycling impacts. This being, impacts from processing secondary materials such as RAP and RCA

1.4.5.2. Landfill:

Not Considered

1.5. Impact assessment

1.5.1. Climate change

Global warming potential (GWP): GWP was used to convert nitrous oxide and methane emissions to a carbon dioxide equivalent using methods outlined by the U.S. EPA and IPCC [64].

Source: IPCC TAR

2. Models and Data Sources

2.1. Material Production

Material LCI (List all the LCI Sources)

Multiple material LCIs were used in this study for information about type and sources see Appendix B: Emission Factors.

2.2. Construction

2.2.1. Maintenance and rehabilitation schedule

See discussion in sections 5.2.3 Process Emissions, 5.2.4 Service Emissions and 5.3 Project Life Cycle Emission Estimation

2.2.2. *Equipment use*

Construction Schedule Analysis: See discussion in section 5.2.2 Process Emissions.

Equipment emission: EPA GHG estimation Methodology (Diesel)

Data source: EPA [44]

Equipment fuel use: Estimated gallons used per hour (Diesel)

Data source: Usage from FieldManager™

Truck emission: On highway combination truck emission factor based on miles travelled. Assumes diesel and fully loaded at 30 tonnes.

Data source: NREL

2.2.3. Construction-related traffic

Work zone traffic analysis: See discussion in sections 4.4.3 Service Component GHG Emissions and 5.2.4 Service Emissions.

Impact from work zone traffic congestion was modeled into methodologies used to estimate the use phase of the pavement life cycle.

Data source: EPA MOVES 6.2

2.3. Use

2.3.1. Vehicle operation

Pavement performance model: Vehicle operation modeled for two types of rural highways.

Data source: EPA MOVES 6.2

2.3.2. Urban heat island

Not Considered

2.3.3. Non-GHG climate change Effects

Not Considered

2.3.4. Leachate

Not Considered

2.3.5. Carbonation

Not Considered

2.3.6. Roadway lighting

Not Considered

2.4. End-of-Life

2.4.1. Recycling

Processing impacts of secondary materials estimated using published emission factors. See Appendix B: Emission Factors

2.4.2. *Landfill*

Not Considered

7. APPENDIX B: EMISSION FACTORS

Table 7-1: Emission Factors

Material Description	Unit	EIO-LCA Sector	GHG GWP MT/$1K	$/Unit (2009)	Factor	Unit	Source
Cement	Ton				8.41E-01	MT/Ton	[7]
Binder	Ton				1.57E-01	MT/Ton	[38]
FlyAsh	Ton				1.78E-02	MT/Ton	[65]
Blast Furnace Slag	Ton				1.51E-02	MT/Ton	[39]
HMA Batch Plant	Tonne				2.86E-02	MTeq/ tonne	[39]
Aggregate	Ton				6.16E-03	MT/Ton	[39]
Recycled Asphalt Pavement	Ton				4.92E-03	MT/Ton	[39]
Concrete Batch Plant	Tonne				7.75E-03	MTeq/ tonne	[39]
RCA	Ton				2.18E-03	MT/Ton	[66]
Load Transfer Assembly	Ft				6.16E-04	MT/Ft	[39]
Steel Reinf	Ea				1.33E-03	MT/Ea	[39]
Cement	Lbs				4.20E-04	MT/Lb	[7]
Steel Reinf Epoxy Coated	Lbs				2.59E-04	MT/Lb	[39]
Steel Reinf Pavement Mesh	Syd				3.51E-03	MT/Lb	[39]
Granular Material	Cyd				1.08E-04	MT/ CYD	[38]
Sand	Cyds				1.08E-04	MT/ CYD	[38]

Table 7-1: Emission Factors

Material Description	Unit	EIO-LCA Sector	GHG GWP MT/$1K	$/Unit (2009)	Factor	Unit	Source
Pavt Mrkg Waterborne Paint White	Gal	325510	0.988	$83.33			[67]
Pavt Mrkg Glass Beads	Lbs	327212	1.070	$0.46			[67]
Silt Fence	Ft	313210	1.180	$0.90			[67]
Pavt Mrkg Plastic Tape	Ft	326112	1.240	$1.74			[67]
Geotextile Liner	Syd	313210	1.180	$1.54			[67]
Expansive Waterstop	Ft	326122	1.060	$3.20			[67]
Fertilizer Chemical Nutrient	Lbs	325311	5.750	$0.19			[67]
Seeding Mixture	Lbs	111421	0.667	$2.00			[67]
Mulch Blanket	Syd	111940	2.440	$0.46			[67]
Pipe Underdrain	Ft	326122	1.060	$0.56			[67]
Dr Structure Precast Concrete Unit	Ea	327390	1.140	$880.00			[67]
Block Conc	Ea	327331	1.470	$1.37			[67]
Curing Compound	Gal	325998	0.960	$18.30			[67]
End Section Concrete	Ea	327330	1.470	$763.43			[67]
End Section Metal	Ea	331110	3.110	$539.71			[67]
Fence Post Steel Woven Wire	Ea	331110	3.110	$32.50			[67]
Fence Woven Wire	Ft	331110	3.110	$4.16			[67]
Fence Post Wood	Ea	32111	0.695	$13.10			[67]
Lane Ties Epoxy Coated	Ea	331110	3.110	$4.73			[67]

Table 7-1: Emission Factors

Material Description	Unit	EIO-LCA Sector	GHG GWP MT/$1K	$/Unit (2009)	Factor	Unit	Source
Drainage Structure Cover	Lbs	327390	1.140	$1.07			[67]
Joint Filler Fiber	Syd	324122	1.090	$17.36			[67]
Joint Sealer Hot Poured Rubber	Lbs	326299	0.836	$1.02			[67]
Dowel Bar Epoxy Coated	Ea	331110	3.110	$4.55			[67]
Pipe Conc	Ft	327330	1.470	$63.14			[67]
Bond Coat	Gal	324121	1.450	$6.90			[67]
Guardrail	Ft	331110	3.110	$29.50			[67]
Underdrain Outlet Ending	Ea	326122	1.060	$1.65			[67]
Pipe Metal	Ft	331110	3.110	$65.88			[67]
Riprap	Syd	21231	1.250	$19.25			[67]
Handhole Heavy Duty Cover	Ea	331110	3.110	$26.75			[67]
Waterproofing Membrane Preformed	Syd	326291	0.836	$15.70			[67]
Pipe RCP 24"	Ft.	327330	1.470	$29.00			[67]
Pipe RCP 15"	Ft	327330	1.470	$14.95			[67]
Culv Class A CSP 12"	Ft	331110	3.110	$12.95			[67]
Pipe RCP 72"	Ft.	327330	1.470	$225.00			[67]
End Section Metal 12"	Ea	331110	3.110	$117.00			[67]
End Section Metal SLP 1:4	Ea.	331110	3.110	$117.00			[67]
End Section Concrete 24"	Ea.	327330	1.470	$410.00			[67]
End Section Metal 15"	Ea.	331110	3.110	$139.00			[67]

Table 7-1: Emission Factors

Material Description	Unit	EIO-LCA Sector	GHG GWP MT/$1K	$/Unit (2009)	Factor	Unit	Source
Neoprene Seal	Ft	325520	1.180	$2.21			[67]
Foam Backer Rod	Ft	326140	1.150	$0.16			[67]
End Section Concrete 72"	Ea.	327330	1.470	$2,325.00			[67]
Piling Steel Sheet	Sft	331110	3.110	$26.50			[67]
Pipe Plastic	Ft	326122	1.060	$34.20			[67]
Joint Filler Fiber	Sft	324122	1.090	$1.93			[67]

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