INTEGRATED LIFE CYCLE ANALYSIS APPROACH (ILCA^2) FOR TRANSPORTATION PROJECT AND PROGRAM DEVELOPMENT

By

Faisal Hameed

Dissertation Research Submitted to the Faculty of the

Virginia Polytechnic Institute and State University

In partial fulfillment of the requirements for the degree of

Doctor of Philosophy

In

Civil Engineering

Kathleen L. Hancock, Chair
Thomas J. Grizzard Jr.
Adil N. Godrej
William E. Roper

April 3, 2013

Keywords: Sustainability, environment, transportation, infrastructure, programming, planning, life cycle assessment, LCA, costs, carbon footprint, urban roadway, life cycle, environmental impacts, waste materials, storm water, life cycle cost analysis, LCCA, integrated life cycle analysis approach, ILCA^2, state transportation improvement program, STIP.

ABSTRACT

Ensuring sustainability is important for balancing economic viability, the environment and the social system. Because transportation infrastructure projects have direct and indirect impacts associated with this balance, it is important for transportation agencies to consider sustainability and environmental impacts in transportation investment decision making. These decisions typically occur during the planning and programming phase.

Life Cycle Assessment (LCA) is an accepted method for quantifying life cycle environmental impacts. Within the transportation sector, current LCA practices are primarily limited to roadway pavements and the determination of greenhouse gas (GHG) emissions or a carbon footprint. An urban roadway facility consists of several additional elements including sidewalks, street lights, traffic signals, lane striping and drainage which also have environmental impacts. In addition to the carbon footprint, roadway life cycle impacts include waste materials and storm water runoff. These life cycle impacts have associated costs.

Life Cycle Cost Analysis (LCCA) is a commonly used methodology which analyzes life cycle costs of projects. However, this methodology does not include costs associated with environmental impacts. When integrated with LCA, the quantification of life cycle environmental impacts and costs for an urban roadway that includes construction, resurfacing and reconstruction as well as impacts related with managing the facility provides important information for making decisions that support sustainability related to transportation infrastructure.

By establishing a reasonable life cycle time frame, representative elements, mostly homogeneous transportation facility types with representative cross sections, and accepted construction, maintenance and rehabilitation practices, a life cycle analysis approach which integrates LCA and LCCA is developed called Integrated Life Cycle Analysis Approach ($ILCA^2$). Because decisions are made during the planning and programming stage, the approach is designed to use a standard cross section with standard materials for a transportation facility – an urban roadway – and three readily available project-specific inputs: length of roadway, number of travel lanes, and

number of bicycle lanes. The methodology quantifies life cycle environmental impacts for carbon footprint of the materials in CO_2 eq, quantity of wasted materials, quantity of storm water runoff and then estimates the costs associated with these impacts.

This research demonstrated the use of $ILCA^2$ for a case study section of an urban roadway and for a sample transportation State Transportation Improvement Program (STIP). Using this approach to evaluate transportation projects provides several opportunities to enhance information used for decision making. Life cycle environmental impact costs can represent a quarter of the total integrated life cycle costs of a transportation program. The case studies showed that the initial costs represent approximately half of life cycle costs for a single project and nearly a twentieth for the sample STIP. Environmental impact costs were higher than direct operation costs, energy costs, and resurfacing costs of an urban roadway. Approximately 90% of material used in construction and rehabilitation of a roadway are removed in the rehabilitation and disposed of in landfills. This shows the potential for recovering, reclaiming, reusing and recycling these materials, potentially resulting in reduced life cycle environmental impacts. Storm water runoff over the life cycle from the roadway was also substantial and the associated cost represents a significant portion of life cycle costs. When used over the life cycle of a transportation program, Low Impact Development (LID) strategies for roadways can result in economic benefits with higher cost savings than traditional drainage practices.

When ILCA2 is applied to an individual project, decision makers have a better understanding of the expected costs and impacts associated with that project. Applying $ILCA^2$ to a program enables decision makers to evaluate the larger impacts of the transportation investments as well as consideration of programmatic changes to practices that support sustainability.

ACKNOWLEDGEMENTS

I am extremely grateful to Dr. Kathleen Hancock who advised me and chaired the committee. She was pivotal in providing me guidance, direction and focus.

I am very much obliged to Dr. Thomas Grizzard who advised me for many years and helped me through my work.

I would like to thank Dr. Adil Godrej for his support in my path to completion.

I will always be grateful to Dr. William Roper, who provided me support, advice and direction all these years.

I would also like to thank the staff at the Occoquan Lab and Virginia Tech Northern Virginia Center for providing me assistance.

DEDICATION

Dedicated to my loving parents, my family, my friends and my teachers. Thank you for believing in me and providing me support and direction all these years.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

AASHTO	American Association of State and Highway Officials
AP	Annual precipitation
C_{CFC}	Carbon cost conversion factor
C_{SWC}	Solid waste cost conversion factor
C_{SRC}	Storm water runoff conversion factor
CFC	Carbon footprint costs
CFR	Code of Federal Register
CO_2	Carbon Dioxide
DDOT	District of Columbia Department of Transportation
DOE	United States Department of Energy
DOT	Department of Transportation
DPW	District of Columbia Department of Public Works
E	Carbon footprint associated with Energy use
EIE	Environmental Impact Estimator
EIO	Economic Input Output
EPA	United States Environmental Protection Agency
FHWA	Federal Highway Administration
GHG	Greenhouse gas
IC	Carbon footprint associated with Initial Construction
$ILCA^2$	Integrated Life Cycle Analysis Approach
ISO	International Organization for Standardization
L	length
Lb	pounds
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
MG	Million gallons
NCHRP	National Cooperative Highway Research Program
NIST	National Institute of Standards and Technology
NHS	National Highway System

R	carbon footprint associated with Resurfacing
RC	carbon footprint associated with Reconstruction
SA	Surface area
SC	Salvage carbon footprint
SRC	Storm water runoff costs
STIP	State Transportation Improvement Program
SWC	Solid waste costs
SWIC	Solid wastes associated with Initial Construction
SWRC	Solid wastes associated with Reconstruction
SWR	Solid wastes associated with Resurfacing
TIP	Transportation Improvement Program
TRB	Transportation Research Board
U.N	United Nations
USC	United States Code

CHAPTER 1

Introduction

Introduction

Ensuring sustainability is important for balancing economic viability, the environment and the social system. Because transportation infrastructure projects have direct and indirect impacts associated with this balance, it is important for transportation agencies to consider sustainability and environmental impacts in transportation investment decision making.

Life Cycle Assessment (LCA) is an accepted method for quantifying life cycle environmental impacts and has been applied to many sectors of society usually at the product level. Because transportation infrastructure is a complex system with multiple components that consist of different materials and products with different environmental impacts, the current LCA approach has limitations for this type of system. However, by establishing an evaluation time frame, categorizing transportation facility types with representative cross sections and associated elements, and identifying accepted construction, maintenance and reconstruction practices, a methodology using LCA principles can be developed that allows transportation decision makers to quantify environmental impacts at the planning and programming phase when decisions are made regarding resource allocations for an agency's transportation infrastructure. Combining these elements allows decision makers to consider the overall environmental impacts of a facility, project, or program.

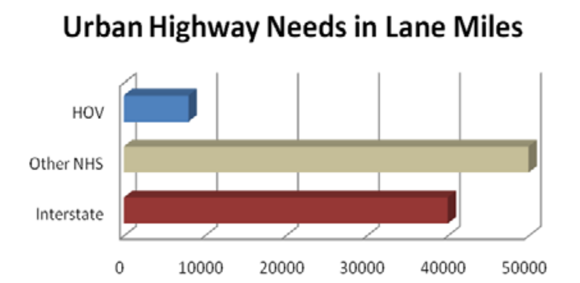
Resource allocation for transportation projects and programs is most commonly based on initial costs associated with each project. A more comprehensive evaluation includes life cycle costs using a procedure such as Life Cycle Cost Analysis (LCCA). If costs are associated with environmental impacts, these impacts can be incorporated into a broader assessment of transportation infrastructure, providing important information for decision makers when considering sustainability.

The research presented in this dissertation develops an improved methodology – Integrated Life Cycle Analysis Approach (ILCA^2) – which integrates LCA with LCCA to assess life cycle environmental impacts and associated costs of transportation facilities at the planning and programming phase.

1. Statement of Problem

Sustainability is defined as meeting the needs of the present without compromising the ability of future generations to meet their own needs (U.N 1987). Sustainability is how environmental, economic, and social systems interact to their mutual advantage or disadvantage at various space-based scales of operation (TRB 1997). The past few years have seen a growing emphasis on incorporating sustainability in transportation decision making, including the need for sustainable transportation infrastructure such as carbon-neutral roads. However, a consistent methodology does not currently exist to quantify the life cycle impacts related to constructing and maintaining transportation projects.

The transportation sector is a major component of the United States economy. There are over 4 million miles of paved public roadways in the United States, out of which 1.1 million miles are urban while 2.9 million miles are rural accounting for over $200 billion in annual expenditures (FHWA 2012). According to AASHTO, to meet the future needs of the country, 40,000 lane-miles should be added to the existing 75,000 urban Interstate lane-miles and an additional 50,000 lane-miles should be added to urban segments of the National Highway System (NHS) as shown in Figure 1 (AASHTO July 2007). A large portion of this highway system is funded through the Federal Aid Highway Program of the United States Department of Transportation (USDOT). To receive these funds, State DOTs have to comply with federal requirements. Planning regulations of the Federal Highway Administration (FHWA) require all State DOTs to develop a financially constrained State Transportation Improvement Program (STIP). FHWA defines a STIP in 23 CFR 450.104 as “a statewide staged, at least four-year, multi-year program of transportation projects that is consistent with the long range statewide transportation plan, metropolitan transportation plans, and Transportation Improvement Program (TIP), and required for projects to be eligible for funding under 23 U.S.C. and 49 U.S.C. Chapter 53" (23 CFR 450.104). A STIP typically includes a listing of all projects programmed for the next 4 years in that State and provides estimated costs of each phase of each project by year. Because major investment decisions for transportation are made at this stage, including an assessment of life cycle impacts and associated costs provides an important opportunity to incorporate sustainability into transportation decision making.



	Interstate	Other NHS	HOV
Lane Miles	40000	50000	8000

Figure 1: Urban Highway Capacity Needs (AASHTO July 2007)

Life Cycle Assessment (LCA) is defined as the assessment of the environmental impact of a given product throughout its lifespan (ISO 2006). Incorporating life cycle thinking into decision making is a way of addressing environmental issues and opportunities from a system or holistic perspective such that a product or service is evaluated or designed with a goal of reducing potential environmental impacts over its life cycle (UNEP 2003). LCA can be applied to roadways by defining a representative life cycle or evaluation period, spatial extent of a project, required and assumed system inputs, and activities necessary to construct and maintain the components of the facility.

Life Cycle Cost Analysis (LCCA) is a method of economic project evaluation in which all costs arising from owning, operating, maintaining, and ultimately disposing of a project are considered to be potentially important to project selection (DOE 1996). LCCA can be applied to any capital investment decision in which higher initial costs are traded for reduced future cost obligations. According to FHWA, LCCA is an evaluation technique that is applicable for the consideration of certain transportation investment decisions including roadways (FHWA 2002).

By integrating LCA impacts and associated costs with the LCCA process, a more comprehensive understanding of environmental impacts would be available to agency decision makers. However, several challenges had to be addressed to accomplish this integration and apply it to transportation facilities.

Maintaining and expanding the roadway system require DOTs to undertake a large number of transportation construction, resurfacing and reconstruction projects every year, ranging from sidewalk repairs to interstate highway construction. Each type of project has different requirements and schedules incorporating different materials and processes, all of which result in different levels of environmental impacts and associated costs. In addition, many transportation facilities result in additional impacts related to operations such as supplying power to traffic signals and street lights and managing water runoff. Because these projects are included in the STIP, estimating life cycle impacts and costs at this stage allows agencies to assess impacts at the program level as well as for individual projects. A challenge associated with assessing impacts at this stage is that project details are unknown, requiring a process that can estimate impacts using limited inputs and representative cross-sections.

Another challenge is that the traditional approach to evaluating the STIP uses initial one-time costs even though roadways are in operation for decades requiring regular maintenance, rehabilitation, and reconstruction. Impacts and associated costs of these activities should be included in the assessment to understand life cycle impacts of the facility. By performing an overall evaluation of the STIP, projects at different stages of their life cycle can be included in a single overall assessment.

An additional challenge in developing such a methodology is having consistent standards. Fortunately, all State DOTs in the United States are member of the American Association of State Highway and Transportation Officials (AASHTO) and use AASHTO standards. The most frequently used AASHTO standards related to this research include:

- AASHTO A Policy on Geometric Design of Highways and Streets (AASHTO 2011)
- Standard Specifications for Transportation Materials (AASHTO 2007)

Developing an integrated life cycle analysis approach and a supporting tool for quantifying environmental impacts and associated costs of constructing, maintaining and operating transportation projects can be very beneficial for transportation professionals and decision makers to support sustainable transportation investment decisions.

2. Research Approach

2. 1. Purpose and Objectives of the research

The purpose of this research was to develop a methodology that can support sustainable decision making for DOTs by developing an Integrated Life Cycle Analysis Approach (ILCA$^{2)}$ along with a supporting tool that calculates life cycle impacts and their associated costs of transportation projects and programs. Because economics is an important part of project selection as well as sustainability assessment, quantification of the life cycle impacts and costs can be used as performance measures to evaluate the sustainability of a transportation system. Since transportation investment decisions are made in the planning and programming phase, the ILCA^2 tool can be applied to the STIP to integrate life cycle impacts and costs into the transportation programming process. This research and tool can be used to provide guidance to DOTs in making sustainable transportation infrastructure investment decisions.

The Objectives of this research are to:

1. Develop a methodology to quantify life cycle impacts of transportation projects
2. Calculate life cycle impacts and associated costs to construct, resurface and reconstruct urban roadways
3. Develop an integrated life cycle analysis approach ($ILCA^2$) and tool that calculated life cycle impacts and costs of a transportation project and program.

2.2. Research Approach

The research approach included understanding the state of the practice in life cycle assessment and life cycle cost analysis to develop an integrated life cycle analysis methodology that can support sustainability in transportation decision making. The research then developed an approach that integrates life cycle impacts and life cycle costs for transportation projects and programs, quantifies life cycle impacts for transportation projects and programs, and establishes a consistent measure for the integrated life cycle analysis as summarized in Figure 2. A decision support tool was developed based on this approach called Integrated Life Cycle Analysis Approach or $ILCA^2$. The tool was the used to evaluate a case study project and STIP.

Determining the life cycle impacts requires defining the specific impacts to be considered and then establishing the life cycle evaluation time, spatial extent, facility type and associated characteristics, and construction and maintenance schedule. Based on the facility type, a representative cross section is defined which allows the procedure to minimize required inputs necessary for estimating materials and quantities based on accepted design standards. Environmental impacts are associated with each material and each part of the project. Costs associated with these impacts are estimated using recognized conversion factors and then added to physical costs of the facility over the evaluation period to obtain overall life cycle costs. This approach was first applied to a case study project and then to a case study STIP. Based on this approach and the selected case studies, a computer tool was developed by using Java programming and a user interface.

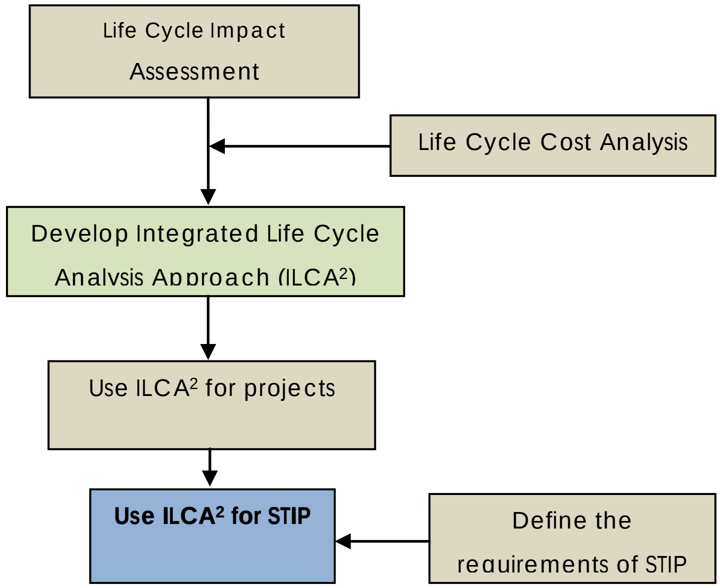


Figure 2: Research Methodology

The case study project consisted of a representative urban roadway. Environmental impacts consisted of carbon footprint and solid wastes related to construction and maintenance and storm water runoff and carbon footprint of electricity related to operating the facility. The case study program used the same facility type and environmental impacts for all projects but included several projects at different states of their life cycle and with different input values. The resulting ILCA^2 tool requires four inputs: length of roadway project, number of vehicular lanes, number of bike lanes, and the type of initial activity i.e. construction, resurfacing or reconstruction. The tool calculates the life cycle impacts of the roadway/STIP as carbon footprint, storm water runoff, and solid wastes along with the overall and component life cycle costs.

2.3. Dissertation Outline

This section briefly describes the outline of the dissertation. The dissertation consists of: introduction, literature review, research methodology, three independent technical papers, summary, conclusions and recommendations. Literature cited in each chapter is listed at the end of each chapter.

Chapter1: Introduction. This chapter includes the background and introduction of the research provided in this dissertation, problem statement, goals and objectives of the research, brief description of the research approach and dissertation outline.

Chapter 2: Literature Review. This chapter includes the review and research of the literature available on the LCA, LCCA, Integrated LCA-LCCA and Transportation programming.

Chapter 3: Research Methodology. This chapter describes in detail the methodology used for this research. This includes the description of the steps involved in developing an integrated life cycle analysis approach ($ILCA^2$). This chapter also includes the description of the activities, scope, analysis boundaries and timeframe as well as input and output data. The case study used in the dissertation is also described in this chapter.

Chapter 4: Quantifying Life Cycle Impacts of Roadways. This is the first independent technical paper in this dissertation. This chapter describes the methodology for analyzing the life cycle environmental impacts of urban roadways. This chapter provides the results and analysis of construction, reconstruction and resurfacing of an urban roadway and provides life cycle impacts as carbon foot print, solid wastes and storm water runoff.

Chapter 5: An Integrated Life Cycle Analysis for Roadways. This is the second independent technical paper in this dissertation. This chapter describes the development of an integrated life cycle analysis approach ($ILCA^2$) for analyzing the life cycle environmental impacts and life cycle costs of roadways. This chapter describes the results of calculating the material quantities and costs of construction, reconstruction and resurfacing of an urban roadway. This chapter also provides the results and analysis of the integrated life cycle analysis approach ($ILCA^2$) as integrated life cycle costs.

Chapter 6: Incorporating Costs of Life Cycle Impacts into Transportation Project and Program Development. This is the third independent technical paper in this dissertation. This chapter describes the methodology of performing integrated life cycle analysis approach for analyzing the life cycle environmental impacts of a State Transportation Improvement Program by focusing on the urban roadways and quantifying these impacts in terms of quantities and costs. This chapter provides the results and analysis of the performance of the integrated life cycle analysis approach (ILCA^2) and provides a comparison of the life cycle impacts and costs of the STIP.

Chapter 7: Summary. This chapter provides a summary of the research, results and conclusions.

Chapter 8: Conclusions and Recommendations. This chapter describes the conclusions of the research, its contribution and application to the science, engineering and industry, limitations of the research, and recommendations for further research and scientific work.

References for Chapter 1

23 CFR. *United State Code of Federal Register Title 23: Highways.* 2009. National Archives and Records Administration. U.S Government Printing Office, Washington DC. 23 CFR 1.2, 1.3, & 771.117.

23 CFR 450. *United State Code of Federal Register Title 23: Highways.* 2009. National Archives and Records Administration. U.S Government Printing Office, Washington DC. 23 CFR 450.104. 2009.

AASHTO July 2007. *Invest in Our Future: A Vision for the 21st Century*. American Association of State and Highway Transportation Officials (AASHTO). 2007. pp 26.

AASHTO 2007. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*. American Association of State and Highway Transportation Officials (AASHTO). 27th Ed. 2007.

AASHTO 2011. *A Policy on Geometric Design of Highways and Streets*. American Association of State and Highway Transportation Officials (AASHTO). 6th Ed. 2011.

Brockenbrough, Roger L. and Boedecker, Kenneth J. *Highway Engineering Handbook.* 2nd Edition. McGraw Hill. 2003. pp 1.1, 1.70-1.82.

Department of Energy (DOE). "*Life Cycle Costing Manual for the Federal Energy Management Program*". U. S Department of Energy, Washington DC. pp 1.1. 1996.

Federal Highway Administration (FHWA). "*Life-Cycle Cost Analysis Primer*". U.S. Department of Transportation, FHWA, Washington DC. pp 7,9. August 2002.

Federal Highway Administration (FHWA) 2012. *Highway Statistics 2010.* Office of Highway Policy Information, FHWA, 1200 New Jersey Avenue, SE Washington, DC. 2012..

International Organization for Standardization (ISO). "*ISO-14040-2006: Environmental Management-Life Cycle Assessment-Principles & Framework*". ISO Geneva, Switzerland. 2006.

Transportation Research Board (TRB), Committee for a Study on Transportation and a Sustainable Environment: "*Towards a Sustainable Future; Addressing the Long-Term Effects of Motor Vehicle Transportation on Climate and Ecology*". National Academy Press. 1997.

United Nations (U.N). "*Report of the World Commission on Environment and Development: Our Common Future*" (Transmitted to the General Assembly as an Annex to *document A/42/427* - Development and International Co-operation: Environment). Gro Harlem Brundtland Commission. 1987.

United Nations Environment Programme (UNEP). "*Evaluation of Environmental Impacts in Life Cycle Assessment*". Pp 1. Division of Technology, Industry and Economics (DTIE). 2003.

CHAPTER 2

Literature Review

Literature Review

This chapter provides a review of documented research related to the underlying methodologies and concepts that were needed for the development of an integrated life cycle analysis approach for transportation project and program development along with limitations of the existing work. The review covers Life Cycle Assessment (LCA), Life Cycle Cost Analysis (LCCA), integration of LCA and LCCA, and an overview of transportation improvements programs.

1. Life Cycle Assessment (LCA)

LCA is a “cradle-to-grave” approach beginning with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth (EPA 2006). By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product and process selection (EPA 2006). The idea of assessing life cycle impacts has been researched for decades. Ian Boustead, in 1972, calculated the total energy used in the production of beverage containers. In the following years, he expanded his methodology to other materials and published the Handbook of Industrial Energy Analysis in 1979 (Boustead 1996). The rapid surge of interest through the late 1980s and early1990s showed that life-cycle assessment methodologies were among the most promising new tools for a wide range of environmental management tasks (EEA 1997). Two LCA approaches are most commonly used (Horvath 2004):

1. Process LCA models
2. Economic Input Output (EIO)-LCA models

1.1. Process based LCA models and tools

Process based LCA models use mass-balance calculations to quantify inputs and outputs at each life cycle phase and often require detail data to be collected directly from companies, data bases or published studies (Sharrard 2007). Process LCA was the basis for creation of the ISO 14040 standards (ISO 2001). International Organization for Standardization (ISO) developed the Life Cycle Assessment principles and framework in 1997. This framework is called *ISO-14040: Environmental Management-Life Cycle Assessment-Principles & Framework* (ISO 2006).

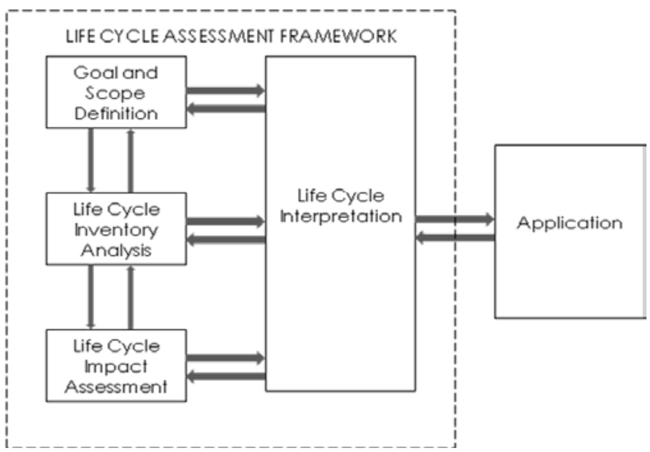


Figure 1: ISO 14040- Life Cycle Assessment Framework (ISO 2006)

Figure 1 illustrates the ISO 14040 framework. According to ISO 14040, the LCA process consists of four components: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO 2006).

- *Goal and Scope Definition* – This includes defining and describing the product, process or activity. Establishing the context in which the assessment is to be made and identifying the boundaries and environmental effects to be reviewed for the assessment.

- Life Cycle *Inventory Analysis* - Identifying and quantifying energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges).
- Life Cycle *Impact Assessment* - Assessing the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis.
- Life Cycle *Interpretation* – Evaluating the results of the inventory analysis and impact assessment.

BEES, Gabi, SimaPro and ATHENA Environmental Impact Estimator (EIE) are some of the software tools available today that apply process LCA to the building construction industry (Sharrard 2007). National Institute of Standards and Technology (NIST) of the United States Department of Commerce developed a model called Building for Environmental and Economic Sustainability (BEES). NIST Healthy and Sustainable Buildings Program began the Building for Environmental and Economic Sustainability (BEES) project in 1994 (NIST 2007). Currently BEES 4.0 is available for public use. This software provides a rational, systematic technique for selecting environmentally-preferred, cost-effective building products and includes actual environmental and economic performance data for over 230 building products (NIST 2007). This model measures the environmental performance of building products using the ISO 14040 LCA approach. Gabi provides construction processes for buildings, civil engineering and machines and is currently more designed for products than processes especially if those processes are construction related; SimaPro provides a whole building mass process and may be helpful as a supporting data base but not to model onsite construction; while ATHENA EIE is a building construction specific LCA tool that allows users to select building system components to model life cycle impact of designed structure (Sharrard 2007).

BenReMod, asPECT, PaLATE, ROAD-RES, CHANGER and PE-2* are examples of LCA software tools applied to road pavements that calculate Greenhouse gas (GHG) emissions from roadway construction. BenReMod (Beneficial Reuse Model) is a web based tool that can be used for quantitatively comparing benefits and disadvantages of different materials by using multi criteria decision making while provides outputs in global warming potential (GWP) and energy use (Apul 2007). asPECT (asphalt Pavement Embodied Carbon Tool) is a software tool that performs LCA of asphalt mixtures (Nicuta 2011). PaLATE (Pavement Life-cycle Assessment Tool for Environmental and Economic Effects is an Excel-based tool for LCA of environmental and economic effects of pavements and roads that provides environmental effects in energy, GWP, NOx, PM10, SO2, CO, Hg, Pb, and hazardous waste generation (Horvath 2012). The tool also provides a simple life-cycle costing mechanism, by material unit-weights and not including labor, overhead, or user costs (Santero et al 2010). ROAD-RES assesses the environmental impact of the materials production, construction, maintenance, and end-of-life phases of the pavement life cycle while particularly focusing on the comparisons of virgin materials to waste products considers eight different impact categories: GWP, photochemical ozone formation, nutrient enrichment, acidification, stratospheric ozone depletion, human toxicity, eco-toxicity, and stored eco-toxicity that cover environmental impacts to air, soil (Santero et al 2010). CHANGER (Calculator for Harmonized Assessment and Normalization of Greenhouse gas Emissions for Roads) is a software tool that performs LCA and providing results in carbon footprint of the roadway construction (Huanga 2012). PE-2 (Project Emission Estimator) is a web based tool that estimates life cycle emissions associated with construction, maintenance and use roadways (MTU 2013). While the PE-2 tool can be used at the project and the network levels, its recommended application is to monitor GHG emissions from construction projects and to benchmark emissions for future projects (Mukherjee 2013).

1.2. Economic Input Output based LCA models and tools

The EIO-LCA models use the economic input-output data from a source such as the United States Department of Commerce (Horvath 2004). The EIO-LCA models provide an assessment on the level of the country's economy at a relatively low cost (Hendrickson et al 1998). The only free EIO-LCA model available in the United States is Carnegie Mellon University's EIO-LCA model (Sharrard et al 2007). Sharrard et al used the LCA concept to develop an Economic Input Output (EIO)-LCA model for construction industry in 2007 in the work on *Greening Construction Processes Using Input-Output Based Hybrid Life Cycle Assessment Model (*Sharrard et al 2007). Horvath et al have used the EIO-LCA method to perform the life cycle assessment of transportation and construction industry (Horvath 2004).

LCA approaches and tools available today for roadways focus on pavement and estimate impacts as greenhouse gas emissions. Roadways include additional elements such as sidewalks, street lights and signals, landscaping and drainage. These elements are not considered in the current research or the LCA approaches available. These elements use different materials which can have impacts. These materials are removed during the resurfacing and reconstruction activities and can end up in landfills. Estimating the quantities of these materials is also important. The storm water runoff from the roadway is another impact not included in the LCA practices today. Another challenge in current LCA practices is the extent of data needed which is not available at programming stage of roadway projects. This research develops a process based LCA methodology that estimates the life cycle environmental impacts of several elements of a roadway as carbon footprint and materials wasted and also includes the storm water runoff from the facility to provide a comprehensive analysis of life cycle impacts of a roadway.

2. Life Cycle Cost Analysis (LCCA)

Life Cycle Cost Analysis (LCCA) is an economic method of project evaluation in which all costs arising from owning, operating, maintaining, and ultimately disposing of a project are considered to be potentially important to that decision (DOE 1996). LCCA can be applied to any capital investment decision in which higher initial costs are traded for reduced future cost obligations. LCCA provides a significantly better assessment of the long term cost effectiveness of a project than alternative economic methods that focus only on first costs or on operation-related costs in the short run (DOE 1996). According to FHWA, LCCA is an evaluation technique applicable for the consideration of certain transportation investment decisions (FHWA 2002). LCCA was legislatively defined in

Section 303, Quality Improvement, of the National Highway System NHS Designation Act of 1995. The definition was modified in the Transportation Equity Act (TEA-21), the transportation authorization bill in 1998, as "*. . . a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future cost, such as maintenance, user, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment" (FHWA 1998).*

There is extensive literature available on Life-Cycle Cost Analysis (LCCA). In 1996, the Department of Energy (DOE) published the *Life Cycle Costing Manual for the Federal Energy Management Program* (DOE 1996). This document is still used by many federal agencies as the guiding document for performing LCCA. LCCA methodologies for roadways and bridges were developed by FHWA and NCHRP shortly after. In 1998, FHWA published *Life-Cycle Cost Analysis in Pavement Design* developed a LCCA methodology for roadway pavement (FHWA 1998). In 2003, NCHRP Report 483: *Bridge Life Cycle Cost Analysis* developed a procedure for life-cycle cost analysis for bridges (NCHRP 2003). These two methodologies provide a comprehensive approach for LCCA for roadway pavements and bridges and provide the foundation for performing LCCA for roadways.

Life cycle cost analysis typically includes both agency costs and user costs. Agency costs include all costs incurred directly by the agency over the life of the project which typically includes preliminary engineering, construction costs, maintenance, resurfacing and rehabilitation costs. User costs include vehicle operating costs, user delay costs, and costs associated with crashes (FHWA 1998).

The most commonly used LCCA tool for roadways is the FHWA RealCost software tool which uses FHWA LCCA methodology to perform effects of cost, service life, and economic inputs on life-cycle cost while calculating the life-cycle values for both agency and user costs associated with construction and rehabilitation (FHWA 2004).

LCCA for roadways is a mature practice. The LCCA approaches available today require data that is not available at programming or planning stage of project development. These approaches use both agency costs as well as user costs such as vehicle delay costs, crash costs and other vehicle fees. This data is also difficult to develop and is usually not in the control of the transportation agency. This research develops a methodology that can be used at planning and programming stage of roadway project that focuses on agency costs using material quantities by using few readily available inputs.

3. Integrated LCA-LCCA

Hybrid LCA is a method that combines process LCA and EIO-LCA approaches (Santero et al 2010).A hybrid analysis that combines LCA and LCCA enhances the value of each approach to give better, more comprehensive answers (Hendrickson 2006). Integrated LCA-LCCA combines life cycle impacts with costs to provide comprehensively life cycle costs to analyze both environmental and economic impacts. Zhang et al used an integrated LCA-LCCA model for pavement overlay systems (Zhang 2008) to evaluate life cycle performance of different pavement systems. Santero and Loijos et al (at MIT) recently developed research that improved the application of LCA by using LCCA to evaluate the cost effectiveness of Green House Gas (GHG) reduction strategies for concrete pavements (Santero et al 2011). PaLATE tool for LCA of environmental and economic effects provides a simple life-cycle costing mechanism, by material unit-weights not including labor, overhead, user (Santero et al 2010) and can be considered an LCA-LCCA tool.

Limited literature is available on Integrated LCA-LCCA. Similar to current LCA practices, Integrated LCA-LCCA practices have been developed for pavements and these practices consider only consider greenhouse gas emissions from pavements. This research develops a methodology by including roadway elements such as sidewalks, street lights and signals, landscaping and drainage and cost of impacts of these elements to assess life cycle environmental impacts and associated costs of transportation facilities.

4. State Transportation Improvement Program (STIP)

Almost one-third of roadways in the United States are funded through the Federal Aid Highway Program of the U.S Department of Transportation Federal Highway Administration (FHWA 2012). To receive these funds, State DOTs have to comply with FHWA requirements. Specifically, transportation planning regulations of 23 CFR 450.216 require all State DOTs to develop a financially constrained State Transportation Improvement Program (STIP). FHWA defines the STIP in 23 CFR 450.104 as "a statewide staged, at least four-year, multi-year program of transportation projects that is consistent with the long range statewide transportation plan, metropolitan transportation plans, and Transportation Improvement Program (TIP), and required for projects to be eligible for funding under 23 U.S.C. and 49 U.S.C. Chapter 53" (23CFR 450).

A STIP typically includes a listing of all projects programmed for the specified time period within a state and provides costs for each phase of each project by year. These transportation programs generally include just the financial and schedule information of projects and do not include life cycle environmental impacts. This research provides a methodology that quantifies these impacts and estimates the associated costs at the programming stage of transportation project development process.

5. Conclusions

Life Cycle Assessment (LCA) is an accepted method for quantifying life cycle environmental impacts and has been applied to roadway pavements. Current LCA practices focus on greenhouse gas emissions due to roadway pavements use and construction. Roadway infrastructure is a complex system with multiple components that consist of different materials and products with different environmental impacts, the current LCA approach has limitations for this type of system. The attempts at integrating LCA and LCCA have also been limited to roadway pavement and greenhouse gas emissions, thus leaving out waste materials and storm water runoff that contribute to life cycle impacts. Current models and approaches provide excellent tools for research;

however, they pose a challenge for practitioners in DOTs because of the extensive data and input requirements which are not usually available at the planning and programming stage of transportation project development. Current state of practice limits the use of life cycle impact assessment by DOT's by focusing only on greenhouse gas emissions, by only considering roadway pavements, by requiring detailed data and by providing results that depend on users and not on agency's decisions.

By establishing an evaluation time frame, categorizing transportation facility types with representative cross sections and associated elements, and identifying accepted construction, maintenance and reconstruction practices, a methodology using LCA principles can be developed that allows DOT's to quantify environmental impacts at the planning and programming stage by using minimal available inputs. This approach based on combining these elements will allow DOT's to consider the overall environmental impacts of a facility, project, or program. This review of current approaches indicates the need for such an integrated life cycle analysis approach (ILCA^2) for transportation project and program development that performs life cycle impact and cost analysis.

References for Chapter 2

23 CFR 450. *United State Code of Federal Register Title 23: Highways.* 2009. National Archives and Records Administration. U.S Government Printing Office, Washington DC. 23 CFR 450.104. 2009.

Apul, Dafne. "*BenReMod: A Web-Based Model for Comparing the Environmental Impacts from Road Construction Materials*" presentation. University of Toledo, OH. 2007.

Boustead, Ian. "*LCA - How it Came About, The Beginning in the UK*". International Journal of Life cycle Assessment 1 (3) 1996.

Department of Energy (DOE). "*Life Cycle Costing Manual for the Federal Energy Management Program*". U. S Department of Energy, Washington DC. pp 1.1. 1996.

Environmental Protection Agency (EPA): "*Life cycle assessment: Principles and practice*". May 2006. Cincinnati, OH: National Risk Management Research Laboratory, Scientific Applications International Corporation (SAIC), EPA/600/R-06/060.

European Environmental Agency (EEA). *Life Cycle Assessment: A guide to approaches, experience, and information sources*. Environmental Issues Series. No. 6. August 1997.

Federal Highway Administration (FHWA). *Life-Cycle Cost Analysis: RealCost User Manual*. Publication No. FHWA, Washington DC. 2004.

Federal Highway Administration (FHWA) 2012. *Highway Statistics 2010*. Office of Highway Policy Information, FHWA, 1200 New Jersey Avenue, SE Washington, DC 20590.

Federal Highway Administration (FHWA). *Life-Cycle Cost Analysis in Pavement Design*. Publication No. FHWA-SA-98-079. FHWA, Washington DC. 1998.

Federal Highway Administration (FHWA). "*Life-Cycle Cost Analysis Primer*". U.S. Department of Transportation, FHWA, Washington DC. pp 7,9. August 2002.

Hammond, Geoff and Jones, Craig. *Inventory of Carbon and Energy*. Version 1.6a. Department of Mechanical Engineering, University of Bath, UK. 2008 updated 2009-2011.

Hendrickson, Chris, Horvath, Arpad. *Resource Use and Environmental Emissions of U.S Construction Sectors*. Journal of Construction Engineering and Management. January-February 2000. pp 38-44.

Hendrickson, Chris., Horvath, A., Lave, L.B. *Use of Economic input-output models for environmental life cycle assessment*. Environmental Science and Technology. April 1998. Volume 32, Issue 7 / pp. 184 A-191 A

Hendrickson, C.T., Lave, L.B., and Matthews, H.S., *Environmental Life Cycle Assessment of Goods and Services.* Washington, DC: Resources for the Future. 2006.

Horvath, A. *Estimation of the environmental implications of construction materials and designs using life-cycle assessment techniques*. PhD Thesis. Department of Civil and Environmental Engineering, Carnegie Mellon University. 1997.

Horvath, Arpad. *Construction Materials and Environment*. Annual Rev. Environ. Resour. 2004. 29:181–204.

Horvath, A., and Hendrickson, C. T. (1998), *A Comparison of the Environmental Implications of Asphalt and Steel-Reinforced Concrete Pavements*. Transportation Research Record, NRC, No. 1626 (Environmental and Social Effects of Transportation), pp. 105-113, DOI:10.3141/1626-13.

Horvath, A., Hendrickson, C. T., Lave, L. B., McMichael, F. C., and Wu, T-S. (1995), *Toxic Emissions Indices for Green Design and Inventory*. Cover article, Environmental Science & Technology, ACS, 29(2), pp. 86-90, DOI:10.1021/es00002a003.

Horvath, Arpad et al. "*Pavement life-cycle assessment tool for environmental and economic effects (PaLATE)*". http://www.ce.berkeley.edu/~horvath/palate.html (accessed 20 February 2012).

Huanga, Yue , Bachar Hakimb1 and Susanna Zammataroc2 *Measuring the carbon footprint of road construction using CHANGER.* International Journal of Pavement Engineering 2012-1-11.

International Organization for Standardization (ISO). "Documentation International Standard DIS 14040 Technical committee 1998. ISO Geneva, Switzerland. March 2001.

International Organization for Standardization (ISO). "ISO-14040-2006: Environmental Management-Life Cycle Assessment-Principles & Framework". ISO Geneva, Switzerland. 2006.

Mukherjee, Amlan and Stawowy, Brian. *The Project Emissions Estimator (PE-2): A tool to aid contractors and agencies assess GHG emissions of Highway Construction*. Transportation Research Board. 92nd Annual Meeting Proceedings of. January 2013.

National Institute of Standards and Technology (NIST) "*Building for Environmental and Economic Sustainability (BEES) 4.0 Manual*. US Department of Commerce. 2007.

NCHRP Report 483. "*Bridge Life Cycle Cost Analysis*". National Cooperative Highway Research Program, Transportation Research Board (TRB), Washington DC 2003.

Nicuta, Alina-Mihaela. "*Life cycle analysis study for new and recycled asphalt pavements*". Technical University of Iasi. Feb 2, 2011.

Santero, N., Masanet, E., and Horvath, A., *Life-Cycle Assessment of Pavements: A Critical Review of Existing Literature and Research*, SN3119a, Portland Cement Association, Skokie, Illinois, USA, 2010, 81 pages.

Santero, Nicholas; Loijos, Alexander; Akbarain, Mehdi and Ochsendorf, John. "*Methods, Impacts, and Opportunities in the Concrete Pavement Life Cycle*". Concrete Sustainability Hub. MIt. August 2011.

Sharrard, Aurora L. "*Greening Construction Processes Using Input-Output Based Hybrid Life Cycle Assessment Model*". PhD Dissertation. Department of Civil & Environmental Engineering. Carnegie Mellon University. April 2007.

Sharrard, Aurora L.; Mathews, H. Scott; Ries, Robert J. "*Estimating Construction Project Environmental Effects Using an input-output Based Hybrid Life-cycle Assessment Model*". Journal of Infrastructure Systems. pp 327-336. ASCE December 2008.

Transportation Research Lab (TRL). Asphalt Pavement Embodied Carbon Tool (asPECT). Available from: http://www.irfghg.org/ (Accessed 21 December 2012).

Michigan Technical University (MTU). Project Emission Estimator (PE2) website. http://www.construction.mtu.edu/cass_reports/webpage/plca_estimator.php. (accessed 20 February 2013).

Zhang, H.; Keoleian, G.A and Lepech, M.D. "An integrated life cycle assessment and life cycle analysis model for pavement overlay systems". Life Cycle Civil Engineering. 2008.

CHAPTER 3

Research Methodology

Research Methodology

This chapter describes the research methodology for the integrated life cycle analysis approach (ILCA^2) for roadway projects. The development of a decision support tool based on ILCA^2 and an overview of the case study transportation program used in the research are also provided.

1. Integrated Life Cycle Analysis Approach (ILCA^2)

Transportation infrastructure is a complex system with multiple components that consist of different materials, products, and processes with different environmental impacts. By establishing a referential life cycle time frame, mostly homogeneous facility types with representative cross sections and/or construction characteristics, representative elements, and accepted construction, maintenance and reconstruction practices, a methodology can be developed that allows transportation decisions makers to quantify environmental impacts and their associated costs for transportation projects and programs. When these characteristics are defined, the approach developed in this research can be used to incorporate sustainability decisions into the planning process of state transportation agencies. This research specifically uses an exemplary urban roadway to develop and demonstrate the methodology. Application to or incorporation of other transportation facilities would require modification to the input values, underlying data, and conversions as outlined in this chapter. However, the overarching process remains the same.

ILCA^2 consists of integrating Life Cycle Assessment with Life Cycle Cost Analysis. First, a life cycle impact assessment method is developed that can capture the complexity of a transportation facility, in this case an urban roadway. After the environmental impacts are quantified, they are converted to costs which can be incorporated into a life cycle cost analysis. This approach is applied to a single representative project and then to a sample STIP of comparable transportation facilities – urban roadways – that are at different stages of construction, resurfacing and reconstruction during the life cycle evaluation period.

A transportation facility does not end and is not removed after a specified time period, thus it does not have a life cycle in the same sense that most products do. Instead, a transportation roadway facility is subject to a schedule of construction, resurfacing and reconstruction. To facilitate the integration of LCA and LCCA and provide a useful comparative analysis of environmental impacts and associated costs, a reference time frame is necessary. Throughout the remainder of this document, the term life cycle is used to reflect this reference time frame and is defined as 35 years based on FHWA policy for performing LCCA (FHWA 1998). To account for the different phases of a construction, resurfacing, and reconstruction, a schedule of activities is established as part of the integrated approach.

1.1. LCA Development

The primary goal of life cycle assessment is to assess environmental impacts related to a product or process. The most commonly referenced environmental impacts within the transportation construction sector include:

- carbon foot print of materials used combined with related construction processes (measured as tons of CO_2 equivalent),
- solid wastes including removed cut material and construction waste such as milled pavement (tons), and
- storm water runoff, (gallons).

As a result, the development of the LCA approach in this research limits the output to these three categories. Because the analysis also includes operating the facility over its life, an additional impact related to electricity use is added to the overall carbon footprint.

Based on current practices and recommended standards accepted in the industry, the ISO 14040 LCA framework is used as the basis for the first component of this research. Steps defined by the ISO framework consist of (1) defining the goal and scope, (2) performing an inventory analysis, (3) performing an impact assessment, and (4) interpreting the results (ISO 2006) as outlined in Figure 1.

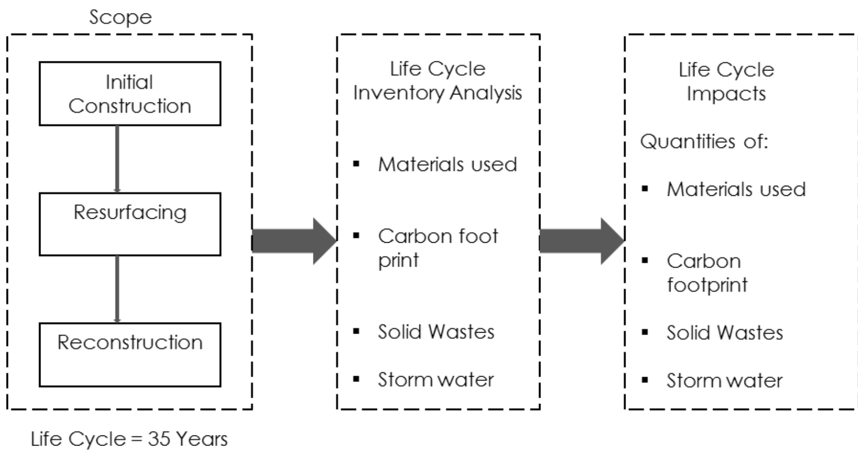


Figure 1: LCA model based on ISO 14040 Frame work

Goal and Scope Definition – The goal is to calculate the life cycle impacts of transportation projects and the Scope is to assess the impacts of the life cycle stages of transportation projects that include: Construction, Resurfacing and Reconstruction related activities.

Life Cycle Inventory Analysis – The life cycle inventory analysis includes calculating inputs and outputs as volumes of materials, storm water runoff and solid waste materials over the life cycle of the project. Inputs include construction materials and energy inputs. Outputs include carbon foot print of the materials and energy, storm water runoff, and solid wastes. Material quantities are calculated based on estimating volume of standard materials needed for roadway construction, resurfacing and reconstruction. Carbon foot print as lb of CO_2 (or tons of CO_2) eq for these materials is calculated using the *Inventory of Carbon and Energy (ICE)* Version 1.6a. 2008-2011 data developed by Hammond and Craig which provides global warming potential (GWP) in terms of lb CO2 per lb of material as given in Table 1 (Hammond et al 2011). Life cycle storm water runoff from the facility is calculated using the surface area per lane mile of a facility and annual average precipitation for the construction site. Solid wastes are estimated as tons of material based on the quantities of materials removed during construction, reconstruction and resurfacing for the life cycle of the facility.

Table 1: Construction materials and carbon conversion factors (Hammond et al 2011)

Material	**Carbon data (**lbCO2/lb)
Asphalt (Roadway)	0.14
Bricks	0.22
Concrete (Road & Pavement)	0.127
Concrete (Fiber Reinforced)	0.45
Concrete (Reinforced)	0.241
Gravel/Aggregate Base	0.017
Soil	0.023
Paint (lanes marking etc)	3.56
Pipe (Iron)	1.91
Pipe/Light & Signal Poles (Steel)	2.7
Pipe (PVC)	2.5
Plastic (signals/lights)	1.71
Stone (General)	0.056
Stone (Gravel)	0.017
Signs (Plastic)	2.53
Signs (LDPE)	1.7

Note: Includes carbon footprint associated with construction processes related to material

Life Cycle Impact Assessment & Interpretation – The life cycle impacts are calculated by estimating the quantities of materials used and their corresponding carbon footprint, storm water runoff from the facility, and solid wastes materials removed based on the schedule of activities.

Based on the LCA framework, life cycle impacts are calculated using equation [1].

$$\textit{life cycle impact} = \Sigma CF + \Sigma SW + \Sigma SR \qquad [1]$$

Where,

CF = Carbon footprint (tons of CO_2 equivalent)

SW = Solid Wastes (tons)

SR = Storm water runoff (million gallons)

Carbon footprint, solid waste, and storm water runoff impacts result in different units of output and cannot be directly added, which is one of the major challenges in quantifying life cycle impacts of a transportation facility. To have a consistent measure for comparing and evaluating life cycle impacts this approach converts volumes to cost according to market costs given in Table 2. Resulting cost impacts can be calculated according to equation [2].

Table 2: Impact cost conversion factor

Impact	Cost $	Source
Carbon	20 / ton	DOE 2012 and Wilson 2012
Solid waste	53 / ton	DPW 2012
Storm water	6500 /million gallon	DC Water 2012

life cycle cost impact = CFC + SWC + SRC [2]

Where,

$CFC = C_{CFC} * (IC + n_{RC}\Sigma\ RC + n_{R}\Sigma\ R + +n_{LC}\ \Sigma\ E - SC)$ [3]

$SWC = C_{SWC} * (SWIC + + n_{RC}\Sigma\ SWC + n_{R}\Sigma\ SWR)$ [4]

$SRC = C_{SRC} * (SA * L \times AP * 7.48 * n_{LC})$ [5]

AP = annual precipitation (ft)

CFC = carbon footprint costs

SWC = solid waste costs

SRC = storm water runoff costs

C_{CFC} = carbon cost conversion factor

C_{SWC} = solid waste cost conversion factor

C_{SRC} = storm water runoff conversion factor

IC= carbon footprint associated with Initial Construction

RC = carbon footprint associated with Reconstruction

R = carbon footprint associated with Resurfacing

L = length (ft)

E = carbon footprint associated with Energy use

SA = surface area (ft^2)

SC = salvage carbon footprint

SWIC = solid wastes associated with Initial Construction

SWRC = solid wastes associated with Reconstruction

SWR = solid wastes associated with Resurfacing

n_{RC} = number of reconstructions during life cycle

n_R = number of resurfacings during life cycle

n_{LC} = life cycle span (years)

When impacts are converted to costs, they can be directly integrated with other life cycle costs as described in the next section.

1.2 Integrating Life Cycle Impacts and Life Cycle Costs

Life costs are calculated for initial construction, resurfacing and construction based on the quantities of the materials, energy used for streetlights and signals for 35 years. This framework is illustrated in Figure 3.2 and calculated as:

$$\textit{life cycle costs} = ICC + n_{RC}\Sigma\ RC + n_R\ \Sigma\ RSC + n_{LC}\ \Sigma\ OC + n_{LC}\ \Sigma\ EC - SV \qquad [6]$$

Where,

EC = annual energy cost of the facility

ICC = cost of Initial Construction

OC = annual operation cost of the facility

RCC = cost of Reconstruction

RC = cost of Resurfacing

SV = Salvage Value

n_{LC} = life cycle span (years)

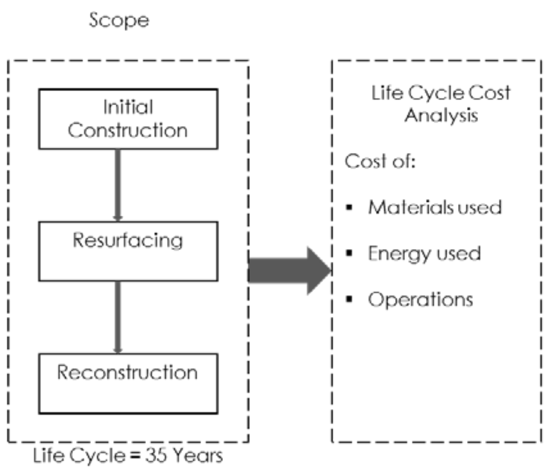


Figure 2: Life cycle costs framework

The framework illustrated in Figure 1 and 2 is integrated to develop the integrated life cycle analysis approach ($ILCA^2$) as shown in Figure 3.

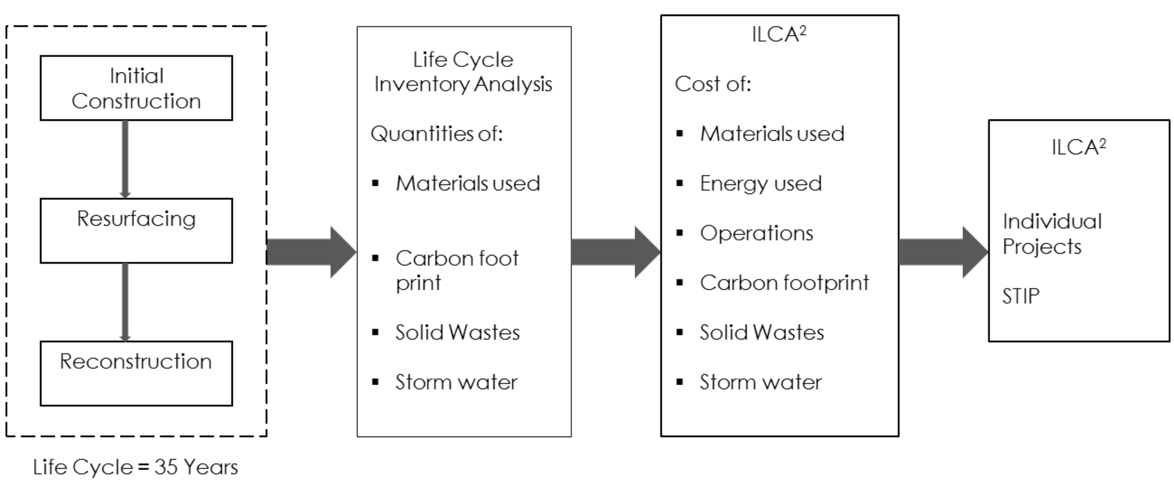


Figure 3: Integrated Life cycle Analysis Approach ($ILCA^2$) framework

Based on this framework, the integrated life cycle costs are calculated as:

$ILCA^2$ = life cycle impact + life cycle costs [7]

Using equation 2 and 6, equation 7 becomes,

$$ILCA^2 = CFC + SWC + SRC + ICC + n_{RC}\Sigma\, RC + n_R\Sigma\, RSC + n_{LC}\Sigma\, OC + n_{LC}\Sigma\, EC - SV \quad [8]$$

Equation [8] is used to calculate the integrated life cycle costs of roadway facilities.

2. Application of ILCA² to a homogenous roadway facility

The ILCA² framework and methodology described in section 1 can be applied to different types of roadway facilities. This research focuses on urban roadways and defines a representative urban roadway cross section as:

- *travel way* – includes vehicular lanes, bicycle lanes, and curb and gutter
- *roadside* – includes tree planting strip and sidewalks.

Figure 4 and 5 illustrate the typical roadway cross sections.

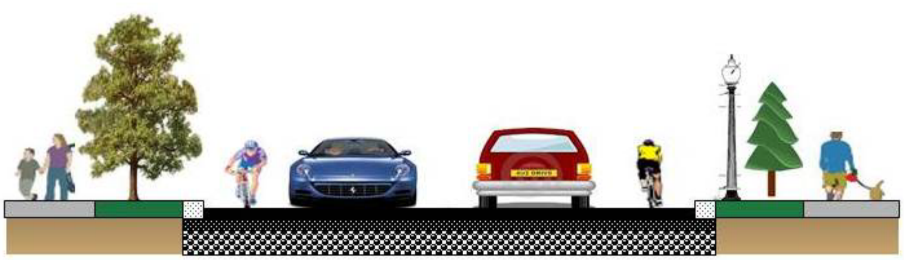


Figure 4: Standard cross section of an urban roadway

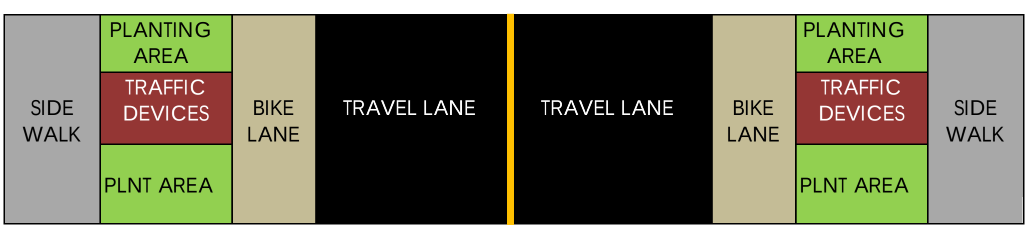


Figure 5: Plan View of an urban roadway

Pavement design follows the 1993 AASHTO Guide basic design equation for flexible pavements. Based on the equation, a nominal pavement section was developed for the pavement thickness that includes 2 inch surface asphalt course, 10 inch Portland cement concrete and 6 inch aggregate base. Table 3 describes the roadway characteristics used to define the representative urban roadway.

Table 3: Urban Roadway Characteristics

Roadway element	dimensions
Lane width	11 ft
Bike Lane width	5 ft
Pavement: Construction	2 inch asphalt, 10 inch PCC
Side walk	6 ft each side
Intersection Traffic Signal spacing	300 ft
Number of Signalized Intersections / mile	18
Planting area width	4 ft each side
Planting area spacing	40 ft
Street light spacing	100 ft

Roadway resurfacing and reconstruction programs play an important role in the condition and maintenance of the roadway. There is no standard time frame for roadway resurfacing and reconstruction and is dependent on a number of factors such as the average daily traffic, pavement index, geotechnical factors, weather conditions and type of traffic (vehicles) using the facility. Based on a review of the pavement restoration program of urban streets for several DOTs, it was determined that urban roadways are resurfaced approximately every 8 to 12 years and reconstructed approximately after 25 to 30 years. From this information, this research used the schedule provided in Table 4.

Table 4: Schedule of phases over the reference life cycle of an urban roadway

Year	Activity
0	Construction
10	Resurfacing
20	Resurfacing
30	Reconstruction
35	End of Life Cycle

3. Tool development

A Java-scripting based decision support $ILCA^2$ prototype tool was developed based on the methodology described in this chapter. The prototype tool was designed to use a minimal number of inputs, shown in Table 5, supplemented by a Table of standard data provided in Table 6. Figure 6 provides a screenshot of the prototype tool while Appendix 3 includes a user manual and Appendix 4 provides the code.

Table 5: Model Inputs

Total Length	in miles
Number of vehicular lanes	number
Number of bike lanes	number

Table 6: Standard data in the model

Service Life (life cycle) in years	35
Lane width	11 ft
Bike Lane width	5 ft
Pavement: Construction	2 inch asphalt, 10 inch PCC
Pavement: Resurfacing	2 inch asphalt
Pavement: Reconstruction	2 inch asphalt, 6 inch PCC
Side walk	6 ft each side
Intersection Traffic Signal spacing	300 ft
Number of Signalized Intersections / mile	18
Planting area width	4 ft each side
Planting area spacing	40 ft
Street light spacing	100 ft

Output from the tool includes values for each phase listed in the schedule shown in Table 3 as well as totals for the overall lifecycle. Appendix 2 provides the complete output from the case studies.

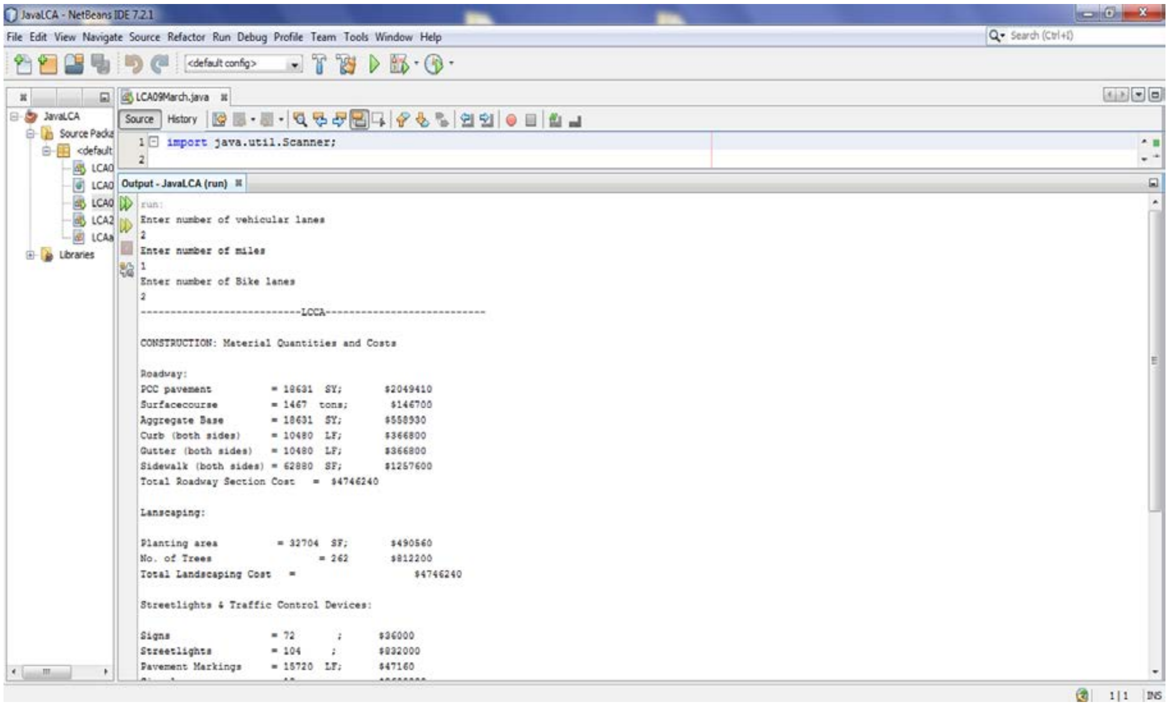


Figure 6: Screen shot of the ILCA² tool

3.4. Case Study

To demonstrate the ILAC² methodology and tool, a case study was performed using information from the District of Columbia DOT and a subset of projects based on the current STIP. The District of Columbia Department of Transportation (DDOT) functions as a State DOT as defined in 23 USC 101 subsection 32 and 23 CFR 1.2. DDOT owns and maintains over 1,600 miles of roadways and alleys as well as 241 small and large bridges (DDOT 2013). DDOT is also a member of AASHTO and uses AASHTO standards for design, construction, and materials.

3.5. Data Collection

The FY 2011-2016 DDOT STIP includes projects from planning to design and construction, as well as many non-roadway projects and programs. From this STIP, sample roadway construction, resurfacing and reconstruction projects were selected for the case study, as shown in Table 7. Information about these projects has been generalized since this case study is designed to demonstrate the methodology and results are not for operational or planning use.

Table 7: Projects from STIP selected for the research (DDOT 2012)

Project Name	Length (miles)	Number of vehicular lanes	Number of bike lanes
CONSTRUCTION			
Project 1	1	2	2
Project 2	1	8	0
RESURFACING			
Project 3	115	6	2
Project 4	20	6	2
RECONSTRUCTION			
Project 5	11	4	2
Project 6	1	6	0
Project 7	0.25	5	2
Project 8	1	6	2
Project 9	0.25	4	2
Project 10	4	4	0
Project 11	0.5	8	2
Project 12	1.5	4	2
Project 13	1	4	2
Project 14	1	6	2

Construction materials needed for a project are determined from DDOT Standard Drawings and DDOT Standards and Specifications based on the typical sections and total length of the project (DDOT 2012). Because DDOT standards and specifications comply with AASHTO standards and specifications, they are similar to other State DOTs. Cost data is obtained from actual DDOT projects related to resurfacing, roadway reconstruction, and roadway construction projects. This data was collected from different projects between 2009 and 2011 and was averaged to 2011 dollars is given Table 8.

Table 8: Cost conversion factor (DDOT 2011)

Description	Unit Cost $	Quantity
Removal of Existing Surface Pavement	$60	Cubic Yard (CY)
Removal of Existing base Pavement	$60	CY
Removal of Existing Sidewalk	$60	CY
Removal of curb and gutter	$60	CY
Excavation	$40	CY
Excavation landscaping	$40	CY
Borrow	$50	CY
Install WQ Inlet	$16,000	Each
Remove Existing Inlet	$2,000	Each
Install 48" I.D. Manhole	$8,150	Each
18" RCP Pipe	$130	Linear Feet (LF)
PCC Pavement, 10"	$110	Square Yard (SY)
2" Superpave, Type C Hot-Mix	$100	TON
6" Graded Aggregate Base Course	$30	SY
Curb	$35	LF
Portland Cement Concrete Gutter	$35	LF
Sidewalk (6ft each side)	$20	Square Feet (SF)
Planting area	$15	SF
Signing	$500	Each
Street Lights	$8,000	Each
Pavement Marking	$3	LF
New Signals	$200,000	Each
Concrete Encased Multi Duct	$100	LF
ponding (6")	$53	CY
soil	$57	CY
aggregate base	$18	LF
Under drain	$2.5	SY
Mulch	$35	LF
Planting area walls	$53	CY
Energy Cost*	$0.134	KWhr
Operation Cost**	$23,000	Lane mile/year

* source DOL 2012

** source FHWA 2011

Categories given in Table 6 are usually used in material quantity calculations by DOTs. By estimating the quantities needed for each category and using the unit cost, the total cost of a project were estimated. These material quantities were used to estimate the life cycle environmental impacts.

References for Chapter 3:

Department of Energy (DOE). *Annual Energy Outlook with Projections to 2035*. Bureau of Labor Statistics. U.S Department of Energy, Energy Information Administration, Washington DC. June 2012.

Department of Labor (DOL). Bureau of Labor Statistics. *Average Energy Prices in Washington-Baltimore*. U. S Department of Labor, Washington DC. February 2012.

District Department of Transportation (DDOT). DDOT website. www.ddot.dc.gov (accessed March 2013).

District Department of Transportation (DDOT). *FY 2011-2016 STIP*. District of Columbia Department of Transportation. 2012.

District Department of Transportation (DDOT). *Cost estimates of roadway construction, resurfacing and reconstruction projects*. Cost data 2009-2011. 2011.

District Department of Transportation (DDOT). *Design and Engineering Manual*. District of Columbia Department of Transportation. April 2009. pp 2-1 to 2-35.

DDOT. *Standard Drawings*. District of Columbia Department of Transportation. April 2009.

DC Water. *Current Water Rates*. http://www.dcwater.com/customercare/rates (accessed April 2012)

EPA 2009. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 –2007*. Environmental Protection Agency. 2009. pp I-3 to I-8.

DC Department of Public Works (www.dpw.dc.gov) (accessed April 2012)

Federal Highway Administration (FHWA) 2012. *Highway Statistics 2010*. Office of Highway Policy Information, FHWA, 1200 New Jersey Avenue, SE Washington, DC 20590.

Federal Highway Administration (FHWA). *Life-Cycle Cost Analysis in Pavement Design*. Publication No. FHWA-SA-98-079. FHWA, Washington DC. 1998.

Hammond, Geoff and Jones, Craig. *Inventory of Carbon and Energy*. Version 1.6a. Department of Mechanical Engineering, University of Bath, UK. 2008 updated 2009-2011.

International Organization for Standardization (ISO). “ISO-14040-2006: Environmental Management-Life Cycle Assessment-Principles & Framework”. ISO Geneva, Switzerland. 2006.

Wilson, Rachel., Luckow, Patrick. Et al. *2012 Carbon Dioxide Carbon Forecast*. 2012.

CHAPTER 4

Quantifying Life Cycle Impacts for Transportation Projects

Quantifying Life Cycle Impacts for Transportation Projects

Faisal Hameed, Kathleen Hancock, Tom Grizzard

Civil and Environmental Engineering Department, Virginia Polytechnic Institute and State University

Abstract

To understand the environmental impacts of a transportation facility its life cycle has to be considered. Life Cycle Assessment (LCA) is a method used to analyze such environmental impacts. Current LCA practices for roadways perform analyses for pavements and focus on GHG emissions. A roadway facility includes a number of elements such as travel way, sidewalks, street lights, traffic signals, lane striping and drainage. These elements require different types of materials and can have numerous impacts. The quantification of life cycle environmental impacts of a roadway that includes construction, resurfacing and reconstruction as well as impacts related with managing the facility by few readily available inputs can help the transportation professional significantly. Quantifying the life cycle impacts of each element can help in identifying elements with high impacts so that those elements can be prioritized for alternate design, material evaluations, reclamation and recycling of materials. The tool developed by this research allows the calculation of life cycle environmental impacts of a roadway as: carbon footprint in CO_2 eq, quantity of storm water runoff from the roadway and quantity of solid waste materials. Results show that the life cycle impacts of unit length of an urban street cross section can be over 10,000 tons of CO_2 eq. carbon footprint, over 100 million gallons of storm water runoff and over 70,000 tons of waste materials. The quantification of life cycle environmental impacts shows that the life cycle impacts are higher than the initial construction impacts. The results show that the life cycle carbon footprint is more than twice the initial construction carbon footprint. The life cycle solid wastes were estimated to be 1.5 times of the initial construction wastes. The results shows that more than 90% of the materials used for construction, resurfacing and reconstruction are typically removed and wasted.

1. Introduction

Roadways are a major element of a transportation system. There are over 4 million miles of paved public roadways in the United States, approximately one-fourth of which are urban (FHWA 2012). The construction, maintenance, and rehabilitation of this system over the life time require consumption of resources which result in environmental impacts. Currently there is no standard comprehensive approach that establishes life cycle environmental impacts of transportation projects. Life Cycle Assessments (LCA) is a methodology typically used to analyze the environmental impacts of a given product throughout its lifespan. By performing LCA of a roadway, its life cycle impacts can be quantified. Roadways are usually designed based on a service life. However, after the serviceable life, the life cycle of a transportation facility does not end and it continues to be used by providing regular maintenance and rehabilitation i.e. resurfacings and reconstructions. The rapid surge of interest through the late 1980s and early1990s showed that life-cycle assessment methodologies are among the most promising new tools for a wide range of environmental management tasks (EEA 1997). There are two types of LCA approaches: Process based LCA and Economic Input Output-LCA (Horvath 2004). Process based LCA models use mass-balance calculations to quantify inputs and outputs at each life cycle phase (Sharrard 2007) while the Economic Input Output -LCA models use the economic input output data such as the U.S Department of Commerce (Horvath 2004). The EIO-LCA models provide an assessment on the level of the country's economy (Hendrickson et al 1998). Process LCA was the basis for creation of the ISO 14040 standards which is most commonly used LCA framework (ISO 2001). By using this framework, a life cycle assessment approach for roadways can be developed that can measure the environmental impacts based on the materials and quantities used in the specified time period for initial construction, resurfacing and reconstruction of roadways. Urban roadway includes several elements such as travel way, sidewalks, street lights, traffic signals, lane striping and drainage which have different impacts. By quantifying the life cycle impacts of each element individually, elements that result in the highest impact can be identified and can be prioritized for alternate design or material evaluations. These impacts can also be assigned costs which can provide a method for quantifying total life cycle impacts of a transportation facility. This can then be used by transportation agency decision makers to evaluate decisions that support sustainability.

The quantification of life cycle environmental impacts of a roadway by using few readily available inputs can help the transportation professional significantly. The approach and tool developed by this research allows the calculation of life cycle environmental impacts of a roadway in terms of carbon footprint of the materials in CO_2 eq, quantity of storm water runoff from the roadway and quantity of used and wasted materials based on a standard cross section of materials and quantities. Quantifying the life cycle impacts of each element separately allows the decision makers to use alternate materials and practices to reduce the impacts of those elements and hence of the facility.

2. Background

BenReMod, asPECT, PaLATE, ROAD-RES, CHANGER and PE-2* are some of the road pavement LCA software tools that have been developed for transportation industry. These tools calculate Greenhouse gas (GHG) emissions from roadway construction. BenReMod (Beneficial Reuse Model) is a web based tool that can be used for quantitatively comparing benefits and disadvantages of different materials by using multi criteria decision making while provides outputs in global warming potential (GWP) and energy use (Apul 2007). asPECT (asphalt Pavement Embodied Carbon Tool) is software tool performs LCA of asphalt mixtures (Nicuta 2011). PaLATE (Pavement Life-cycle Assessment Tool for Environmental and Economic Effects is an Excel-based tool for LCA of environmental and economic effects of pavements and roads that provides environmental effects in energy, GWP, NOx, PM10, SO2, CO, Hg, Pb, and hazardous waste generation (Horvath 2012). The tool also provides a simple life-cycle costing mechanism, by material unit-weights not including labor, overhead, user (Santero et al 2010). ROAD-RES assesses the environmental impact of the materials production, construction, maintenance, and end-of-life phases of the pavement life cycle while particularly focusing on the comparisons of virgin materials to waste products considers eight different impact categories: GWP, photochemical ozone formation, nutrient enrichment, acidification, stratospheric ozone depletion, human toxicity, eco-toxicity, and stored eco-toxicity that cover environmental impacts to air, soil (Santero et al 2010). CHANGER (Calculator for Harmonized Assessment and Normalization of Greenhouse gas Emissions for Roads) is a software tool that performs LCA and providing results in carbon footprint of the roadway construction (Huanga 2012). PE-2 (Project Emission Estimator) is a web based tool that estimates life cycle emissions associated with construction, maintenance and use of the roadway (MTU 2013). The PE-2 tool can be used 27 at the project and the network levels while its recommended application is to monitor GHG emissions from construction projects, and to benchmark emissions for future projects (Mukherjee 2013). These models concentrate on roadway or pavement construction and provide impacts in GHG emissions. A roadway facility includes additional elements such as travel way, sidewalks, street lights, traffic signals, lane striping and drainage which consist of different types of materials with different impacts. The results of the models and research also vary because of the differences in system definitions. These models also pose a challenge for practitioners in DOTs because of the need for data and inputs which are usually not available during planning, project development and preliminary design /engineering of transportation projects.

3. Quantifying Life Cycle Impacts

Quantifying life cycle environmental impacts can be used as performance measures to provide guidance on making environmentally sustainable transportation investment decisions. To determine these performance measures a standard procedure is necessary which should include the life cycle length, physical extent of the project and cross section elements. Roadways are usually designed for 20 or more years. After the design life, a transportation facility does not end but continues to be used by providing regular maintenance and rehabilitation. However, to understand the environmental impacts of a transportation facility, a time frame for its life cycle has to be defined. Federal Highway Administration (FHWA) Life cycle Cost Analysis (LCCA) policy recommends an analysis period of at least 35 years (FHWA 1998) which is used for this research.

The ISO 14040 LCA framework was used for developing a life cycle impact assessment approach. The framework consists of: goal and scope definition, inventory analysis, impact assessment, and interpretation. Figure 1 provides a schematic of how this framework was applied on roadway projects. The scope includes construction, resurfacing and reconstruction of roadways during 35 years of use. The material quantities are calculated by using the standard materials needed for roadway construction, resurfacing and reconstruction.

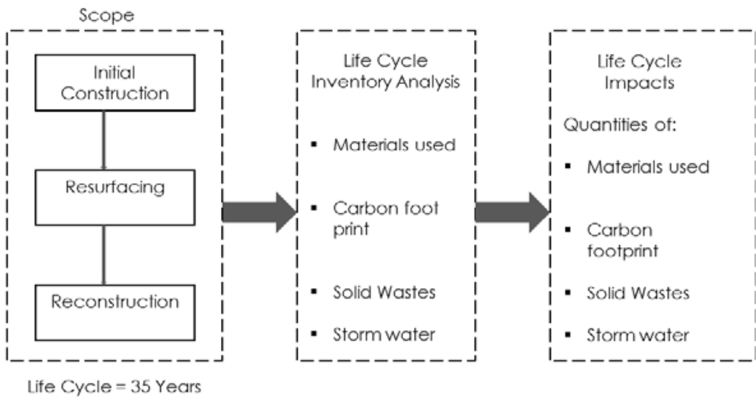


Figure 1: LCA model based on ISO 14040 Frame work

Life cycle inputs include construction materials while impacts which are used as performance measures include carbon foot print of the materials used as tons of CO_2 equivalent, Storm water runoff from the facility and Solid waste materials. It should be noted that the storm water runoff is not a measure of the construction, resurfacing and reconstruction but a measure of life cycle impacts due to the operating the facility and is only included in life cycle impact discussions. The performance measures used are given in Table 1.

Table 1: Performance Measures

Life Cycle Impacts	Unit
Carbon footprint	Tons of CO2
Storm water runoff	Million Gallons
Solid Waste	Tons

- The research uses carbon footprint as CO_2 equivalent as one of the measures of life cycle impacts. The CO_2 equivalent is used to measure the impact of the Greenhouse Gases and is sometimes also called Global Warming Potential (GWP). Carbon foot print as tons of CO_2 eq for these materials is calculated using the *Inventory of Carbon and Energy (ICE)* Version 1.6a 2008-2011 data (Hammond et al 2011).

- Life cycle storm water runoff from the facility is calculated as million gallons for the 35 year life cycle by calculating the runoff as Gallons/day and Gallons/mile using the surface area of the facility and the annual average precipitation.

- The solid wastes are estimated as tons of solid wastes by calculating the quantities of materials removed during all construction, reconstruction and resurfacing for the life cycle of the facility.

4. Analysis

To demonstrate the use of the methodology an example scenario was defined and evaluated. The scenario consists of a two lane urban street that includes bike lanes, planting area and sidewalks on both sides as shown in Figure 2. These calculations were done using the conventional virgin construction materials. This was done to provide a baseline that can show the potential of using products and practices that can offset these impacts.

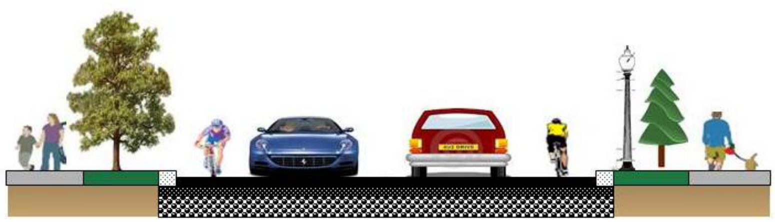


Figure 2: Standard cross section of an urban roadway

4.1. Data Set:

The "life cycle" was defined as 35 years. The spatial boundary includes the length and cross section of the roadway. Cross section includes Width: width across the travel way for vehicular lanes and bicycle lanes, side walk widths, curb and gutter, tree planting and width; and Depth: Surface asphalt course, pavement base course, aggregate sub base. Figure 3 shows the cross section details of an urban roadway used.

Figure 3: Typical section of roadway with cross section widths

The materials and quantities needed for a roadway project is based on DDOT Standard Drawings (DDOT 2009) and DDOT Standards and Specifications (DDOT 2009) based on the typical sections and the total length of the project.

4.2 Performance Measures:

The performance measures as given in Table 1 were used:

1. Life cycle Environmental impacts of the roadway as carbon footprint
2. Life cycle environmental impacts of the roadway as solid waste materials

3. Life cycle environmental impacts of the roadway as storm water runoff

4.3 Results and Discussion:

In order to determine the total life cycle impacts construction, resurfacing and reconstruction activities must be considered. One of the first outputs of the tool is the material quantities for the major elements of the facility:

- Grading: Grading includes removal of existing surface pavement, pavement base, sidewalks, curb and gutter, excavation and borrow
- Drainage: Drainage includes drainage inlets, manholes and pipes
- Roadway: Roadway includes surface pavement, pavement base and aggregate base for bike lanes, vehicular lanes, curb and gutter.
- Sidewalks
- Landscaping: Landscaping includes planting strip and trees
- Storm water management: Storm water management includes low impact development bio-retention zones
- Streetlight and traffic control: Street lights and traffic control includes lane marking, traffic signs, traffic signals, streetlight and ducts

Construction:

The results show that the initial construction of an urban street can use 76,958 tons of different types of materials that have a carbon footprint of 3669 tons of CO_2 eq. Table 6 shows the material quantities needed, Carbon foot print as CO_2 eq. and waste materials for each section.

Table 2: Construction material quantities & environmental Impacts of project

Construction Activity	Construction Materials	Environmental Impacts	
		Carbon footprint	Solid Waste
	tons	Tons CO2	tons
Grading	46,104	973	46,104
Drainage	950	121	0
Roadway	18,916	1,784	0
Sidewalk	2,330	296	0
Street lights and Traffic Control	513	241	0
Landscaping	2,949	68	0
Low Impact Development	5,196	187	0
Total	**76,958**	**3,669**	**46,104**

The results show that grading is the activity/element that uses largest quantity of materials i.e. 46,000 tons and represents 60% of the total quantity of materials used as shown in Figure 4, however, for carbon footprint it results in 973 tons CO_2 eq. which is only 26% of the total carbon footprint of the roadway as shown in Figure 5. This is due to the fact that the grading activities in the construction stage only require removing soil and soil as a material has much lower carbon foot print (0.023 $lbCO_2/lb$ of material) than most of the materials used in construction. Roadway or travel way is the second in terms of materials used and represents 18,916 tons of materials which represent 24% of the total quantity of materials as shown in Figure 4. However, for carbon footprint it is the highest and results in 1784 tons CO_2 eq. which is 49% of the total carbon footprint of the entire roadway which is due to the fact that the travel way includes sections of asphalt, PCC base and aggregate sub base. Asphalt and PCC has higher carbon foot print compared to soil i.e. 0.14 $lbCO_2/lb$ of material Asphalt and 0.127 $lbCO_2/lb$ of material of PCC. Low impact development (LID) is third in terms of materials used and represent 7% of the total quantity of materials as shown in Figure 4 however, for carbon footprint LID represents 5% of the total carbon footprint of the entire roadway as shown in Figure 5. This due to the fact that main materials used in LID construction is also soil. Sidewalks are the fourth in terms of materials used and represent only 3% of the total quantity of materials however, for carbon footprint they represent 8% of the total carbon footprint of the entire roadway which is due to the fact that main materials used in sidewalks construction is concrete (PCC) which has a higher carbon foot print. Another interesting result is the Streetlights and Traffic control devices. These represent only 1 % of the total quantity of materials however, for carbon footprint they represent 7% of the total carbon footprint of the entire roadway. This is primarily due to the streetlight poles and paint used for pavement markings. Figure 4 and 5 illustrate these results.

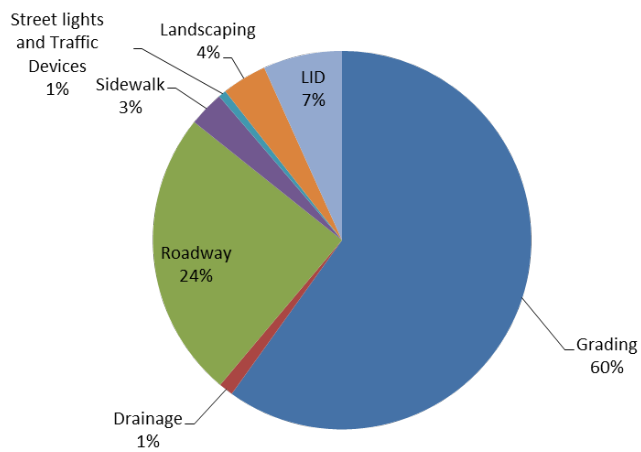


Figure 4: Construction Material Quantities

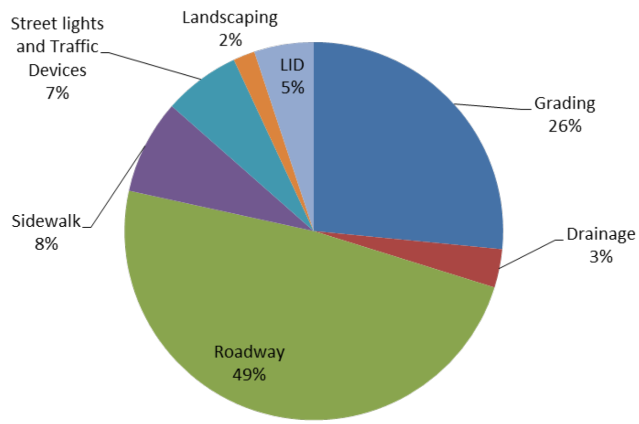


Figure 5: Construction Carbon footprint

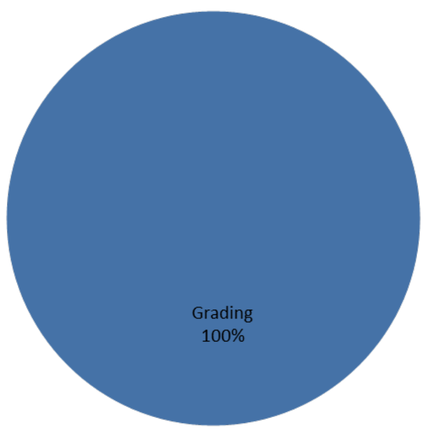


Figure 6: Construction Solid Waste Material

The only waste materials are the materials removed in grading which represents 100% of the solid waste materials as shown in Figure 6.

Resurfacing:
The results show that the resurfacing of the urban street can use 2946 tons of different types of materials which have a carbon footprint of 454 tons of CO2 as shown in Table 3.

Table 3: Resurfacing material quantities & environmental impacts of project

Resurfacing	Resurfacing Materials	Environmental Impacts	
		Carbon footprint	Waste Materials
	tons	Tons CO2	tons
Grading	1,467	205	0
Drainage	0	0	0
Roadway	1,467	205	1,467
Sidewalk	0	0	0
Street lights and Traffic Devices	12	44	12
Landscaping	0	0	0
Low Impact Development	0	0	0
Total	**2,946**	**454**	**1,479**

Grading uses 1467 tons of materials and represents 50% of the total quantity used as shown in Figure 7 while it results in 205 tons CO2 eq. which is 45% of the total carbon footprint as shown in Figure 8. Roadway uses 1467 tons of materials which represent 45% of the total quantity of materials. The carbon footprint of this section is 205 tons CO2 eq. which is 45% of the total carbon footprint. The results of both grading and roadway are exactly the same. It is due to the fact that the only grading occurring in resurfacing is the removal of the asphalt surface course which is being replaced by the exact same amount in the resurfacing activity. Another interesting result is the Streetlights and Traffic control. These represent less than 1 % of the total quantity of materials however, for carbon footprint they represent 10% of the total. This is primarily due to the paint used for pavement markings. Figure 7 and 8 illustrate these results. It should be noted that these results are for only one resurfacing activity.

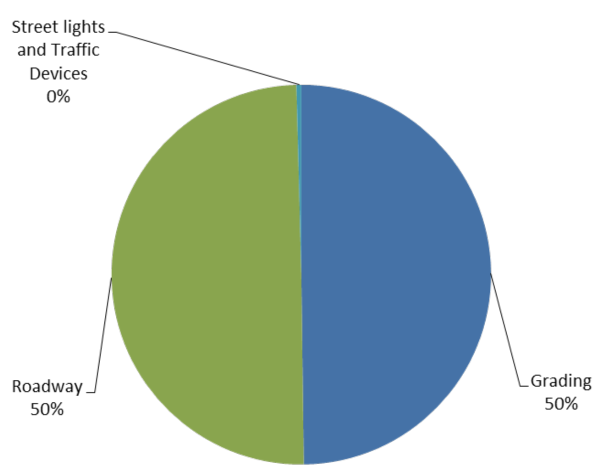


Figure 7: Resurfacing Material Quantities

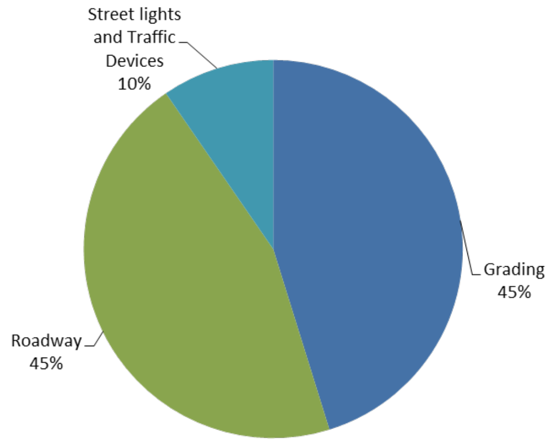


Figure 8: Resurfacing Carbon Footprint

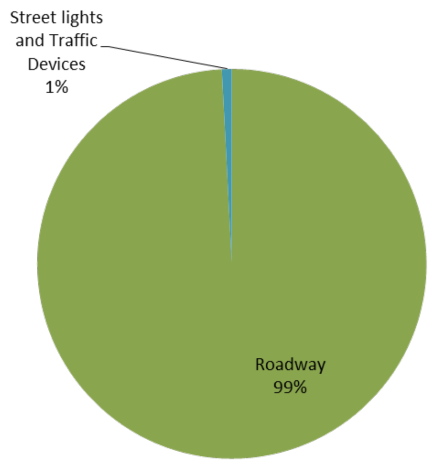


Figure 9: Resurfacing Solid Waste Materials

The materials wasted and sent to landfill include the asphalt surface course removed in the roadway and the paint for pavement markings. Surface course removal of the roadway represents 99% of the total materials wasted as illustrated in Figure 9.

Reconstruction:

The results show that the reconstruction of the urban street can use 33,933 tons of different types of materials which have a carbon footprint of 3557 tons of CO_2 as shown in Table 4.

Table 4: Reconstruction material quantities & environmental impacts of project

Reconstruction	Reconstruction Materials	Environmental Impacts	
		Carbon footprint	Waste Materials
	tons	Tons CO2	tons
Grading	14,794	1,898	0
Drainage	287	36	238
Roadway	7,939	1,027	12,464
Sidewalk	2,330	296	2,330
Street lights and Traffic Devices	137	93	137
Landscaping	3,780	87	3,780
Low Impact Development	4,666	119	4,666
Total	**33,933**	**3,557**	**23,614**

The results show that grading is the category that uses 14,794 tons of materials and represents 44% of the total as shown in Figure 10; however, for carbon footprint it results in 1,898 tons CO_2 eq. which is 53% of the total carbon footprint as shown in Figure 11. This is due to the fact that the grading activities in the construction stage only require removal of the surface course asphalt and PCC base. Roadway or travel way is the second in terms of materials used and represents 7,939 tons of materials which represent 23% of the total quantity of materials. The carbon footprint of this section is 1,027 tons CO_2 eq. which is 29% of the total carbon footprint. Low impact development (LID) is third in terms of materials used and represent 14% of the total quantity of materials however, for carbon footprint they represent 3% of the total carbon footprint of the entire roadway. This due to the fact that main materials used in LID construction is also soil. Sidewalks represent 7% of the total quantity of materials however, for carbon footprint they represent 8% of the total carbon footprint of the entire roadway. Streetlights and Traffic control devices represent less than 1 % of the total quantity of materials while for carbon footprint they represent 3% of the total carbon footprint of the entire roadway. This is primarily due to the fact that not all of the poles have to be replaced at reconstruction. Figure 10 and 11 illustrate these results.

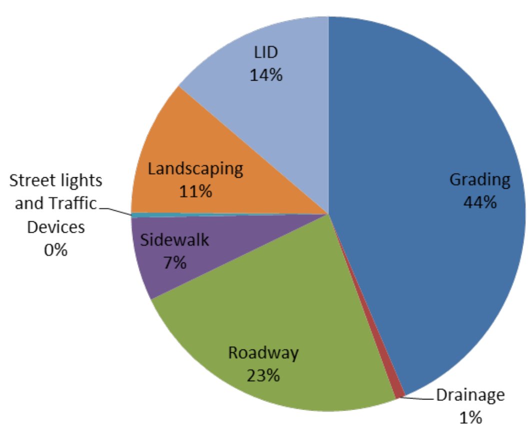


Figure 10: Reconstruction Material sQuantities

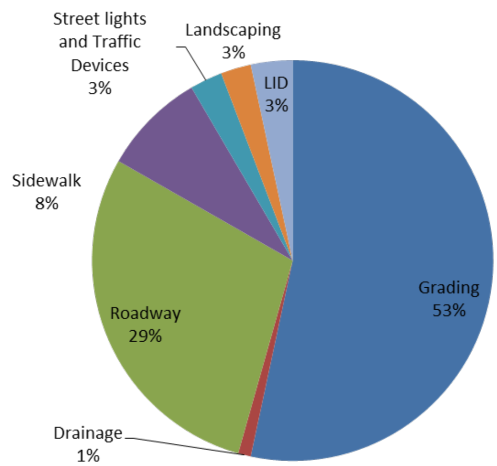


Figure 11: Reconstruction Carbon Footprint

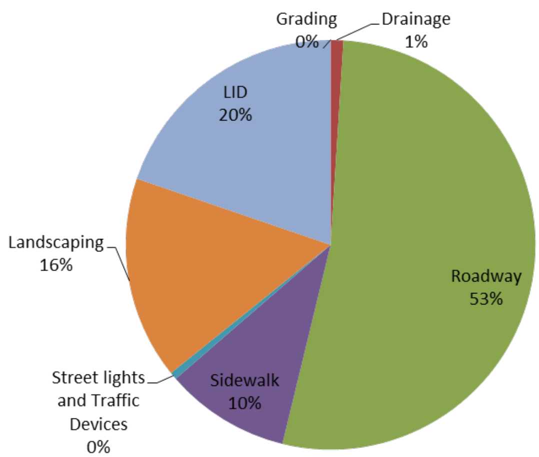


Figure 12: Reconstruction Solid Waste Materials

The results show that grading is the category that uses 14,794 tons of materials and represents 44% of the total as shown in Figure 10; however, for waste material it results in no waste while roadway results in 12,464 tons of waste and represents 53% of the total wastes as shown in Figure 12. This is one the major challenges of assessing impacts of roadways. Even though removal of asphalt and pavement is usually listed under grading however, the waste generated in due to roadway materials. Also, the pavement removed actually was put in the construction stage.

Life Cycle:

The results of the life cycle include one construction, two resurfacing and one reconstruction. The results show that the over the life cycle the urban street can use 116,784 tons of different types of materials which have a carbon footprint of 10, 498 tons of CO_2. The storm water runoff from the street can be 208 million gallons over the life cycle. Detailed results are presented in Table 5.

Table 5: Life Cycle material quantities & environmental impacts of project

Life Cycle	Life Cycle Materials	Environmental Impacts: Carbon footprint	Waste materials	Storm water
	tons	tons CO2	tons	Million gallons
Activities related with materials				
Grading	63,832	1,701	46,104	
Drainage	1,237	127	238	
Roadway	29,790	2,366	15,398	
Sidewalk	4,660	345	2,330	
Street lights and Traffic Devices	6,729	344	162	
Landscaping	675	82	3,780	
Low Impact Development	9,862	207	4,666	
Activities related with Life cycle of the facility use and not with materials				
Energy		5,327		
Storm water runoff				208
Total	**116,784**	**10,498**	**72,677**	**208**

The results show that over the life cycle grading uses 63,832 tons of materials and represents 55% of the total quantity of materials used as shown in Figure 13, however, for carbon footprint it results in 1,701 tons CO_2 eq. which is only 16% of the total life cycle carbon footprint as shown in Figure 14. Roadway is the second in terms of materials used and represents 15,398 tons of materials which represent 25% of the total quantity of materials as shown in Figure 13 however the carbon footprint of this section is 2,366 tons CO_2 eq. which is 23% of the total carbon footprint as shown in Figure 14. Low impact development (LID) represents 8 % of the total quantity of materials however, for carbon footprint LID represents 2% of the total carbon footprint of the entire roadway. This due to the fact that main materials used in LID construction is also soil. Sidewalks represent 4% of the total quantity of materials as shown in Figure 13 however, for carbon footprint they represent 3% of the total carbon footprint of the entire roadway as shown in Figure 14.

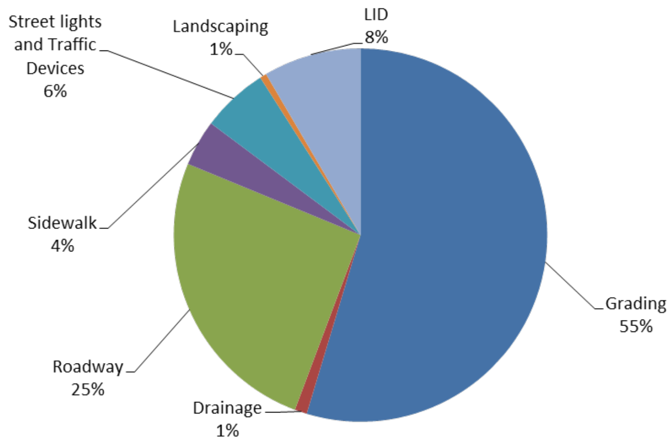


Figure 13: Life cycle material quantities

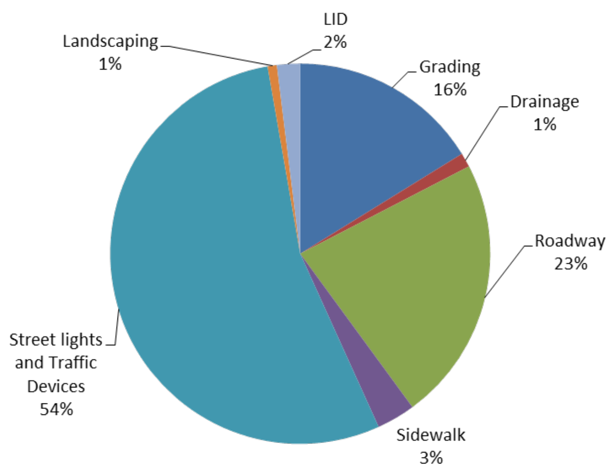


Figure 14: Life cycle carbon footprint

Streetlights and Traffic control devices represent 6 % of the total quantity of materials as shown in Figure 13 while for carbon footprint they represent 54% of the total carbon footprint of the roadway as shown in Figure 14. This is due to the primarily due to the fact that in life cycle carbon footprint the energy used by streetlights and the traffic signals is included in the carbon footprint calculation. If the energy use footprint is not included in Streetlight section as shown in Figure 15 then Streetlights and traffic devices only represent only 7% of the carbon footprint while roadway section represents the highest (46%) of the total carbon footprint.

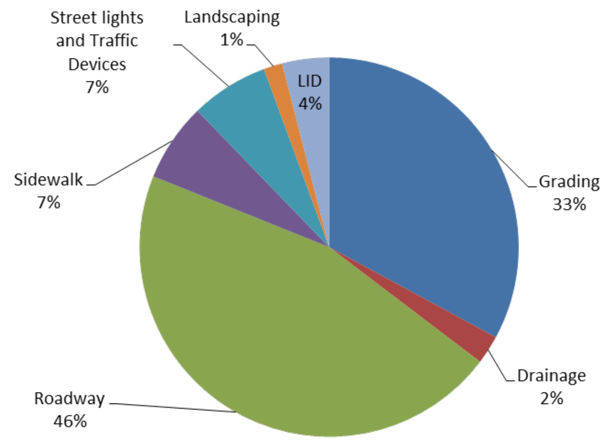


Figure 15: Life cycle carbon footprint without energy

The analysis of solid wastes shows that over the lifecycle grading results in 46,104 tons of solid waste and represents 64% of the materials wasted as shown in Figure 16. The roadway results in 15, 398 tons of waste and represents 21% of the total wastes. LID results in 4,666 tons of wastes while it represents 7% of the lifecycle wastes as shown in Figure 16.

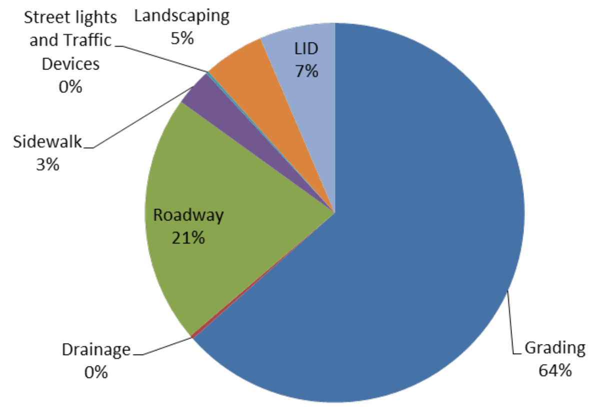


Figure 16: LCA Solid Materials Wasted

Quantification of the materials by lifecycle phase is provided in Table 6. The analysis of these results show that construction represents 66% of the materials used, reconstruction represents 29% and the two resurfacings represent 5% of the total carbon footprint of the street as shown in Figure 17.

Table 6: Comparison of life cycle material quantities

	Construction	Resurfacing	Reconstruction	Lifecycle
	tons	tons	tons	tons
Grading	46,104	1,467	14,794	63,832
Drainage	950	0	287	1,237
Roadway	18,916	1,467	7,939	29,790
Sidewalk	2,330	0	2,330	4,660
Street lights and Traffic Devices	513	12	137	6,729
Landscaping	2,949	0	3,780	675
LID	5,196	0	4,666	9,862
Total	**76,958**	**2,946**	**33,933**	**116,784**

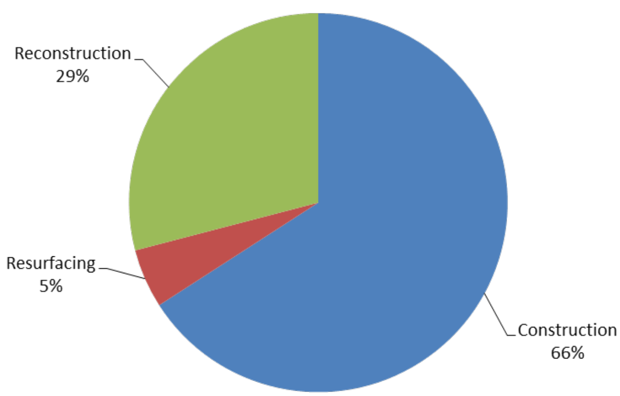


Figure 17: Materials quantities by lifecycle phase

Quantification of the carbon footprint by lifecycle phase is provided in Table 7. The results show that construction represents 45% of the total carbon footprint, reconstruction represents 44% and the two resurfacings represent 11% of the total carbon footprint of the street as shown in Figure 18.

Table 7: Comparison of life cycle carbon footprint

	Construction	Resurfacing	Reconstruction	Lifecycle
	tons	tons	tons	tons
Grading	973	205	1,898	1,701
Drainage	121	0	36	127
Roadway	1,784	205	1,027	2,366
Sidewalk	296	0	296	345
Street lights and Traffic Devices	241	44	93	5,671*
Landscaping	68	0	87	82
LID	187	0	119	207
Total	**3,669**	**454**	**3,557**	**10,498**

*includes energy use for the roadway operations

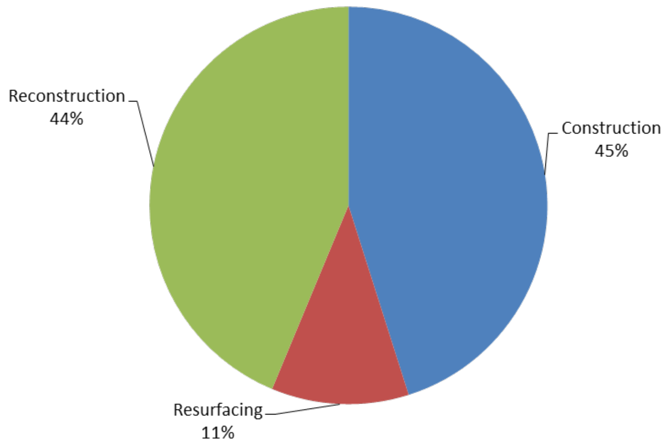


Figure 18: Life cycle carbon footprint by lifecycle phase

Quantification of the solid waste materials by lifecycle phase is provided in Table 7. The results show that construction represents 63% of the total solid waste materials, reconstruction represents 33% and the two resurfacings represent 4% of the total carbon footprint of the street as shown in Figure 19.

Table 7: Comparison of life cycle solid waste materials

	Construction	Resurfacing	Reconstruction	Lifecycle
	tons	tons	tons	tons
Grading	46,104	0	0	46,104
Drainage	0	0	238	238
Roadway	0	1,467	12,464	15,398
Sidewalk	0	0	2,330	2,330
Street lights and Traffic Devices	0	12	137	162
Landscaping	0	0	3,780	3,780
LID	0	0	4,666	4,666
Total	**46,104**	**1,479**	**23,614**	**72,677**

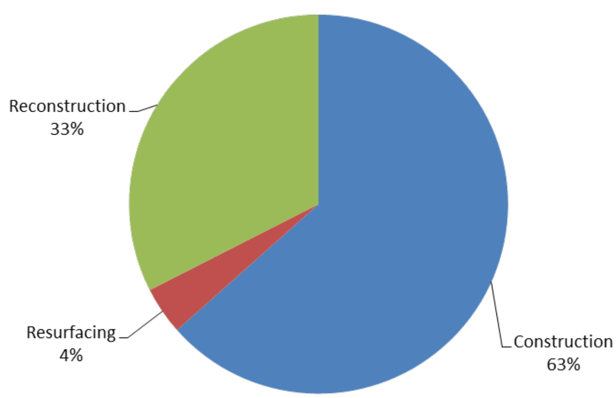


Figure 19: Life cycle solid waste materials

Comparison of these results shows that construction uses the largest amount of materials and has the largest share in solid waste materials while resurfacing has the smallest share. However, reconstruction uses almost half the quantity of materials used during construction however it has the same carbon footprint as construction.

The result of the analysis shows that over the life cycle the urban roadway uses over 110,000 tons of materials during its life and results in over 72,000 tons of waste materials and a carbon foot print of over 10,000 tons of CO_2 eq. Storm water runoff over the life cycle is over 100 million gallons. The results show that carbon footprint is one of the life cycle impacts and other life cycle impacts such as storm water and solid waste materials can also be quite substantial.

5. Conclusions

The quantification of life cycle environmental impacts of an urban street shows that life cycle impacts can be much higher than the initial construction impacts. In its life cycle of 35 years an urban street goes through one construction, two resurfacings and one reconstruction. Compared to the carbon footprint of the initial construction, the lifecycle carbon footprint is more than twice. The life cycle solid wastes are 1.5 times of the initial construction. The storm water runoff can be in millions of gallons. Life cycle phase analysis shows that construction results in the largest quantity of waste materials compared to reconstruction and resurfacings. However, reconstruction has almost the same footprint as construction. The results show that in addition to GHG, roadways have additional environmental impacts which include storm water runoff and solid waste materials. Pavement impacts represent only a portion of the life cycle environmental impacts and attention should also be given to all elements of a roadway such as drainage, street lights and sidewalks. Quantifying these impacts over the life cycle provides the opportunity to analyze the potential to use different materials, reclamation of materials, recycling and using storm water management techniques that can help incorporate sustainability in transportation decision making.

References for Chapter 4

Apul, Dafne. "*BenReMod: A Web-Based Model for Comparing the Environmental Impacts from Road Construction Materials*" presentation. University of Toledo, OH. 2007.

Boustead, Ian. "*LCA - How it Came About, The Beginning in the UK*". International Journal of Life cycle Assessment 1 (3) 1996.

District Department of Transportation (DDOT). *Cost estimates of roadway construction, resurfacing and reconstruction projects*. Cost data 2009-2011. 2011.

District Department of Transportation (DDOT). *Design and Engineering Manual*. District of Columbia Department of Transportation. April 2009. pp 2-1 to 2-35.

DDOT. *Standard Drawings*. District of Columbia Department of Transportation. April 2009.

European Environmental Agency (EEA). *Life Cycle Assessment: A guide to approaches, experience, and information sources*. Environmental Issues Series. No. 6. August 1997.

Federal Highway Administration (FHWA) 2012. *Highway Statistics 2010*. Office of Highway Policy Information, FHWA, 1200 New Jersey Avenue, SE Washington, DC 20590.

Hammond, Geoff and Jones, Craig. *Inventory of Carbon and Energy*. Version 1.6a. Department of Mechanical Engineering, University of Bath, UK. 2008 updated 2009-2011.

Hendrickson, Chris, Horvath, Arpad. *Resource Use and Environmental Emissions of U.S Construction Sectors*. Journal of Construction Engineering and Management. January-February 2000. pp 38-44.

Horvath, Arpad. *Construction Materials and Environment*. Annual Rev. Environ. Resour. 2004. 29:181–204.

Horvath, Arpad et al. "*Pavement life-cycle assessment tool for environmental and economic effects (PaLATE)*". http://www.ce.berkeley.edu/~horvath/palate.html (accessed 20 February 2012).

Huanga, Yue , Bachar Hakimb1 and Susanna Zammataroc2 *Measuring the carbon footprint of road construction using CHANGER.* International Journal of Pavement Engineering. 2012.

International Organization for Standardization (ISO). "Documentation International Standard DIS 14040 Technical committee 1998. ISO Geneva, Switzerland. March 2001.

International Organization for Standardization (ISO). "ISO-14040-2006: Environmental Management-Life Cycle Assessment-Principles & Framework". ISO Geneva, Switzerland. 2006.

Mukherjee, Amlan and Stawowy, Brian. *The Project Emissions Estimator (PE-2): A tool to aid contractors and agencies assess GHG emissions of Highway Construction*. Transportation Research Board. 92nd Annual Meeting Proceedings of. January 2013.

National Institute of Standards and Technology (NIST) "*Building for Environmental and Economic Sustainability (BEES) 4.0 Manual*. US Department of Commerce. 2007.

Nicuta, Alina-Mihaela. "*Life cycle analysis study for new and recycled asphalt pavements*". Technical University of Iasi. Feb 2, 2011.

Santero, N., Masanet, E., and Horvath, A., *Life-Cycle Assessment of Pavements: A Critical Review of Existing Literature and Research*, SN3119a, Portland Cement Association, Skokie, Illinois, USA, 2010, 81 pages.

Santero, Nicholas; Loijos, Alexander; Akbarain, Mehdi and Ochsendorf, John. "*Methods, Impacts, and Opportunities in the Concrete Pavement Life Cycle*". Concrete Sustainability Hub. MIt. August 2011.

Sharrard, Aurora L. "*Greening Construction Processes Using Input-Output Based Hybrid Life Cycle Assessment Model*". PhD Dissertation. Department of Civil & Environmental Engineering. Carnegie Mellon University. April 2007.

Sharrard, Aurora L.; Mathews, H. Scott; Ries, Robert J. "*Estimating Construction Project Environmental Effects Using an input-output Based Hybrid Life-cycle Assessment Model*". Journal of Infrastructure Systems. pp 327-336. ASCE December 2008.

Transportation Research Lab (TRL). Asphalt Pavement Embodied Carbon Tool (asPECT). Available from: http://www.irfghg.org/ (Accessed 21 December 2012).

Michigan Technical University (MTU). Project Emission Estimator (PE2) website. http://www.construction.mtu.edu/cass_reports/webpage/plca_estimator.php. (accessed 20 February 2013).

Zhang, H.; Keoleian, G.A and Lepech, M.D. "An integrated life cycle assessment and life cycle analysis model for pavement overlay systems". Life Cycle Civil Engineering. 2008.

Chapter 5

An Integrated Life Cycle Analysis Approach for Transportation Projects

An Integrated Life Cycle Analysis Approach for Transportation Projects

Faisal Hameed, Kathleen Hancock, Tom Grizzard

Civil and Environmental Engineering Department, Virginia Polytechnic Institute and State University, Blacksburg, VA USA

Abstract

Costs can play an important role in transportation investment decisions. Life cycle cost analysis (LCCA) methods available today do not include life cycle impact costs. Life cycle assessment (LCA) is an accepted methodology to analyze the life cycle impacts. The current LCA practices focus on pavements and provide results in greenhouse gas (GHG) emissions. Solid waste materials and storm water runoff are environmental impacts that should also be considered in life cycle impact assessment. In addition to pavement roadways include other elements. Quantifying the life cycle impacts of each element can help in identifying elements with high impacts so that those elements can be prioritized for alternate design, material evaluations, reclamation and recycling of materials. These life cycle impacts have associated costs. When integrated with LCA, the quantification of life cycle environmental impacts and costs for a roadway that includes construction, resurfacing and reconstruction as well as impacts related with managing the facility by few readily available inputs can help the transportation professional significantly. By establishing a reasonable life cycle time frame, representative elements, mostly homogeneous facility types with representative cross sections, and accepted construction, maintenance and reconstruction practices, a life cycle analysis approach which integrates LCA and LCCA is developed called Integrated Life Cycle Analysis Approach ($ILCA^2$). ILCA2 measures life cycle impacts as: carbon footprint of the materials in CO2 eq, quantity of wasted materials, quantity of storm water runoff and costs of these impacts. Using this methodology, the life cycle cost of a case study urban roadway was estimated to be over $28 million. Environmental impact costs represent nearly one-fifth of these costs and are higher than the operation costs, energy costs, and the resurfacing costs. Calculating these costs provides the agency decision makers a tool to develop and analyze decisions to incorporate sustainability in transportation decision making.

1. Introduction

Transportation projects can result in a number of impacts over the life cycle. By estimating the impacts on environment and economics over the life cycle of a roadway project, decisions can be made that balance environment and economics to support sustainability. By quantifying the life cycle impacts of each element of a roadway, elements that result in the highest impact can be identified which can be prioritized for alternate design or material evaluations. Investment decisions are usually made based on costs. One of the challenges in using life cycle impacts in transportation decisions is the lack of consistent measure for environmental impacts. In order to have a consistent measure for the life cycle impacts, cost can be used as the reference or consistent unit by calculating the costs of these impacts. An integrated life cycle analysis approach (ILCA^2) using a materials based approach that includes construction, resurfacing and reconstruction activities of roadways can be used that calculates the life cycle impacts of roadways as costs can be used to provide guidance on making environmentally sustainable transportation investment decisions. Quantification and costs of environmental impacts during the life cycle of transportation projects can be used as performance measures to enhance the sustainability of a transportation system. The quantification of life cycle environmental impacts of a roadway through its life cycle that includes construction, resurfacings and reconstructions using a consistent temporal lifecycle by using few readily available inputs can help the transportation professional significantly. The ILCA^2 and ILCA^2 tool developed by this research allows the calculation of life cycle environmental impacts of a roadway in terms costs of carbon footprint of the materials, cost of storm water runoff from the roadway, cost of solid waste materials, and integrated life cycle costs of the roadway.

2. Background

The estimation of costs of environmental impacts of the transportation system is a complex issue. Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) are used by many industrial sectors. LCA calculate the life cycle impacts while LCCA looks at the life cycle costs of constructing and maintaining a facility. BenReMod, asPECT, PaLATE, ROAD-RES, CHANGER and PE-2* are some of the road pavement LCA software tools that have been developed for transportation industry. These tools calculate Greenhouse gas (GHG) emissions from roadway construction. BenReMod (Beneficial Reuse Model) is a web based tool that can be used for quantitatively comparing benefits and disadvantages of different materials by using multi criteria decision making while provides outputs in global warming potential (GWP) and energy use (Apul 2007). asPECT (asphalt Pavement Embodied Carbon Tool) is software tool performs LCA of asphalt mixtures (Nicuta 2011). PaLATE (Pavement Life-cycle Assessment Tool for Environmental and Economic Effects is an Excel-based tool for LCA of environmental and economic effects of pavements and roads that provides environmental effects in energy, GWP, NOx, PM10, SO2, CO, Hg, Pb, and hazardous waste generation (Horvath 2012). The tool also provides a simple life-cycle costing mechanism, by material unit-weights not including labor, overhead, user (Santero et al 2010). ROAD-RES assesses the environmental impact of the materials production, construction, maintenance, and end-of-life phases of the pavement life cycle while particularly focusing on the comparisons of virgin materials to waste products considers eight different impact categories: GWP, photochemical ozone formation, nutrient enrichment, acidification, stratospheric ozone depletion, human toxicity, eco-toxicity, and stored eco-toxicity that cover environmental impacts to air, soil (Santero et al 2010). CHANGER (Calculator for Harmonized Assessment and Normalization of Greenhouse gas Emissions for Roads) is a software tool that performs LCA and providing results in carbon footprint of the roadway construction (Huanga 2012). PE-2 (Project Emission Estimator) is a web based tool that estimates life cycle emissions associated with construction, maintenance and use of the roadway (MTU 2013). The PE-2 tool can be used 27 at the project and the network levels while its recommended application is to monitor GHG emissions from construction projects, and to benchmark emissions for future projects (Mukherjee 2013).

Integrated LCA-LCCA that combines life cycle impacts with costs can provide comprehensively life cycle costs to analyze both environmental and economic impacts. Zhang et al used an integrated LCA-LCCA model for pavement overlay systems (Zhang 2008) to evaluate life cycle performance of different pavement systems. Santero and Loijos et al (at MIT) recently developed research that improved the application of LCA by using LCCA to evaluate the cost effectiveness of Green House Gas (GHG) reduction strategies for concrete pavements (Santero et al 2011). PaLATE tool for LCA of environmental and economic effects provides a simple life-cycle costing mechanism, by material unit-weights not including labor, overhead, user (Santero et al 2010) and can be considered an LCA-LCCA tool. These models concentrate on roadway or pavement construction and provide impacts in GHG emissions. A roadway facility includes additional elements such as travel way, sidewalks, street lights, traffic signals, lane striping and drainage which consist of different types of materials with different impacts. The results of the models and research also vary because of the differences in system definitions. These models also pose a challenge for practitioners in DOTs because of the need for data and inputs which are usually not available during planning, project development and preliminary design /engineering of transportation projects. This research develops a methodology by including roadway elements such as sidewalks, street lights and signals, landscaping and drainage and cost of impacts of these elements to assess life cycle environmental impacts and associated costs of transportation facilities.

3. Integrated Life Cycle Analysis Approach ($ILCA^2$)

The integrated life cycle analysis approach ($ILCA^2$) establishes a common set of characteristics which include the scope, temporal boundary, and spatial boundary. The scope includes construction, resurfacing and reconstruction of urban streets. The temporal scope is the life cycle of the roadway which is defined as 35 years. The spatial boundary includes both length and cross section.

The material quantities are calculated by using the standard materials needed for roadway construction, resurfacing and reconstruction. Life cycle inputs include construction materials while material and impact costs which are used as performance measures include cost of construction, resurfacing, reconstruction and life cycle costs, life cycle impacts costs and integrated life cycle analysis $ILCA^2$ costs. The life cycle impact costs are based on the costs of the carbon foot print of the materials used as tons of CO2 equivalent, Storm water runoff from the facility and Solid waste materials. It should be noted that the storm water runoff is not a measure of the construction, resurfacing and reconstruction but a measure of life cycle impacts due to the operating the facility and is only included in life cycle impact discussions. The life cycle costs are calculated for initial construction, resurfacing and construction based on the quantities of the materials, energy used for streetlights and signal for 35 years. $ILCA^2$ does not include the user costs as described in the scope of the research. $ILCA^2$ methodology is illustrated in Figure 1.

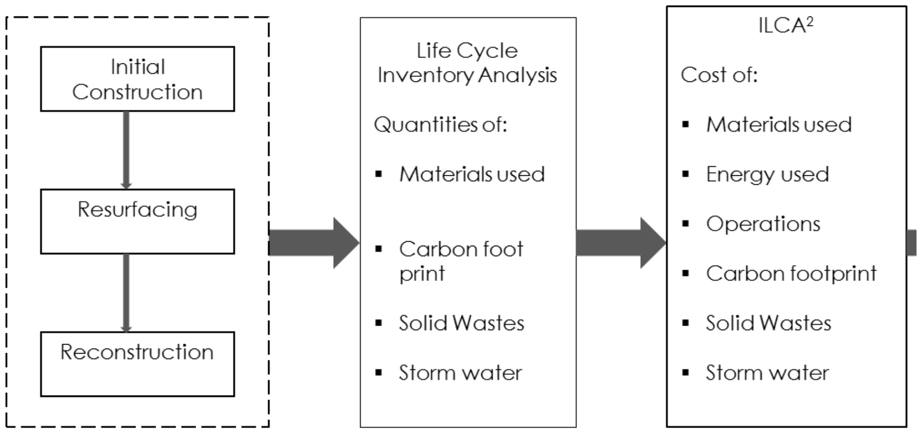


Figure 1: Integrated Life cycle Analysis Approach ($ILCA^2$)

The integrated life cycle costs are calculated as:

$$ILCA^2 = CFC + SWC + SRC + ICC + n_{RC}\Sigma\ RCC + n_R\Sigma\ RSC + n_{LC}\Sigma\ OC + n_{LC}\Sigma\ EC - SV \quad [8]$$

Where,

CFC = carbon footprint costs
EC = annual energy cost of the facility
SWC = solid waste costs
SRC = storm water runoff costs
ICC = cost of Initial Construction
OC = annual operation cost of the facility
RCC = cost of Reconstruction
RSC = cost of Resurfacing
SV = Salvage Value
n_{LC} = life cycle span (years)
n_{RC} = number of reconstructions during life cycle
n_R = number of resurfacings during life cycle

The performance measures used are given in Table 1.

Table 1: Performance Measures

Life Cycle Impacts	Unit
Carbon footprint	$
Storm water runoff	$
Solid Waste cost	$
Life cycle Impact	$
Life cycle cost	$
Integrated life cycle	$

- The research uses carbon footprint costs as one of the measures of life cycle impacts. Carbon footprint is measured as the CO_2 equivalent to measure the impact of the Greenhouse Gases which is sometimes also called Global Warming Potential (GWP). Carbon footprint as tons of CO_2 eq for these materials is calculated using the *Inventory of Carbon and Energy (ICE)* Version 1.6a 2008-2011 data (Hammond et al 2011). Cost of CO_2 was used as $ 20/ton of CO2 based on the current market cost per ton of CO_2 (DOE 2012 and Wilson 2012)

- Storm water runoff costs from the facility is calculated by estimating the storm water runoff as million gallons for the 35 year life cycle by calculating the runoff as Gallons/day and Gallons/mile using the surface area of the unit cross section and the annual average precipitation. The cost used was $ 6550/million gallons of water based on Washington DC are water costs (DC Water 2012).

- Solid waste costs are calculated by calculating the quantities of materials removed during all construction, reconstruction and resurfacing for the life cycle of the facility. The cost used was $ 53/ ton solid waste based on Washington DC area waste management costs (DPW 2012).

4. Analysis

To demonstrate the use of the methodology an example scenario was defined and evaluated. The scenario consists of a two lane urban street that includes bike lanes, planting area and sidewalks on both sides as shown in Figure 2. These calculations were done using the conventional virgin construction materials. This was done to provide a baseline that can show the potential of using products and practices that can offset these impacts.

Figure 2: Standard cross section of an urban roadway

4.1. Data Set:

The "life cycle" was defined as 35 years. The spatial boundary includes the length and cross section of the roadway. Cross section includes Width: width across the travel way for vehicular lanes and bicycle lanes, side walk widths, curb and gutter, tree planting and width; and Depth: Surface asphalt course, pavement base course, aggregate sub base. Figure 3 shows the cross section details of an urban roadway used.

Figure 3: Typical section of roadway with cross section widths

The materials and quantities needed for a roadway project are based on DDOT Standard Drawings (DDOT 2009) and DDOT Standards and Specifications (DDOT 2009) based on the typical sections and the total length of the project.

4.2 Performance Measures:

The following performance measures were identified to study the performance of the integrated life cycle analysis ILCA^2 approach and tool:

1. Cost of construction
2. Cost of resurfacing
3. Cost of reconstruction
4. Life cycle cost
5. Life cycle impact cost
6. Integrated life cycle costs using ILCA^2

4.3 Results and Discussion:

In order to determine the total life cycle costs construction, resurfacing and reconstruction activities must be considered. One of the first outputs of the tool is the material quantities for the major elements of the facility given below:

- Grading: Grading includes removal of existing surface pavement, pavement base, sidewalks, curb and gutter, excavation and borrow
- Drainage: Drainage includes drainage inlets, manholes and pipes
- Roadway: Roadway includes surface pavement, pavement base and aggregate base for bike lanes, vehicular lanes, curb and gutter.
- Sidewalks
- Landscaping: Landscaping includes planting strip and trees
- Storm water management: Storm water management includes low impact development bio-retention zones
- Streetlight and traffic control: Street lights and traffic control includes lane marking, traffic signs, traffic signals, streetlight and ducts

Construction:

Results show that the initial cost of construction of the urban street can be $ 19.53 million. Table 2 and Figure 4 provide the detail cost breakdown. The analysis of these costs shows that the traffic control section has the highest costs and represents 27% of the total cost. This is due to the fact that traffic signals are usually very expensive. Roadway represents 25% of the cost, while engineering costs represent almost 14%. The engineering costs however are not part of the life cycle impacts. An interesting aspect of this analysis that the LID costs represent only 3% and the drainage system represents 11% of the total costs. Both LID and standard drainage systems are included in the calculation because in ultra-urban environment both LID and drainage systems may be needed. The comparison of these costs at the construction estimates can be misleading because of the maintenance costs associated with LID and the costs of storm water runoff associated with the standard drainage. In order to make a comparison between the two life cycle costs are needed.

Table 2: Construction Costs

Description	Cost $
Grading	$1,088,000
Drainage	$2,188,000
Sidewalks	$1,258,000
Roadway	$4,746,000
Landscaping	$1,303,000
Streetlights & Traffic Control	$5,046,000
Low Impact Development	$657,000
Engineering Costs	$2,729,000
TOTAL PROJECT COST	**$19,533,000**

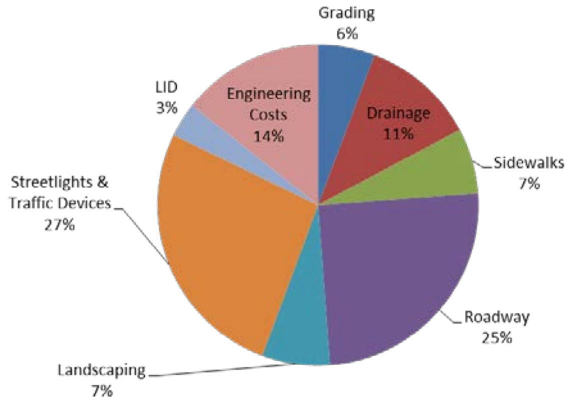


Figure 4: Construction Costs

Resurfacing:

The cost of resurfacing of the urban street was estimated to be $ 340,000. Table 3 and Figure 5 provide the cost breakdown. Resurfacing only involves removal of existing surface course of the pavement and replacing it with new pavement while also repainting lane markings. That is why roadway, grading, and traffic control represent the majority of the costs. Resurfacing represents only a small portion of the construction cost of the street.

Table 3: Resurfacing Costs

Description	Cost $
Grading	$62,000
Drainage	$0
Sidewalks	$0
Roadway	$147,000
Landscaping	$0
Streetlights & Traffic Control	$47,000
Low Impact Development	$0
Engineering Costs	$53,000
TOTAL PROJECT COST	**$340,000**

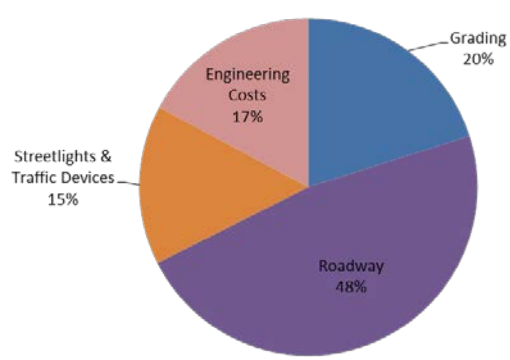


Figure 5: Resurfacing Costs

Reconstruction:
The cost of reconstruction of the urban street was estimated to be $ 9.17 million. Table 4 and Figure 6 provide the cost breakdown. The analysis shows that roadway represents 33% of the reconstruction costs, followed by sidewalks, engineering costs and streetlights and traffic control. Total reconstruction costs are almost half of the original construction cost of the street. This is due to the fact that normally in reconstruction only the roadway and sidewalks are completely replaced while the rest of the elements are partially replaced.

Table 4: Reconstruction Costs

Description	Cost $
Grading	$462,000
Drainage	$565,000
Sidewalks	$1,258,000
Roadway	$3,163,000
Landscaping	$832,000
Streetlights & Traffic Control	$1,297,000
Low Impact Development	$657,000
Engineering Costs	$1,363,000
TOTAL PROJECT COST	**$9,173,000**

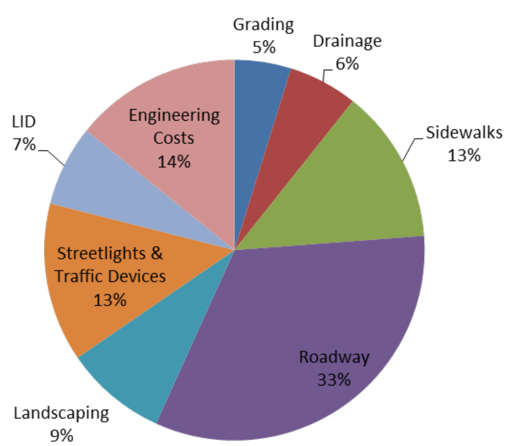


Figure 6: Reconstruction Costs

Life Cycle:
The life cycle cost of the urban street was estimated to be $ 23.35 million. Table 5 and Figure 7 provide the cost breakdown. The operation costs included in the life cycle costs were calculated by using the FHWA 2010 Highway Statistics. DDOT incurred an annual operation cost of $ 23,054 / lane mile (FHWA 2012). This operation/service/maintenance

cost was used for the analysis. Energy costs were estimated by determining the energy (power) usage of streetlights and street signals per mile and then using the Department of Labor statistics for energy (power) costs per KWh for the Washington DC area. The life cycle cost analysis results show a similar trend as construction and reconstruction results where roadway and street light and traffic control as the highest cost elements. Operation costs represent 3% and energy costs represent 4% of the life cycle costs. These two elements are only included in life cycle costs because they are associated with the life cycle of the project and not with individual construction, resurfacing or reconstruction.

Table 5: Life Cycle Costs

Description	Construction Cost $	Resurfacing Cost $	Reconstruction Cost $	Energy Cost $	Salvage Value $	Life cycle Costs $
Grading	1,088,076	62,104	461,702		384,751	1,289,234
Drainage	2,188,060		565,015		470,845	2,282,229
Sidewalks	1,257,600		1,257,600		1,048,000	1,467,200
Roadway	4,746,262	146,706	3,162,617		2,635,514	5,566,777
Landscaping	1,302,760	0	831,850		693,208	1,441,401
Streetlights & Traffic Control	5,045,560	47,160	1,296,760		1,080,633	5,356,000
Low Impact Development	657,081	0	657,081		547,567	766,594
Costs related to life cycle and not the materials						
Energy				782,558		782,558
Engineering Costs	2,728,796	53,066	1,362,516	117,384	1,135,430	3,179,397
Operations cost						713,838
TOTAL PROJECT COST	**19,532,255**	**339,940**	**9,171,295**	**899,942**	**7,642,746**	**23,354,462**

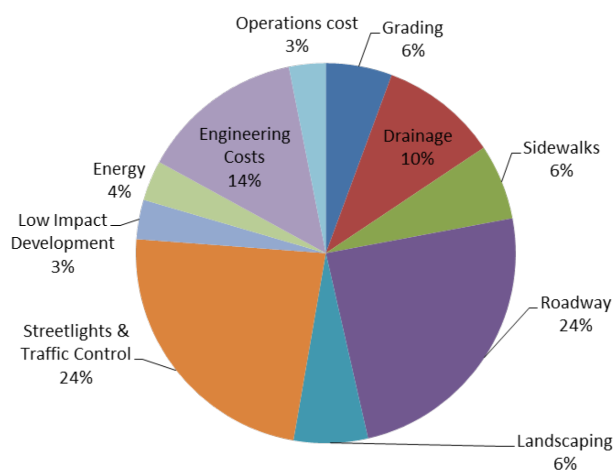


Figure 7: Life Cycle costs

The life cycle impacts costs of the same street were estimated to be $ 5.427 million. Table 6 and Figure 8 provide the cost breakdown. The results of the life cycle impact costs show that solid wastes represent 71%, storm water runoff represents 25% while carbon footprint represent 4% of the life cycle impact costs.

Table 6: Life Cycle Impacts Costs

Description	Carbon footprint Cost $	Storm water Cost $	Solid Waste Cost $	Life cycle Impact Cost $
Grading	34,010		2,443,505	2,477,516
Drainage	2,534		12,589	15,124
Sidewalks	6,904			6,904
Roadway	54,215		939,569	993,784
Landscaping	1,646		200,331	201,977
Streetlights & Traffic Control	6,870		8,577	122,000
Low Impact Development	4,133		247,291	251,425
Costs related to life cycle and not the materials				
Energy	106,522			106,522
Storm water		1,365,795		1,365,795
TOTAL PROJECT COST	**209,964**	**1,365,795**	**3,851,865**	**5,427,625**

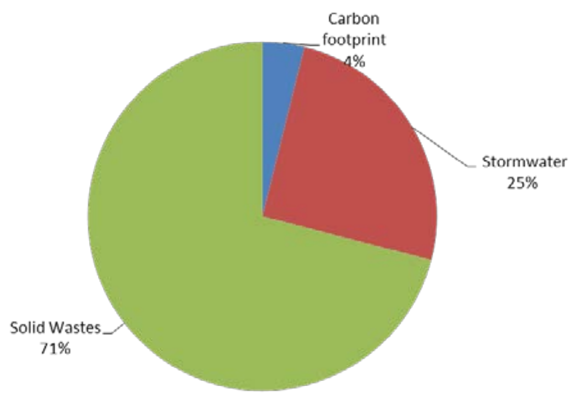


Figure 8: Life cycle impact costs

The integrated life cycle costs of the urban street were estimated to be $ 28.78 million by using the ILCA^2 tool. Table 7 and Figure 9 provide the cost breakdown.

Table 7: Integrated Life Cycle Costs

Description	Life cycle Impact Costs $	Life Cycle Costs $	Integrated Life Cycle Costs $
Grading	2,477,516	1,289,234	3,706,319
Drainage	15,124	2,282,229	2,297,354
Sidewalks	6,904	1,467,200	1,815,553
Roadway	993,784	5,566,777	6,986,788
Landscaping	201,977	1,441,401	1,643,379
Streetlights & Traffic Control	122,000	5,356,000	5,478,000
Low Impact Development	251,425	766,594	1,018,019
Costs related to life cycle and not the materials			
Energy	106,522	782,558	889,110
Storm water	1,365,795		1,365,795
Engineering Costs		3,179,397	3,179,397
Operations cost		713,838	713,838
TOTAL PROJECT COST	**5,427,625**	**23,354,462**	**28,782,088**

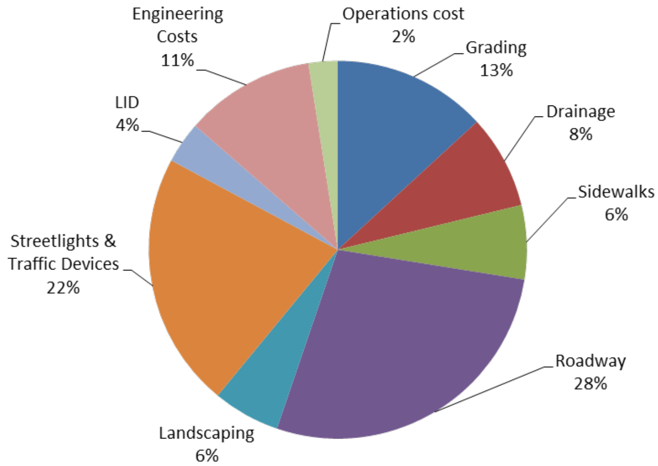


Figure 9: Integrated Life Cycle Costs (using ILCA^2)

Table 8: Integrated Life Cycle Costs using ILCA^2

Description	Integrated Life Cycle Costs $
Construction	19,532,255
Resurfacing (twice)	679,879
Reconstruction	9,171,295
Energy	899,942
Salvage Value	7,642,746
Carbon Footprint	209,964
Storm water	1,365,796
Solid Waste	3,851,865
Operation costs	713,838
Total Integrated Project Cost	**28,782,088**

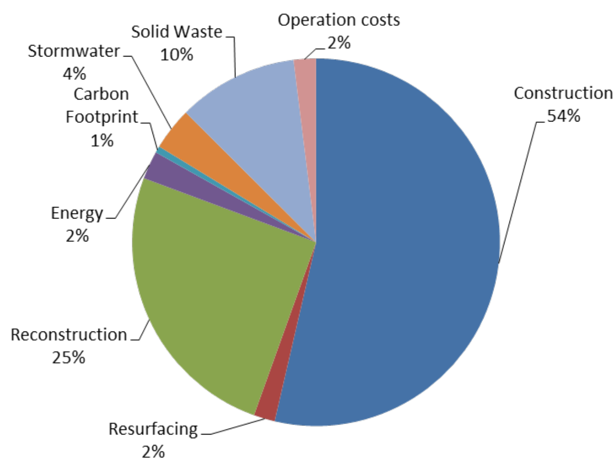


Figure 10: Breakdown of Integrated Life Cycle Costs (using ILCA^2)

When tabulated according to activity as shown in Table 8, the results show that construction costs represent 54% of the total life cycle costs of the roadway while reconstruction can represent 25% of the total costs. These costs are followed by life cycle impact costs with solid waste costs representing 10%, storm water costs as 4% and carbon footprint as 1%.These results are shown in Figure 10.

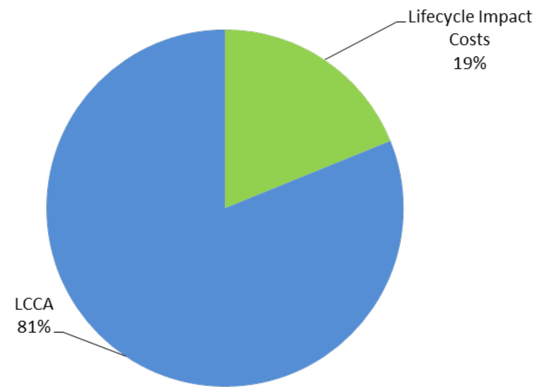


Figure 11: Comparisons of Life Cycle Cost and Life Cycle Impact Cost

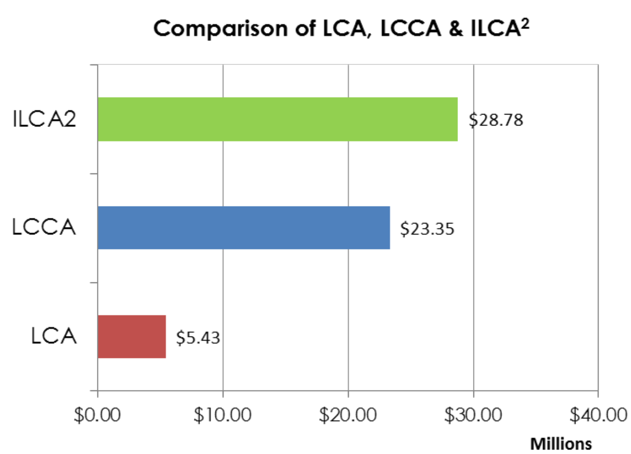


Figure 12: Comparison of Life cycle impact costs, Life cycle costs and ILCA^2 costs

The results show that life cycle impact costs are more than the life cycle resurfacing costs, energy costs, and operation costs combined. During transportation decision making most of the weight is given to the onetime cost of the construction, resurfacing or reconstruction activity. The analysis provided here shows that the life cycle impact costs are more than one-fourth of the cost of construction, half the cost of reconstruction while one-fifth of the total integrated life cycle costs of a roadway as shown in Figure 11 and 12. This shows the tremendous potential of focusing on life cycle impacts to reduce the life cycle costs thus meeting the “environment” and “economics” elements of sustainability.

5. Conclusions

By using an integrated life cycle analysis approach true life cycle costs for transportation projects can be determined that includes the environmental costs over the life cycle of the project. The construction cost of a roadway per lane mile is only half the total life cycle costs. Normally at transportation decision making stage only the onetime costs such as the construction costs are considered which as results show are a portion of the life cycle costs. The life cycle environmental impact cost represent one-fifth of the life cycle costs. The costs of environmental impacts was found to be hhigher than the life cycle operation costs, energy costs and resurfacing costs all combined. This analysis can provide the agency decision makers a tool to evaluate the agency life cycle costs to develop and analyze decisions such as using different materials, alternate design practices, reclamation of materials and their recycling. By focusing on these costs the life cycle impacts can be reduced.

References for Chapter 5

Apul, Dafne. "*BenReMod: A Web-Based Model for Comparing the Environmental Impacts from Road Construction Materials*" presentation. University of Toledo, OH. 2007.

Boustead, Ian. "*LCA - How it Came About, The Beginning in the UK*". International Journal of Life cycle Assessment 1 (3) 1996.

District Department of Transportation (DDOT). DDOT website. www.ddot.dc.gov (accessed March 2013).

District Department of Transportation (DDOT). *Cost estimates of roadway construction, resurfacing and reconstruction projects*. Cost data 2009-2011. 2011.

District Department of Transportation (DDOT). *Design and Engineering Manual*. District of Columbia Department of Transportation. April 2009. pp 2-1 to 2-35.

DDOT. *Standard Drawings*. District of Columbia Department of Transportation. April 2009.

DC Water. *Current Water Rates*. http://www.dcwater.com/customercare/rates (accessed April 2012)

DC Department of Public Works (www.dpw.dc.gov) (accessed April 2012)

Department of Energy (DOE). "*Life Cycle Costing Manual for the Federal Energy Management Program*". U. S Department of Energy, Washington DC. pp 1.1. 1996.

Environmental Protection Agency (EPA): "*Life cycle assessment: Principles and practice*". May 2006. Cincinnati, OH: National Risk Management Research Laboratory, Scientific Applications International Corporation (SAIC), EPA/600/R-06/060.

European Environmental Agency (EEA). *Life Cycle Assessment: A guide to approaches, experience, and information sources*. Environmental Issues Series. No. 6. August 1997.

Federal Highway Administration (FHWA). *Life-Cycle Cost Analysis: RealCost User Manual*. Publication No. FHWA, Washington DC. 2004.

Federal Highway Administration (FHWA) 2012. *Highway Statistics 2010*. Office of Highway Policy Information, FHWA, 1200 New Jersey Avenue, SE Washington, DC 20590.

Federal Highway Administration (FHWA). *Life-Cycle Cost Analysis in Pavement Design*. Publication No. FHWA-SA-98-079. FHWA, Washington DC. 1998.

Federal Highway Administration (FHWA). "*Life-Cycle Cost Analysis Primer*". U.S. Department of Transportation, FHWA, Washington DC. pp 7,9. August 2002.

Hammond, Geoff and Jones, Craig. *Inventory of Carbon and Energy*. Version 1.6a. Department of Mechanical Engineering, University of Bath, UK. 2008 updated 2009-2011.

Hendrickson, Chris, Horvath, Arpad. *Resource Use and Environmental Emissions of U.S Construction Sectors*. Journal of Construction Engineering and Management. January-February 2000. pp 38-44.

Hendrickson, Chris., Horvath, A., Lave, L.B. *Use of Economic input-output models for environmental life cycle assessment*. Environmental Science and Technology. April 1998. Volume 32, Issue 7 / pp. 184 A-191 A

Hendrickson, C.T., Lave, L.B., and Matthews, H.S., *Environmental Life Cycle Assessment of Goods and Services.* Washington, DC: Resources for the Future. 2006.

Horvath, A. *Estimation of the environmental implications of construction materials and designs using life-cycle assessment techniques*. PhD Thesis. Department of Civil and Environmental Engineering, Carnegie Mellon University. 1997.

Horvath, Arpad. *Construction Materials and Environment*. Annual Rev. Environ. Resour. 2004. 29:181–204.

Horvath, A., and Hendrickson, C. T. (1998), *A Comparison of the Environmental Implications of Asphalt and Steel-Reinforced Concrete Pavements*. Transportation Research Record, NRC, No. 1626 (Environmental and Social Effects of Transportation), pp. 105-113, DOI:10.3141/1626-13.

Horvath, A., Hendrickson, C. T., Lave, L. B., McMichael, F. C., and Wu, T-S. (1995), *Toxic Emissions Indices for Green Design and Inventory*. Cover article, Environmental Science & Technology, ACS, 29(2), pp. 86-90, DOI:10.1021/es00002a003.

Horvath, Arpad et al. "*Pavement life-cycle assessment tool for environmental and economic effects (PaLATE)*". http://www.ce.berkeley.edu/~horvath/palate.html (accessed 20 February 2012).

Huanga, Yue , Bachar Hakimb1 and Susanna Zammataroc2 *Measuring the carbon footprint of road construction using CHANGER.* International Journal of Pavement Engineering 2012-1-11.

International Organization for Standardization (ISO). "Documentation International Standard DIS 14040 Technical committee 1998. ISO Geneva, Switzerland. March 2001.

International Organization for Standardization (ISO). "ISO-14040-2006: Environmental Management-Life Cycle Assessment-Principles & Framework". ISO Geneva, Switzerland. 2006.

Mukherjee, Amlan and Stawowy, Brian. *The Project Emissions Estimator (PE-2): A tool to aid contractors and agencies assess GHG emissions of Highway Construction*. Transportation Research Board. 92nd Annual Meeting Proceedings of. January 2013.

National Institute of Standards and Technology (NIST) "*Building for Environmental and Economic Sustainability (BEES) 4.0 Manual*. US Department of Commerce. 2007.

NCHRP Report 483. "*Bridge Life Cycle Cost Analysis*". National Cooperative Highway Research Program, Transportation Research Board (TRB), Washington DC 2003.

Nicuta, Alina-Mihaela. "*Life cycle analysis study for new and recycled asphalt pavements*". Technical University of Iasi. Feb 2, 2011.

Santero, N., Masanet, E., and Horvath, A., *Life-Cycle Assessment of Pavements: A Critical Review of Existing Literature and Research*, SN3119a, Portland Cement Association, Skokie, Illinois, USA, 2010, 81 pages.

Santero, Nicholas; Loijos, Alexander; Akbarain, Mehdi and Ochsendorf, John. "*Methods, Impacts, and Opportunities in the Concrete Pavement Life Cycle*". Concrete Sustainability Hub. MIt. August 2011.

Sharrard, Aurora L. "*Greening Construction Processes Using Input-Output Based Hybrid Life Cycle Assessment Model*". PhD Dissertation. Department of Civil & Environmental Engineering. Carnegie Mellon University. April 2007.

Sharrard, Aurora L.; Mathews, H. Scott; Ries, Robert J. "*Estimating Construction Project Environmental Effects Using an input-output Based Hybrid Life-cycle Assessment Model*". Journal of Infrastructure Systems. pp 327-336. ASCE December 2008.

Transportation Research Lab (TRL). Asphalt Pavement Embodied Carbon Tool (asPECT). Available from: http://www.irfghg.org/ (Accessed 21 December 2012).

Michigan Technical University (MTU). Project Emission Estimator (PE2) website. http://www.construction.mtu.edu/cass_reports/webpage/plca_estimator.php. (accessed 20 February 2013).

Zhang, H.; Keoleian, G.A and Lepech, M.D. "An integrated life cycle assessment and life cycle analysis model for pavement overlay systems". Life Cycle Civil Engineering. 2008.

CHAPTER 6
Incorporating Costs of Life Cycle Impacts into Transportation Project and Program Development

Incorporating Costs of Life Cycle Impacts into Transportation Project and Program Development

Faisal Hameed, Kathleen Hancock, Tom Grizzard

Civil and Environmental Engineering Department, Virginia Polytechnic Institute and State University, Blacksburg, VA USA

Abstract

The decisions included in a transportation program influence economy, environment and social system and hence can affect sustainability. By calculating the impacts on environment and economics over the life cycle of a transportation program, decisions can be made that balance environment and economics to meet the social needs. By quantifying the life cycle impacts of each element of a roadway in a transportation program, elements that result in the highest impact can be identified. The transportation programs are usually used as investment decisions based on costs. An integrated life cycle analysis approach ($ILCA^2$) using a materials based calculation that includes construction, resurfacing and reconstruction activities of roadways can be used that calculates the life cycle impacts of roadways as costs and can be used to provide guidance using alternate design, materials and practices that lead to making environmentally sustainable transportation investment decisions. Quantification and costs of environmental impacts during the life cycle of transportation projects can be used as performance measures to enhance the sustainability of a transportation system. The $ILCA^2$ and $ILCA^2$ tool developed by this research allows the calculation of life cycle environmental impacts of a roadway in terms costs of carbon footprint of the materials, cost of storm water runoff, cost of solid waste materials, and integrated life cycle costs of individual roadway projects and the transportation program. By performing the $ILCA^2$ on a larger scale enables roadway designers, planners and decision makers to evaluate the larger impacts of the transportation investments. By using the traditional life cycle analysis the life cycle cost can be under estimated by one-fourth. While making decision regarding transportation investments only the initial construction costs of the project are considered. The results show that the initial costs only about one-twentieth of the life cycle costs of the project. By focusing on the integrated life cycle costs of roadways decisions can be made that support environment, economics and social system and hence the sustainability.

1. Introduction

State DOTs in the United States own more than 4 million miles of roadways with capital investments of more than $75 billion every year (FHWA 2012). Federal regulations require DOTs to develop a State Transportation Improvement Program (STIP) for every state, which includes all projects programmed for the next 4 years in that State. The transportation projects in these programs use a number of materials which in turn have impacts over the life time of the project. These transportation programs include investment decision in the form of transportation projects that have a long life cycle and can have long term impacts. Currently there is no standard approach that analyzes the life cycle impacts of roadways as individual projects or as part of a transportation program such that sustainability can be incorporated in the transportation decision making. Transportation programs deal with the entire transportation system of the area, region or state. Transportation system is an important part of the social system. It connects communities, provides access, and moves people and goods. The decisions included in a transportation program influence economy, environment and social system and hence can affect sustainability. By calculating the impacts on environment and economics over the life cycle of a transportation program, decisions can be made that balance environment and economics to meet the social needs. By quantifying the life cycle impacts of each element of a roadway in a transportation program, elements that result in the highest impact can be identified. The transportation programs are usually used as investment decisions based on costs.

One of the challenges in using life cycle impacts in transportation decisions is the lack of consistent measure for environmental impacts. In order to have a consistent measure for the life cycle impacts, cost can be used as the reference or consistent unit by calculating the costs of these impacts. An integrated life cycle analysis approach (ILCA^2) using a materials based approach that includes construction, resurfacing and reconstruction activities of roadways can be used that calculates the life cycle impacts of roadways as costs can be used to provide guidance using alternate design, materials and practices that lead to making environmentally sustainable transportation investment decisions. Quantification and costs of environmental impacts during the life cycle of transportation projects can be used as performance measures to enhance the sustainability of a transportation system. The quantification of life cycle environmental impacts of a roadway by using few readily available inputs can help the transportation professional significantly. The ILCA^2 and ILCA^2 tool developed by this research allows the calculation of life cycle environmental impacts of a roadway in terms costs of carbon footprint of the materials, cost of storm water runoff, cost of solid waste materials, and integrated life cycle costs of individual roadway projects and the transportation program. By performing the ILCA^2 on a larger scale enables roadway designers, planners and decision makers to evaluate the larger impacts of the transportation investments.

2. Background

Almost one-third of roadways in the United States are funded through the Federal Aid Highway Program of the U.S Department of Transportation Federal Highway Administration (FHWA 2012). To receive these funds, State DOTs have to comply with FHWA requirements. Specifically, transportation planning regulations of 23 CFR 450.216 require all State DOTs to develop a financially constrained State Transportation Improvement Program (STIP). FHWA defines the STIP in 23 CFR 450.104 as “a statewide staged, at least four-year, multi-year program of transportation projects that is consistent with the long range statewide transportation plan, metropolitan transportation plans, and Transportation Improvement Program (TIP), and required for projects to be eligible for funding under 23 U.S.C. and 49 U.S.C. Chapter 53” (23CFR 450). Decisions regarding transportation infrastructure investments are made at this programming stage. At the programming stage normal practice is not to consider life cycle costs or life cycle impact costs are not considered.

This can be achieved by integrating LCA with LCCA. Zhang et al used an integrated LCA-LCCA model for pavement overlay systems (Zhang 2008) to evaluate life cycle performance of different pavement systems. Santero and Loijos et al (at MIT) recently developed research that improved the application of LCA by using LCCA to evaluate the cost effectiveness of Greenhouse Gas (GHG) reduction strategies for concrete pavements (Santero et al 2011). However, these approaches did not consider all the elements of a roadway and were not used on a transportation program. PaLATE tool for LCA of environmental and economic effects provides a simple life-cycle costing mechanism, by material unit-weights not including labor, overhead, user (Santero et al 2010) and can be considered an LCA-LCCA tool. However, these models concentrate on roadway or pavement construction and provide impacts in GHG emissions and do not include additional elements such as travel way, sidewalks, street lights, traffic signals, lane striping and drainage which consist of different types of materials with different impacts. These models require data and inputs which are usually not available during planning and programing stage and hence limit their applicability to transportation programs.

3. Extending the STIP to incorporate environmental impacts and associated costs

A STIP typically includes a listing of all projects programmed for the specified time period within a state and provides costs for each phase of each project by year. These transportation programs generally include just the financial and schedule information of projects and do not include life cycle environmental impacts. At the programming stage normal practice is not to consider life cycle costs or life cycle impact costs are not considered. Incorporating Life cycle costs and impacts with a transportation program can provide comprehensive life cycle costs for analyzing both environmental and economic impacts of the transportation program. This research provides a methodology-integrated life cycle analysis approach ($ILCA^2$) - that quantifies these impacts and estimates the associated costs at the programming stage of transportation project development process. Applying $ILCA^2$ to a STIP enables decision makers to evaluate the larger impacts of transportation investments as well as consideration of programmatic changes to practices that support sustainability. $ILCA^2$ establishes a common set of characteristics which include the scope, temporal boundary, and spatial boundary. The scope includes construction, resurfacing and reconstruction of urban streets. The temporal scope is the life cycle of the roadway which is defined as 35 years. The spatial boundary includes both length and cross section. The $ILCA^2$ approach as illustrated in Figure 1 allows the ability to capture the key elements of a roadway project which make up the transportation program. Using this approach environmental impacts and associated costs can be incorporated in the transportation programs.

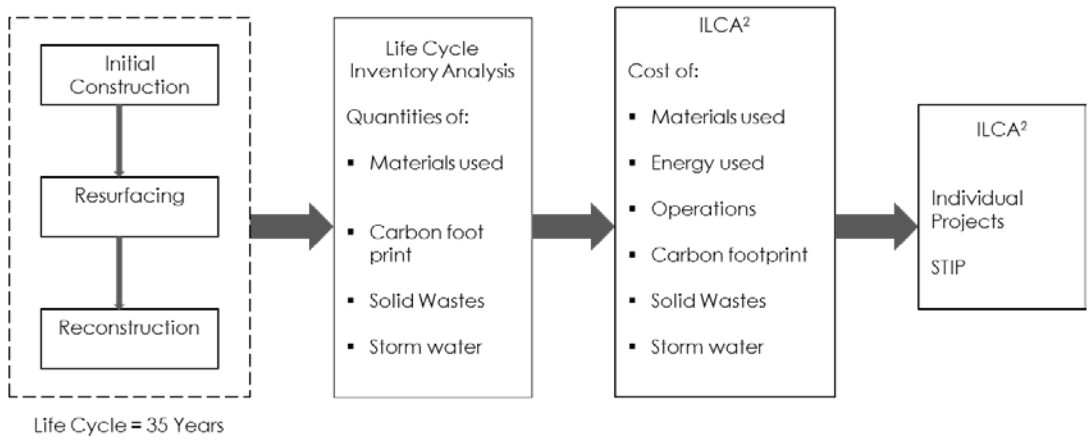


Figure 1: Integrated Life cycle Analysis Approach (ILCA^2)

The integrated life cycle costs are calculated as:

$$ILCA^2 = CFC + SWC + SRC + ICC + n_{RC}\Sigma\ RCC + n_R\Sigma\ RSC + n_{LC}\Sigma\ OC + n_{LC}\Sigma\ EC - SV \quad [8]$$

Where,

CFC = carbon footprint costs
EC = annual energy cost of the facility
SWC = solid waste costs
SRC = storm water runoff costs
ICC = cost of Initial Construction
OC = annual operation cost of the facility
RCC = cost of Reconstruction
RSC = cost of Resurfacing
SV = Salvage Value
n_{LC} = life cycle span (years)
n_{RC} = number of reconstructions during life cycle
n_R = number of resurfacings during life cycle

The performance measures used are given in Table 1.

Table 1: Performance Measures

Life Cycle Impacts	Unit
Carbon footprint cost of	$
Storm water runoff cost of	$
Solid Waste cost of program	$
Life cycle Impact cost of	$
Life cycle cost of program	$
Integrated life cycle cost of	$

- The research uses carbon footprint costs as one of the measures of life cycle impacts. Carbon footprint is measured as the CO_2 equivalent to measure the impact of the Greenhouse Gases which is sometimes also called Global Warming Potential (GWP). Carbon footprint as tons of CO_2 eq for these materials is calculated using the *Inventory of Carbon and Energy (ICE)* Version 1.6a 2008-2011 data (Hammond et al 2011). Cost of CO_2 was used as $ 20/ton of CO2 based on the current market cost per ton of CO_2 (DOE 2012 and Wilson 2012)

- Storm water runoff costs from the facility is calculated by estimating the storm water runoff as million gallons for the 35 year life cycle by calculating the runoff as Gallons/day and Gallons/mile using the surface area of the unit cross section and the annual average precipitation. The cost used was $ 6550/million gallons of water based on Washington DC are water costs (DC Water 2012).

- Solid waste costs are calculated by calculating the quantities of materials removed during all construction, reconstruction and resurfacing for the life cycle of the facility. The cost used was $ 53/ ton solid waste based on Washington DC area waste management costs (DPW 2012).

4. Analysis

To demonstrate the use of the methodology an example scenario was defined and evaluated. The scenario consists of a two lane urban street that includes bike lanes, planting area and sidewalks on both sides as shown in Figure 2. These calculations were done using the conventional virgin construction materials. This was done to provide a baseline that can show the potential of using products and practices that can offset these impacts.

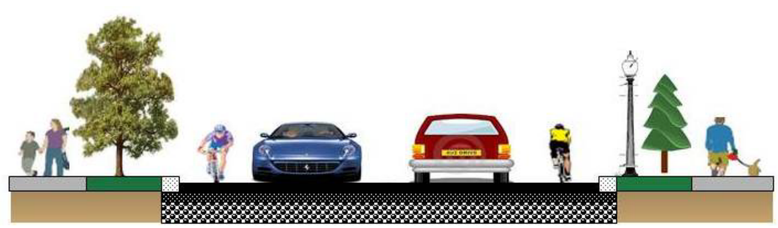


Figure 2: Standard cross section of an urban roadway

4.1. Data Set:

The “life cycle” was defined as 35 years. The spatial boundary includes the length and cross section of the roadway. Cross section includes Width: width across the travel way for vehicular lanes and bicycle lanes, side walk widths, curb and gutter, tree planting and width; and Depth: Surface asphalt course, pavement base course, aggregate sub base. Figure 3 shows the cross section details of an urban roadway used.

Figure 3: Typical section of roadway with cross section widths

The materials and quantities needed for a roadway project are based on DDOT Standard Drawings (DDOT 2009) and DDOT Standards and Specifications (DDOT 2009) based on the typical sections and the total length of the project.

ILCA[2] was performed on the portion of the STIP shown in Table 2:

Table 2: Project from Case study STIP (DDOT 2012)

Project Name	Length (miles)	Number of vehicular lanes	Number of bike lanes
CONSTRUCTION			
Project 1	1	2	2
Project 2	1	8	0
RESURFACING			
Project 3	115	6	2
Project 4	20	6	2
RECONSTRUCTION			
Project 5	11	4	2
Project 6	1	6	0
Project 7	0.25	5	2
Project 8	1	6	2
Project 9	0.25	4	2
Project 10	4	4	0
Project 11	0.5	8	2
Project 12	1.5	4	2
Project 13	1	4	2
Project 14	1	6	2

4.2 Performance Measures:

The following performance measures were identified to study the performance of the integrated life cycle analysis approach ($ILCA^2$) and tool:

1. Cost of construction
2. Cost of resurfacing
3. Cost of reconstruction
4. Life cycle cost
5. Life cycle impacts
6. Life cycle impact cost
7. Integrated life cycle costs using $ILCA^2$

4.3 Results and Discussion:

In order to determine the total life cycle costs construction, resurfacing and reconstruction activities must be considered. One of the first outputs of the tool is the material quantities for the major elements of the roadway given below:

- Grading: Grading includes removal of existing surface pavement, pavement base, sidewalks, curb and gutter, excavation and borrow
- Drainage: Drainage includes drainage inlets, manholes and pipes
- Roadway: Roadway includes surface pavement, pavement base and aggregate base for bike lanes, vehicular lanes, curb and gutter.
- Sidewalks
- Landscaping: Landscaping includes planting strip and trees
- Storm water management: Storm water management includes low impact development bio-retention zones
- Streetlight and traffic control: Street lights and traffic control includes lane marking, traffic signs, traffic signals, streetlight and ducts

The results show that the onetime impacts of the case study transportation program can be 1.1 million tons of CO_2 and 1.4 million tons of waste while the life cycle impacts can be 2.4 million tons of CO_2 and 21 million tons of waste materials. One time cost of the roadway projects is $400 million while life cycle cost is $ 5.4 billion. The life cycle impacts cost $1.6 billion and the $ILCA^2$ cost is $ 6.9 billion as shown in Table 3 and Figure 4. This shows that by using the without considering the life cycle impact costs the life cycle cost can be under estimated by 29%. This also establishes the reason for focusing on the environmental costs of project which can be $1.6 billion which represents 23% of the integrated life cycle analysis costs.

Table 3: Case study STIP cost results

Project Name	Cost $	Life cycle cost $	Life cycle impact cost $	integrated life cycle cost $
CONSTRUCTION				
Project 1	19,532,255	23,354,463	5,427,625	28,782,088
Project 2	45,286,530	65,094,717	21,092,212	86,186,930
MAINTENANCE/RESURFACING				
Project 3	92,560,145	3,994,580,026	1,170,422,525	5,165,002,551
Project 4	16,258,391	701,656,665	205,587,261	907,243,926
RECONSTRUCTION				
Project 5	116,028,870	313,685,684	84,268,147	397,953,831
Project 6	8,725,359	24,751,002	6,824,877	31,575,879
Project 7	2,882,368	7,972,556	2,247,524	10,220,080
Project 8	10,505,149	29,629,363	8,681,482	38,310,845
Project 9	2,256,117	6,099,444	1,638,547	7,737,991
Project 10	42,259,111	114,705,479	28,244,391	142,949,871
Project 11	6,943,826	20,212,993	6,276,284	26,489,277
Project 12	16,115,121	43,567,456	11,703,909	55,271,365
Project 13	7,520,390	20,331,480	5,461,824	25,793,304
Project 14	13,793,396	38,903,736	11,398,898	50,302,634
TOTAL	**400,667,027**	**5,404,545,065**	**1,569,275,508**	**6,973,820,573**

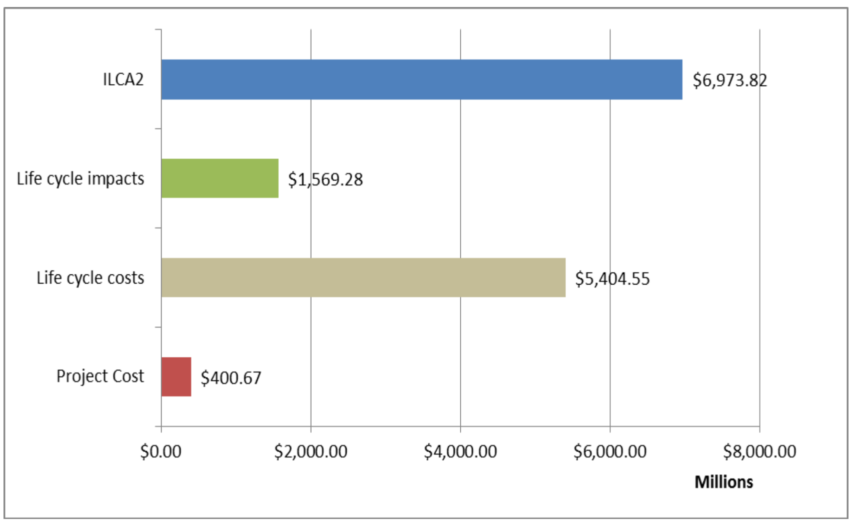


Figure 4: Comparison of life cycle impact costs, life cycle costs, ILCA^2 costs and project costs in the case study STIP

While making decision regarding transportation investments only the initial construction costs of the project are considered. As we can see from these results the initial costs only represent 6% of the life cycle costs of the project. This is due to the fact that not all projects in the STIP are construction. Most of the projects are either reconstruction or re-surfacing. The initial costs are usually the costs considered when making transportation investment decisions in the programming process. The integrated life cycle analysis approach and the case study results show that how the initial or one-time costs in the transportation programs are far lower than the life cycle costs.

Table 4: Case study STIP life cycle impact results

Project Name	Carbon footprint Tons	Storm water MG	Waste Materials Tons
CONSTRUCTION			
Project 1	10,498	209	72,677
Project 2	28,721	836	283,834
MAINTENANCE/RESURFACING			
Project 3	1,791,729	45,961	15,727,241
Project 4	314,721	8,073	2,762,524
RECONSTRUCTION			
Project 5	140,824	3,284	1,130,951
Project 6	10,853	267	91,659
Project 7	3,577	88	30,185
Project 8	13,290	341	116,655
Project 9	2,738	64	21,991
Project 10	50,102	1,095	378,716
Project 11	9,061	248	84,400
Project 12	19,559	456	157,076
Project 13	9,127	213	73,302
Project 14	17,450	448	153,170
TOTAL	**2,422,249**	**61,581**	**21,084,380**

Another important aspect of the ILCA[2] results for the case study is the life cycle impact results. The analysis shows that life cycle environmental impacts of the case study transportation program are 2.42 million tons of CO_2, 61581 million gallons (MG) of storm water and 21 million tons of waste materials as shown in Table 27. These results show that even though when analyzed from the perspective of an individual project the life cycle impacts may not seem very high, however, these individual projects when combined as a transportation program show a tremendous potential of analyzing life cycle impacts. Table 6 results are based using the characteristics of virgin construction materials and carbon footprint of those materials. These results can be used to compare the life cycle impacts of using alternate materials or recycled materials for the program.

The life cycle impact costs of the case study are given in Table 5 and illustrated in Figure 2. The results show that the life cycle impact costs are $48 million for carbon footprint, $400 million for storm water and S1.1 billion for waste materials. These results use virgin materials.

Table 5: Case study STIP life cycle impact costs

Project Name	Carbon footprint cost $	Storm water cost $	Waste material cost $	Life cycle impact cost $
CONSTRUCTION				
Project 1	209,964	1,365,796	3,851,865	5,427,625
Project 2	574,421	5,474,565	15,043,227	21,092,212
RESURFACING				
Project 3	35,834,571	301,044,188	833,543,765	1,170,422,525
Project 4	6,294,420	52,879,066	146,413,774	205,587,261
RECONSTRUCTION				
Project 5	2,816,473	21,511,286	59,940,389	84,268,147
Project 6	217,050	1,749,926	4,857,901	6,824,877
Project 7	71,549	576,195	1,599,780	2,247,524
Project 8	265,799	2,232,963	6,182,720	8,681,482
Project 9	54,765	418,275	1,165,508	1,638,547
Project 10	1,002,036	7,170,429	20,071,926	28,244,391
Project 11	181,213	1,621,883	4,473,189	6,276,284
Project 12	391,177	2,987,679	8,325,054	11,703,909
Project 13	182,549	1,394,250	3,885,025	5,461,824
Project 14	348,998	2,931,909	8,117,991	11,398,898
TOTAL	**48,444,984**	**403,358,409**	**1,117,472,115**	**1,569,275,508**

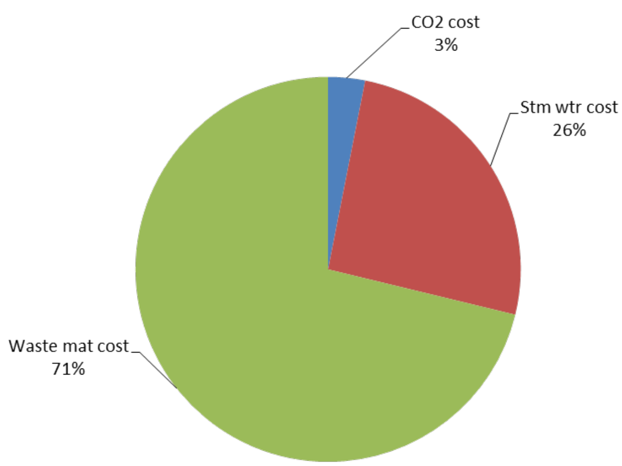


Figure 5: Life cycle costs of the transportation program

As illustrated in Figure 5, waste material costs represent 71% of the total life cycle costs of the program. Storm water represents 26% while CO2 footprint represents 3% of the costs. This is similar to the results found for project level results. Further breakdown of the environmental impact costs transportation program shows that the program results in 1 million ton of carbon footprint for all the projects in the program which result in life cycle impact of 2.4 million tons of carbon footprint that costs $48 million. This carbon footprint includes the carbon footprint of energy used. Energy footprint represents 35% of the total carbon footprint. The energy (power) usage has a higher footprint because of the footprint used for fossil fuel based power. Use of wind, hydro or solar energy has a carbon footprint many times lowers than fossil fuel.

Table 6 shows the results of life cycle impacts for the case study STIP using 20% recycled asphalt and PCC pavement materials. The results show that the life cycle carbon footprint reduces to 2.27 million tons of CO_2 eq. This shows a 6% decrease in carbon footprint compared to when virgin materials were used. The recycled pavement materials are not typically recycled on location and are shipped to a pavement plant to be recycled therefore they may not result in a direct waste material decrease. However, if they can be recycled on site then they also result in approximately 5 million tons of waste material decrease as shown in Table 6. This shows a 20% decrease in waste materials compared to when virgin materials were used.

Table 6: Case study STIP life cycle impact results using 20% recycled asphalt and PCC

Project Name	Carbon footprint Tons	Storm water MG	Waste Materials Tons
CONSTRUCTION			
Project 1	10,083	209	58,141
Project 2	26,495	836	227,068
MAINTENANCE/RESURFACING			
Project 3	1,678,372	45,961	12,581,793
Project 4	294,810	8,073	2,210,019
RECONSTRUCTION			
Project 5	133,260	3,284	904,761
Project 6	10,211	267	73,327
Project 7	3,367	88	24,148
Project 8	12,449	341	93,324
Project 9	2,591	64	17,593
Project 10	47,705	1,095	302,972
Project 11	8,425	248	67,520
Project 12	18,508	456	125,661
Project 13	8,637	213	58,642
Project 14	16,346	448	122,536
TOTAL	**2,271,259**	**61,581**	**16,867,504**

Similar to Table 7, if 20% recycled pavement materials are used the life cycle impact cost also decreases by $ 227 million which is 15% reduction in life cycle impact costs of the transportation program. This means that the total integrated life cycle costs of the transportation program can be reduced from $6.9 billion to $6.7 billion which is a reduction of over $ 200 million. As a comparison the actual cost of projects in the STIP was $ 400 million.

Table 7: Case study STIP life cycle impact costs using 20% recycled asphalt and PCC

Project Name	Carbon footprint cost $	Storm water cost $	Waste material cost $	Life cycle impact cost $
CONSTRUCTION				
Project 1	201,663	1,365,796	3,081,492	4,648,952
Project 2	529,908	5,474,565	12,034,581	18,039,055
RESURFACING				0
Project 3	33,567,444	301,044,188	666,835,012	1,001,446,645
Project 4	5,896,195	52,879,066	117,131,020	175,906,280
RECONSTRUCTION				0
Project 5	2,665,192	21,511,286	47,952,311	72,128,789
Project 6	204,210	1,749,926	3,886,320	5,840,457
Project 7	67,333	576,195	1,279,824	1,923,353
Project 8	248,983	2,232,963	4,946,176	7,428,122
Project 9	51,823	418,275	932,406	1,402,504
Project 10	954,100	7,170,429	16,057,541	24,182,070
Project 11	168,502	1,621,883	3,578,551	5,368,936
Project 12	370,166	2,987,679	6,660,043	10,017,887
Project 13	172,744	1,394,250	3,108,020	4,675,014
Project 14	326,918	2,931,909	6,494,393	9,753,219
TOTAL	**45,425,182**	**403,358,409**	**893,977,692**	**1,342,761,283**

While making decision regarding transportation investments only the initial construction costs of the project are considered. As we can see from these results the initial costs only represent 6% of the life cycle costs of the project. This is due to the fact that not all projects in the STIP are construction. Most of the projects are either reconstruction or re-surfacing. The initial costs are usually the costs considered when making transportation investment decisions in the programming process. The integrated life cycle analysis approach ILCA^2 and the case study results show that how the initial or one-time costs in the transportation programs are far lower than the life cycle costs.

5. Conclusions

By using an integrated life cycle analysis approach (ILCA^2) life cycle costs for transportation projects can be determined that includes the environmental costs over the life cycle of the project. Since transportation projects are planned over multiple years and STIP are used for transportation investment decisions, integrated life cycle analysis performed on a STIP provides the actual life cycle costs and impacts of the transportation investment decisions. This tool can also be effectively used for carbon cap-and-trade systems, where this tool allows the calculation of the carbon footprint of the transportation program for the next 5 years. The ability of the tool to provide carbon foot print of construction, resurfacing and reconstruction as well as life cycle impacts of these three activities can be an effective tool to make decisions regarding the type of activity to undertake. In carbon cap-and-trade scenarios this tool can help the decision makers to see where they can achieve reduction in carbon foot print. With the recent focus on performance measures this tool can also provide opportunities for transportation planners, designers and decision makers to analyze the various impacts of the transportation system and their life cycle costs. Performance measures can be developed that can be implemented on the transportation program by using this approach and tool. This tool can also be used for developing the recycling potential of a transportation system and the reductions in waste quantities and carbon footprint achieved. By using the traditional LCCA methodology the actual life cycle cost can be under estimated. The life cycle environmental impact costs of projects which can be almost one-fourth of the life cycle costs. While making decision regarding transportation investments only the initial construction costs of the project are considered. The results show that the initial costs only represent nearly a twentieth of the life cycle costs of the program. By performing the life cycle analysis using $ILCA^2$ on a larger scale enables roadway designers, planners and decision makers to evaluate the larger impacts of the transportation investments. It can also identify areas and opportunities to: develop alternate design, use alternate materials, and alternate practices to reduce the impacts of those elements. This can provide roadway designers, planners and decision makers an effective tool to evaluate the life cycle environmental impacts and costs of agency's investment decisions for the next many year.

References for Chapter 5

Apul, Dafne. "*BenReMod: A Web-Based Model for Comparing the Environmental Impacts from Road Construction Materials*" presentation. University of Toledo, OH. 2007.

Boustead, Ian. "*LCA - How it Came About, The Beginning in the UK*". International Journal of Life cycle Assessment 1 (3) 1996.

District Department of Transportation (DDOT). DDOT website. www.ddot.dc.gov (accessed March 2013).

District Department of Transportation (DDOT). *FY 2011-2016 STIP*. District of Columbia Department of Transportation. 2012.

District Department of Transportation (DDOT). *Cost estimates of roadway construction, resurfacing and reconstruction projects*. Cost data 2009-2011. 2011.

District Department of Transportation (DDOT). *Design and Engineering Manual*. District of Columbia Department of Transportation. April 2009. pp 2-1 to 2-35.

DDOT. *Standard Drawings*. District of Columbia Department of Transportation. April 2009.

DC Water. *Current Water Rates*. http://www.dcwater.com/customercare/rates (accessed April 2012)

DC Department of Public Works (www.dpw.dc.gov) (accessed April 2012)

Department of Energy (DOE). "*Life Cycle Costing Manual for the Federal Energy Management Program*". U. S Department of Energy, Washington DC. pp 1.1. 1996.

Environmental Protection Agency (EPA): "*Life cycle assessment: Principles and practice*". May 2006. Cincinnati, OH: National Risk Management Research Laboratory, Scientific Applications International Corporation (SAIC), EPA/600/R-06/060.

European Environmental Agency (EEA). *Life Cycle Assessment: A guide to approaches, experience, and information sources*. Environmental Issues Series. No. 6. August 1997.

Federal Highway Administration (FHWA). *Life-Cycle Cost Analysis: RealCost User Manual*. Publication No. FHWA, Washington DC. 2004.

Federal Highway Administration (FHWA) 2012. *Highway Statistics 2010*. Office of Highway Policy Information, FHWA, 1200 New Jersey Avenue, SE Washington, DC 20590.

Federal Highway Administration (FHWA). *Life-Cycle Cost Analysis in Pavement Design*. Publication No. FHWA-SA-98-079. FHWA, Washington DC. 1998.

Federal Highway Administration (FHWA). "*Life-Cycle Cost Analysis Primer*". U.S. Department of Transportation, FHWA, Washington DC. pp 7,9. August 2002.

Hammond, Geoff and Jones, Craig. *Inventory of Carbon and Energy*. Version 1.6a. Department of Mechanical Engineering, University of Bath, UK. 2008 updated 2009-2011.

Hendrickson, Chris, Horvath, Arpad. *Resource Use and Environmental Emissions of U.S Construction Sectors*. Journal of Construction Engineering and Management. January-February 2000. pp 38-44.

Hendrickson, Chris., Horvath, A., Lave, L.B. *Use of Economic input-output models for environmental life cycle assessment*. Environmental Science and Technology. April 1998. Volume 32, Issue 7 / pp. 184 A-191 A

Hendrickson, C.T., Lave, L.B., and Matthews, H.S., *Environmental Life Cycle Assessment of Goods and Services.* Washington, DC: Resources for the Future. 2006.

Horvath, A. *Estimation of the environmental implications of construction materials and designs using life-cycle assessment techniques*. PhD Thesis. Department of Civil and Environmental Engineering, Carnegie Mellon University. 1997.

Horvath, Arpad. *Construction Materials and Environment*. Annual Rev. Environ. Resour. 2004. 29:181–204.

Horvath, A., and Hendrickson, C. T. (1998), *A Comparison of the Environmental Implications of Asphalt and Steel-Reinforced Concrete Pavements*. Transportation Research Record, NRC, No. 1626 (Environmental and Social Effects of Transportation), pp. 105-113, DOI:10.3141/1626-13.

Horvath, A., Hendrickson, C. T., Lave, L. B., McMichael, F. C., and Wu, T-S. (1995), *Toxic Emissions Indices for Green Design and Inventory*. Cover article, Environmental Science & Technology, ACS, 29(2), pp. 86-90, DOI:10.1021/es00002a003.

Horvath, Arpad et al. "*Pavement life-cycle assessment tool for environmental and economic effects (PaLATE)*". http://www.ce.berkeley.edu/~horvath/palate.html (accessed 20 February 2012).

Huanga, Yue , Bachar Hakimb1 and Susanna Zammataroc2 *Measuring the carbon footprint of road construction using CHANGER.* International Journal of Pavement Engineering 2012-1-11.

International Organization for Standardization (ISO). "Documentation International Standard DIS 14040 Technical committee 1998. ISO Geneva, Switzerland. March 2001.

International Organization for Standardization (ISO). "ISO-14040-2006: Environmental Management-Life Cycle Assessment-Principles & Framework". ISO Geneva, Switzerland. 2006.

Mukherjee, Amlan and Stawowy, Brian. *The Project Emissions Estimator (PE-2): A tool to aid contractors and agencies assess GHG emissions of Highway Construction*. Transportation Research Board. 92nd Annual Meeting Proceedings of. January 2013.

National Institute of Standards and Technology (NIST) "*Building for Environmental and Economic Sustainability (BEES) 4.0 Manual*. US Department of Commerce. 2007.

NCHRP Report 483. "*Bridge Life Cycle Cost Analysis*". National Cooperative Highway Research Program, Transportation Research Board (TRB), Washington DC 2003.

Nicuta, Alina-Mihaela. "*Life cycle analysis study for new and recycled asphalt pavements*". Technical University of Iasi. Feb 2, 2011.

Santero, N., Masanet, E., and Horvath, A., *Life-Cycle Assessment of Pavements: A Critical Review of Existing Literature and Research*, SN3119a, Portland Cement Association, Skokie, Illinois, USA, 2010, 81 pages.

Santero, Nicholas; Loijos, Alexander; Akbarain, Mehdi and Ochsendorf, John. "*Methods, Impacts, and Opportunities in the Concrete Pavement Life Cycle*". Concrete Sustainability Hub. MIt. August 2011.

Sharrard, Aurora L. "*Greening Construction Processes Using Input-Output Based Hybrid Life Cycle Assessment Model*". PhD Dissertation. Department of Civil & Environmental Engineering. Carnegie Mellon University. April 2007.

Sharrard, Aurora L.; Mathews, H. Scott; Ries, Robert J. "*Estimating Construction Project Environmental Effects Using an input-output Based Hybrid Life-cycle Assessment Model*". Journal of Infrastructure Systems. pp 327-336. ASCE December 2008.

Transportation Research Lab (TRL). Asphalt Pavement Embodied Carbon Tool (asPECT). Available from: http://www.irfghg.org/ (Accessed 21 December 2012).

Michigan Technical University (MTU). Project Emission Estimator (PE2) website. http://www.construction.mtu.edu/cass_reports/webpage/plca_estimator.php. (accessed 20 February 2013).

Zhang, H.; Keoleian, G.A and Lepech, M.D. "An integrated life cycle assessment and life cycle analysis model for pavement overlay systems". Life Cycle Civil Engineering. 2008.

Chapter 7

Summary

Summary

Sustainability can be an important factor in transportation agency decisions because of environmental impacts of transportation facilities. To evaluate these environmental impacts, an understanding of the elements that make up the facility and their corresponding impacts over the operational life of a facility is necessary. A typical urban roadway includes sidewalks, street lights, pavement markings and a drainage system in addition to pavement. The materials used in construction, resurfacing and reconstruction as well as drainage and electricity use during operations result in substantial impacts. Most of the available models and tools perform analyses for individual products and focus on GHG emissions. These models and tools pose a challenge for practitioners in DOTs due to the extensive need for data and inputs which are usually not available at the planning and programming stage of transportation project development.

This research developed a methodology that supports state DOTs in making sustainable decisions by quantifying environmental impacts of transportation projects through calculating life cycle impacts and corresponding costs to construct, resurface, reconstruct and operate urban roadways using an integrated life cycle analysis approach ($ILCA^2$). A prototype tool was developed to implement this methodology.

The $ILCA^2$ methodology and the prototype tool were used to evaluation two case studies, a single urban roadway project and a sample transportation program STIP for DC DOT.

Environmental Impacts of an Urban Roadway Section

The case study evaluation of a unit length of a typical urban street began with estimating the environmental impacts, consisting of the carbon footprint, waste material, and storm water runoff, over a 35-year evaluation life cycle which included initial construction, two resurfaces and one reconstruction.

Results indicate that this roadway facility is estimated to require over 75,000 tons of materials per mile for construction and over 116,000 tons per mile over the life cycle period. The carbon footprint per mile is estimated at over 3,600 tons of CO_2 eq. for original construction while it is 10,000 tons of CO_2 eq. over the life cycle. Solid wastes are estimated at over 46,000 tons per mile of construction and 72,000 tons per mile over the life cycle period.

Comparison of the materials used and carbon footprint show that over the life cycle, grading uses over 50% of the materials as shown in Figure 1 but represents only 16% of the carbon footprint as shown in Figure 2. The roadway section uses 25% of the materials as shown in Figure 1 and represents 23% of the total carbon footprint as shown in Figure 2.

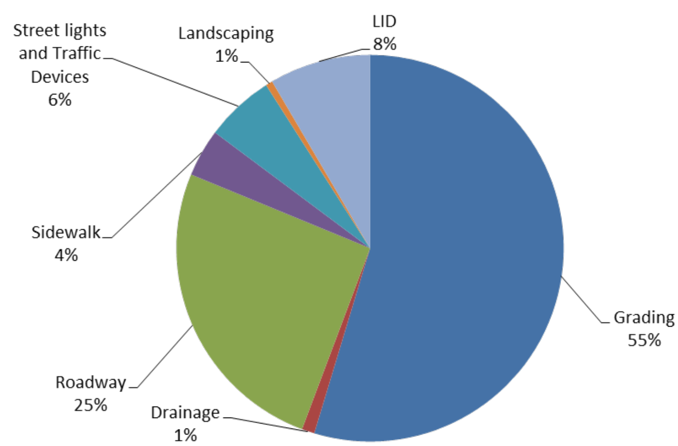


Figure 1: Life cycle material quantities

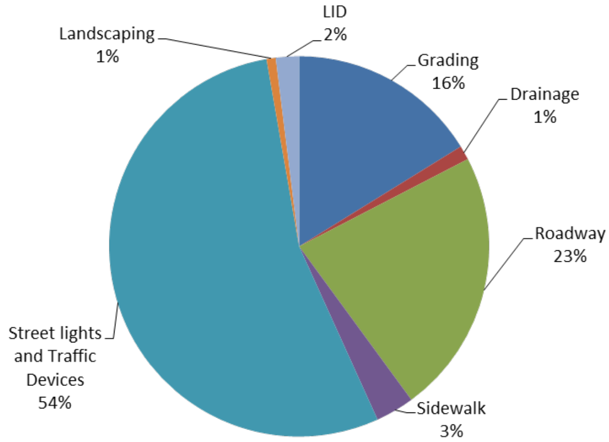


Figure 2: Life cycle carbon footprint

The storm water runoff was estimated at over 3 million gallons per year per mile and over 100 million gallons over the life cycle period. Storm water management as Low impact development (LID) units represents 8% of the total quantity of materials as shown in Figure 1. However, for carbon footprint, they represent only 2% of the total carbon footprint as shown in Figure 2. This is due to the fact that the primary material used in LID construction is soil.

Sidewalks represent 4% of the total quantity of materials as shown in Figure 1 while for carbon footprint they represent 3% as shown in Figure 2. Streetlights and Traffic control devices represent 6 % of the total quantity of materials as shown in Figure 1 while for carbon footprint they represent 54% of the total carbon footprint as shown in Figure 2. This is primarily due to the fact that the energy used by streetlights and the traffic signals over the life cycle evaluation period is included in the carbon footprint calculation. If energy use is excluded, streetlights and traffic devices represent only 7% of the carbon footprint and the roadway section becomes the highest contributor at 46% of the total carbon footprint as shown in Figure 3.

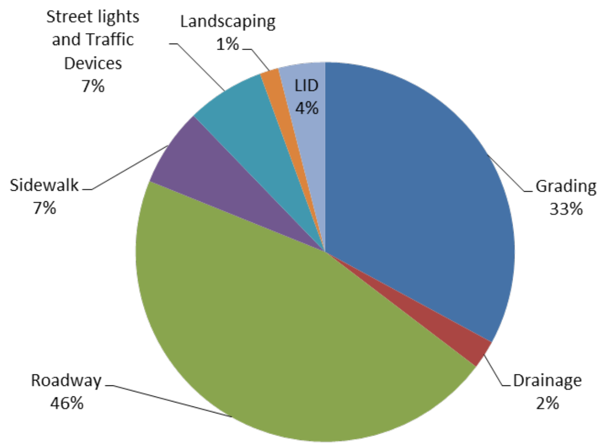


Figure 3: Life cycle carbon footprint without energy

Over the life cycle, construction represents 45%, resurfacing represents 11% while reconstruction represents 44% of the life cycle carbon footprint as shown in Figure 4.

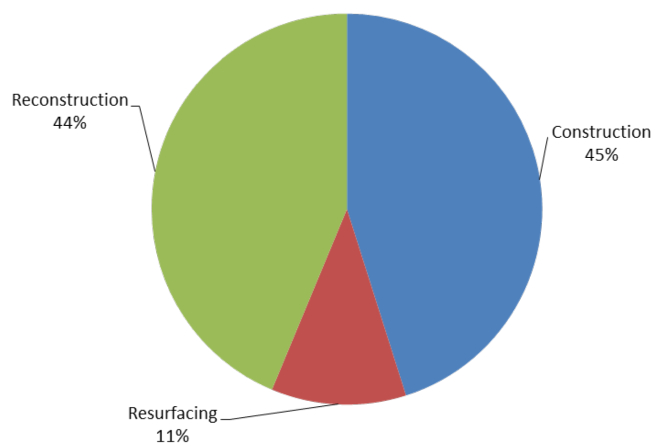


Figure 4: Life cycle carbon footprint by lifecycle phase

The analysis of solid wastes shows that grading represents 64%, roadway represents 21%, LID represents 7%, Landscaping represent 5%, sidewalks represent 3% and street light and traffic devices represent less than 1% of the lifecycle wastes as shown in Figure 5. Analysis of the solid wastes by life cycle phase shows that construction contributes the most to solid wastes and represents 63% of the life cycle wastes, reconstruction represents 33% and the two resurfacings represent 4% of the life cycle waste materials as shown in Figure 6.

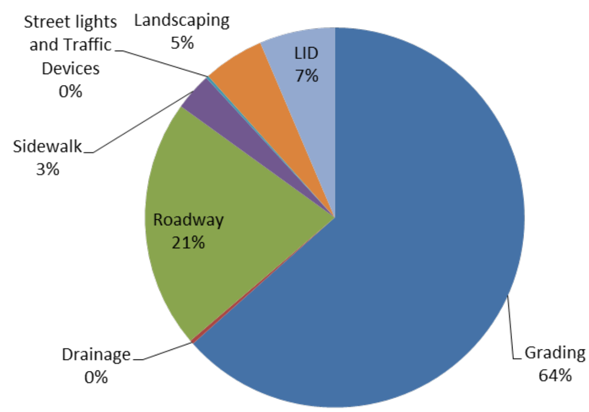


Figure 5: Life cycle solid waste materials

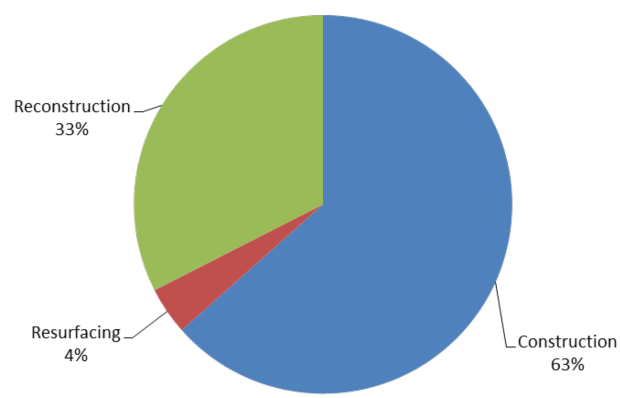


Figure 6: Solid waste materials by lifecycle phase

The quantification of life cycle environmental impacts shows that the life cycle impacts are higher than the initial construction impacts. The results show that the life cycle carbon footprint is more than twice the initial construction carbon footprint. The life cycle solid wastes were estimated to be 1.5 times of the initial construction wastes. The results shows that more than 70% of the materials used for construction, resurfacing and reconstruction are typically removed and wasted.

Integrated Life Cycle Analysis Approach for an Urban Road Segment

The case study evaluation of a unit length of a typical urban street was expanded by estimating the life cycle costs that included the costs of the environmental impacts, over a 35-year evaluation life cycle which included initial construction, two resurfaces and one reconstruction.

Results indicate that this roadway facility is estimated to cost over $ $28 million per mile over the life cycle period which include environmental impact costs. The environmental impact costs are estimated to be over $ 5 million or 20% of the life cycle costs and are higher than the operation costs, energy costs, and the resurfacing costs of the urban roadway. The results of the life cycle impact costs show that solid wastes represent 71%, storm water runoff represents 25% while carbon footprint represent 4% of the impact costs as shown in Figure 7.

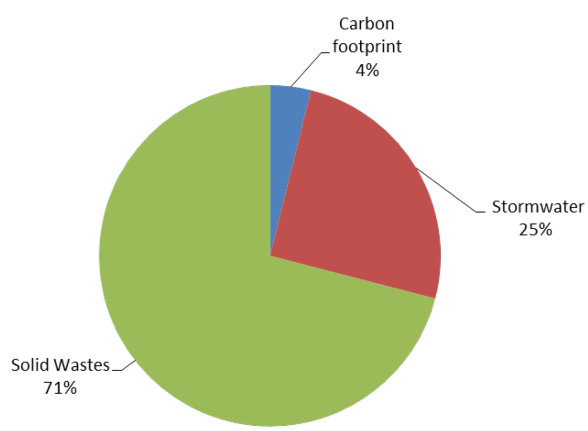


Figure 7: Life cycle impact costs

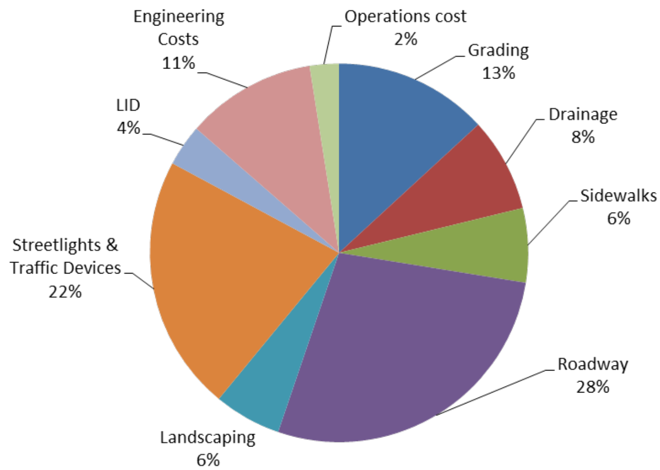


Figure 8: Life Cycle Costs (using ILCA[2])

The results show that that roadway represents 28%, street light and traffic control represent 22% , grading represent 13%, drainage represent 8%, sidewalks represent 6%, LID represents 4%, operation costs represent 3% and energy costs represent 4% of the life cycle costs as shown in Figure.8.

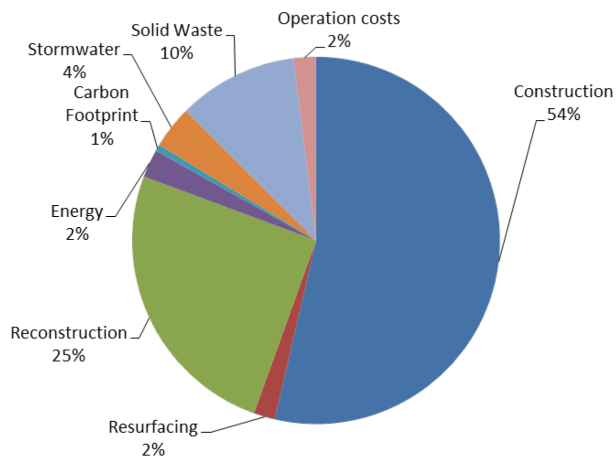


Figure 9: Breakdown of Life Cycle Costs

When tabulated according to life cycle phase, the results show that construction costs represent 54% of the total life cycle costs of the roadway while reconstruction can represent 25% of the total costs as shown in Figure 9. These costs are followed by life cycle impact costs with solid waste costs representing 10%, storm water costs as 4% and carbon footprint as 1% as shown in Figure 9.

Integrated Life Cycle Analysis Approach for a STIP

The case study evaluation of a sample STIP for DC DOT included 14 different typical urban street projects. This evaluation began with estimating the environmental impacts, consisting of the carbon footprint, waste material, and storm water runoff for each project to estimate the life cycle costs of the case study STIP. The environmental impact estimation was followed by estimating the life cycle costs of these projects to estimate the life cycle costs of the case study STIP. Both life cycle impacts and costs were evaluated over a 35-year evaluation life cycle which included initial construction, two resurfaces and one reconstruction for each project.

Results show that life cycle impacts for the case study STIP were estimated to be 2.4 million tons of carbon foot print, 21 million tons of waste materials and 61,000 million gallons of storm water. The costs of these impacts were estimated to be $48.4 million for carbon foot print, $400 million for storm water runoff and $1.12 billion for waste materials. Results indicate that the life cycle impact costs were estimated to be one-fourth of the total life cycle costs of the case study STIP. The costs of the projects in the STIP were found to be a small portion of the life cycle costs. The life cycle cost of the case study STIP was estimated to be $ 6.9 billion which includes the life cycle impacts cost of $1.57 billion. The results show that without considering the life cycle impact costs the life cycle cost can be under estimated by 29%.

In order to understand the effects of using recycled material, a case study scenario was analyzed by using 20% recycled asphalt and PCC pavement materials for all the projects in the case study STIP. The results show that by using 20% recycled pavement life cycle carbon footprint of the case study STIP decreased by 6% and waste material decreased which is a 20%. This also resulted in 15% decrease in life cycle impact costs. For the case study STIP this results in life cycle cost decrease of over $ 200 million. As a comparison the cost of projects in the case study STIP was $ 400 million.

This analysis was also used to compare the LID life cycle costs with traditional drainage for the case study STIP. By using 1.2” retention requirements for storm water, life cycle LID costs were estimated to be $ 385 million while the life cycle storm water treatment costs using a traditional drainage system was estimated to be $ 390M which shows that over life cycle LID can result in cost savings over traditional drainage system especially if used over a transportation program.

Chapter 8

Conclusions and Recommendations

Conclusions and Recommendations

The conclusions, contributions, applications, and limitations of this research are discussed in this section followed by recommendations for further research.

8.1. Conclusions

Because sustainability is important to our future needs and transportation infrastructure impacts this sustainability, transportation investment decisions should include methods to quantify and evaluate environmental impacts and their corresponding costs associated with infrastructure. Life Cycle Assessment (LCA) is an accepted practice used to analyze such environmental impacts. When integrated with Life Cycle Cost Analysis (LCCA), the quantification of life cycle environmental impacts and costs for a roadway that includes construction, resurfacing and reconstruction as well as impacts related with managing the facility by few readily available inputs can help the transportation professional significantly. By establishing a reasonable life cycle time frame, representative elements, mostly homogeneous facility types with representative cross sections, and accepted construction, maintenance and reconstruction practices, a life cycle analysis approach which integrates LCA and LCCA is developed called Integrated Life Cycle Analysis Approach ($ILCA^2$).

Using $ILCA^2$ for evaluating transportation projects shows several benefits. By quantifying environmental impacts and associated costs for transportation projects and adding these costs to direct construction and rehabilitation costs, important information is available to support investment decisions. Based on this research environmental impact costs can be higher than direct operation costs, energy costs, and resurfacing costs of an urban roadway.

An urban roadway facility consists of several elements such as travel way, sidewalks, street lights, traffic signals, lane striping and drainage which all have environmental impacts. Quantifying the life cycle impacts of each element helps in identifying which elements have higher impacts so that those elements can be prioritized for alternate design, material evaluations, reclamation and recycling of materials.

In addition to greenhouse gas (GHG) emissions, or carbon footprint, additional environmental impacts include waste materials and storm water runoff. Roadway construction, resurfacing and reconstruction can result in large quantities of materials which must be removed and disposed of in landfills. This is an important finding of this research since more than 90% of material used in construction and rehabilitation of a roadway can result in waste and is typically removed. This shows the potential for recovering, reclaiming, reusing and recycling these materials, potentially resulting in reducing life cycle environmental impacts.

Similarly, storm water runoff over the life cycle from the roadway can also be substantial and the associated can represent a significant portion of the life cycle costs. When used over the life cycle of a transportation program, Low Impact Development (LID) strategies for roadways can result in economic benefits with higher cost savings than traditional drainage practices. It was found that the life cycle environmental impact costs can represent a quarter of the total integrated life cycle costs of a transportation program.

At the programming stage when decisions are made regarding transportation infrastructure investments, normal practice is to consider only the onetime initial cost for programmed projects. This research showed that these initial costs represent a small portion of life cycle costs. Applying ILCA^2 to a STIP, enables decision makers to evaluate the larger impacts of transportation investments as well as consideration of programmatic changes to practices that support sustainability.

8.2. Contributions

This research makes the economic case for considering life cycle environmental impacts in transportation investment decision making. Because this research developed a methodology that expanded environmental impacts from estimating carbon foot print to solid waste materials and storm water runoff, a more comprehensive understanding of impacts related to the construction, rehabilitation and management of transportation facilities is possible.

Sustainability is becoming an increasingly important element of transportation decision making. This research developed a methodology and prototype decision support tool for evaluating transportation investments based on an Integrated Life Cycle Analysis Approach ($ILCA^2$). Because the approach uses standard cross sectional information and minimal input to develop life cycle impacts and associated costs, it is readily applied to the STIP, providing important information for programming funds and resources for a state's transportation infrastructure.

$ILCA^2$ was used to show the benefits of including life cycle environmental impact analysis for an individual transportation project as well as a more comprehensive program. It identified costs associated with life cycle impacts as a share of overall costs of a project. Because impacts and costs are estimated for each phase of the project's life cycle as well as for each element in the project, decision makers have the information necessary to develop and analyze alternatives such as using different materials, alternate design practices, and reclamation and recycling of materials. This research provides a tool that can be used for carbon cap-and-trade decisions.

With the recent focus on performance measures and the requirements in the recently passed federal Transportation Authorization Bill MAP 21 (USGPO 2012), $ILCA^2$ provides a planning tool for transportation planners, designers and decision makers to establish and analyze performance measures associated with environmental impacts of programmed projects in their transportation system.

8.3. Limitations

The scope of this research included construction, resurfacing, reconstruction and operation related to power requirements of urban roadways and did not include life cycle impacts of snow removal, cleaning activities, office facilities, or agency personnel or vehicles. More importantly, it also does not include user impacts. This approach uses standard design information available at the planning stage and is not intended to be used for detailed engineering design analysis or for structural performance of materials or operational performance of the facility. This research focused on urban streets and roadways and did not include interstate highways or other transportation facilities. However, with additional research, the overarching approach is extensible and, with additional research, can be modified for use on other mostly homogenous facilities. The research assumes flat vertical and straight horizontal alignment and does not take into consideration resulting changes to the standard cross section. This research does not consider any grade separated intersections.

The roadway section consisted of a composite pavement design, i.e. asphalt and PCC which is used for most of the urban streets. Other types of pavement types, i.e. flexible pavement (asphalt) and fixed pavement (concrete) were not considered. For the purposes of this research, the nominal pavement thicknesses recommended by States and cities was used. For resurfacing and reconstruction activities, the research assumes removal of the surface course and pavement course thickness from AASHTO or DDOT standards. For a more detailed analysis, geotechnical analysis and pavement samples are needed to determine the condition of the surface and subsurface to determine the type and depth of resurfacing and/or reconstruction. Quantities and estimates of materials and their costs were developed for a planning application and are not representative of detailed design.

Consumer utilities such as power lines, water lines, gas lines, fiber optic/telecommunication lines also typically use the transportation right of way. However, since these are not part of standard operations of a transportation agency, these utilities were not considered. Only the poles, drainage lines and manholes, and electrical ducts needed for transportation purposes were included in the estimates.

The research primarily used generalized cost data from DC DOT from 2008-2011 and all costs are based on 2011 dollars. However, costs of construction and materials vary across states and cities with higher costs typically occurring in urban areas. The case study assumed conventional virgin construction materials. This was done to provide a baseline for evaluating use of alternate products and practices.

The case study focuses on Washington DC only. DC is the smallest state DOT with a correspondingly small STIP. For bigger states the STIP will be larger with a wider range of similar transportation facility types. Therefore, additional work would be required to modify the approach for each type of facility to evaluate the broader STIP.

The purpose of the research is not to recommend the best life cycle rehabilitation/maintenance program for a roadway facility. The purpose was to develop a methodology to estimate the costs and impacts over the life cycle and test it for different scenarios so that decision makers can see the effects of including environmental impacts of a facility before resources have been allocated.

8.4. Application of Research

The primary application of this research is in supporting decisions related to sustainability of transportation infrastructure. This research and the resulting $ILCA^2$ methodology and tool can provide agency decision makers a method to evaluate life cycle costs of a transportation facility that includes costs associated with environmental impacts. With an understanding of these costs, better decisions can be made that support the three elements of sustainability – improving the environment, strengthening economics and providing a transportation system that supports the social structure.

Life cycle environmental impacts of a transportation facility are quantified by performing a baseline $ILCA^2$ for construction, reconstruction, and maintenance of roadways using a standard cross section and a few readily available inputs designed for ready use by practitioners. This research supports the calculation of life cycle environmental impacts of a roadway in terms of carbon footprint, storm water runoff, and solid wastes. By quantifying the life cycle impacts of each element separately, attention can be paid to developing alternate designs, using alternate materials, and indentifying alternate practices to reduce the impacts of those elements and hence of the facility. This approach can also identify elements that result in the highest impact so that those elements can be prioritized for alternate design or material evaluations.

A state's STIP is a critical part of transportation investment decisions because projects are programmed based on this document. Being able to apply $ILCA^2$ at the STIP level provides agency decision makers with a tool to evaluate program-wide decisions that support sustainability. Such decisions include supporting carbon cap-and-trade systems, where $ILCA^2$ allows the estimation of the carbon footprint for all programmed transportation projects (investments). This tool can also be used to evaluate specific strategies such as the use recycled material, reductions in waste quantities, and for comparing the costs of LID with traditional drainage systems. With the recent focus on performance-driven accountability, this tool can allows agencies to establish and analyze performance measures tied to environmental impacts related to constructing and rehabilitating transportation infrastructure.

8.5. Recommendations and future research

The methodology and tool were developed for urban roadways. However the $ILCA^2$ can easily be extended for use with other transportation facilities, particularly highways and rural roadways, by adding representative cross sections and obtaining related costs. Consideration should be given to including additional roadway elements such as noise barriers, retaining walls, ITS systems, structures and grade separated intersections. Additional construction materials could be considered such as asphalt only pavements, flexible pavement, concrete pavement, and recycled materials. Maintaining the current standard cross section and minimal input requirements is important, since at the planning and programming stages, detailed engineering information is not available.

ILCA^2 and the corresponding tool are a means to an end. Its objective is to provide support for transportation investment decision making for transportation agencies. Agencies consider many factors before making a decision regarding investments. Life cycle costs and environmental impacts are just one and the results from this process are estimates that are based on standard information. Additional work would be required to incorporate a more detailed level of analysis including consideration of weather patterns, non-standard cross-sections, and different rehabilitation policies and operations.

Impacts of adding utilities impacts and costs to ILCA^2 should also be researched. Utility lines such as water lines, power lines, gas lines and communication cables normally use the transportation right of way (ROW). These utilities are not needed due to a roadway however due to their use of ROW sometimes these utilities have to be moved or reconstructed due to a roadway reconstruction and sometimes due to the repair, upgrade or relocation of a utility line the roadway has to be reconstructed. The type and size of these utilities varies depending upon the population density and users in the area. The utility lines include pipes, poles, ducts, wires and cables which are made of different types of materials and in turn have different environmental impacts. Relocation and reconstruction of these utilities can also be very expensive. ILCA^2 for roadways should be expanded to include the impacts and costs of these utilities.

Impacts of adding roadway user impacts and costs to ILCA^2 should be researched.

The tool that was developed for this research is a prototype and to be useful in practice should be redesigned and turned into a comprehensive, extensible, and scalable decision support system. If and when the methodology is expanded to other facilities, the tool should also be expanded to facilitate evaluation of a complete STIP. Including the ability to analyze alternatives while performing the assessment could expand the usefulness of the tool.

References for Chapter 8

United States Government Printing Office (USGPO). Moving Ahead for Progress in the Twenty First Century (MAP 21). An Act to authorize funds for Federal-aid highways, highway safety programs, and transit programs. 112th Congress, Public Law 141. 2012.

Appendices

Appendices

List of Appendices:

1. Conversion factors
2. Detailed results
3. Users Guide to $ILCA^2$ tool
4. Java Programming code for developing the $ILCA^2$ tool

Appendix 1

Conversion Factors

GWP as CO_2 Equivalent:

- Source: *Inventory of Carbon and Energy (ICE)* Version 1.6a *by* Hammond, Geoff and Jones, Craig (2011).

Description	Conversion factor lb material/lbCO2
Grading	
Removal of Existing Surface Pavement	0.14
Removal of Existing base Pavement	0.127
Removal of Existing Sidewalk	0.127
Removal of curb and gutter	0.127
Excavation	0.127
Excavation landscaping	0.023
Borrow	0.023
Drainage	
Install WQ Inlet	0.127
Remove Existing Inlet	0.127
Install 48" I.D. Manhole	0.127
18" RCP Pipe	0.127
Roadway and Sidewalks	
PCC Pavement, 10"	0.127
2" Superpave, Type C Hot-Mix	0.14
6" Graded Aggregate Base Course	0.017
Curb	0.127
Portland Cement Concrete Gutter	0.127
Sidewalk (6ft each side)	0.127
Landscaping	
Planting area	0.023
Street lights and Traffic Control Devices	
Signing	2.53
Street Lights	2.7
Pavement Marking	3.56
New Signals	2.7
Concrete Encased Multi Duct	0.127
Stormwater Management	
ponding (6")	0.023
soil	0.017
aggregate base	2.5
underdrain	0.02
Mulch	0.127
Planting area walls	0.023

Material Densities:

- Source: *Inventory of Carbon and Energy (ICE)* Version 1.6a *by* Hammond, Geoff and Jones, Craig (2011).

Description	Density Lb/ft3
Grading	
Removal of Existing Surface Pavement	106.25
Removal of Existing base Pavement	150.00
Removal of Existing Sidewalk	150.00
Removal of curb and gutter	150.00
Excavation	150.00
Excavation landscaping	91.25
Borrow	91.25
Drainage	
Install WQ Inlet	150.00
Remove Existing Inlet	150.00
Install 48" I.D. Manhole	150.00
18" RCP Pipe	150.00
Roadway and Sidewalks	
PCC Pavement, 10"	150.00
2" Superpave, Type C Hot-Mix	106.25
6" Graded Aggregate Base Course	140.00
Curb	150.00
Portland Cement Concrete Gutter	150.00
Sidewalk (6ft each side)	150.00
Landscaping	
Planting area	91.25
Street lights and Traffic Control Devices	
Signing	86.25
Street Lights	490.63
Pavement Marking	75.00
New Signals	490.63
Concrete Encased Multi Duct	150.00
Stormwater Management	
ponding (6")	91.25
soil	140.00
aggregate base	86.25
underdrain	31.50
Mulch	65.63
Planting area walls	91.25

Unit Cost:

- Source: *Various DDOT construction projects between FY2009-2011. Costs averaged to 2011 dollars*

Description	Cost $	Quantity
Grading		
Removal of Existing Surface Pavement	$60	Cubic Yard (CY)
Removal of Existing base Pavement	$60	CY
Removal of Existing Sidewalk	$60	CY
Removal of curb and gutter	$60	CY
Excavation	$40	CY
Excavation landscaping	$40	CY
Borrow	$50	CY
Drainage		
Install WQ Inlet	$16,000	Each
Remove Existing Inlet	$2,000	Each
Install 48" I.D. Manhole	$8,150	Each
18" RCP Pipe	$130	Linear Feet (LF)
Roadway and Sidewalks		
PCC Pavement, 10"	$110	Square Yard (SY)
2" Superpave, Type C Hot-Mix	$100	TON
6" Graded Aggregate Base Course	$30	SY
Curb	$35	LF
Portland Cement Concrete Gutter	$35	LF
Sidewalk (6ft each side)	$20	Square Feet (SF)
Landscaping		
Planting area	$15	SF
Street lights and Traffic Control Devices		
Signing	$500	Each
Street Lights	$8,000	Each
Pavement Marking	$3	LF
New Signals	$200,000	Each
Concrete Encased Multi Duct	$100	LF
Stormwater Management		
ponding (6")	$53	CY
soil	$57	CY
aggregate base	$18	LF
underdrain	$2.5	SY
Mulch	$35	LF
Planting area walls	$53	CY

Appendix 2
Detailed Results

Construction:

Description	Quantity	Unit	Unit Cost	Amount	% of
1. Grading					
Removal of Existing Surface Pavement	-	CY	$60.00	$0	
Removal of Existing base Pavement		CY	$60.00		
Removal of Existing Sidewalk	-	CY	$60.00	$0	
Removal of curb and gutter		CY	$60.00	$0	
Excavation	18,359	CY	$40.00	$734,376	
Excavation landscaping	3,105	CY	$40.00	$124,207	
Borrow	4,590	CY	$50.00	$229,493	
GRADING			TOTAL	$1,088,076	6%
2. Drainage					
a. Install WQ Inlet	36	EA	$16,000.00	$576,000	
b. Remove Existing Inlet	-	EA	$2,000.00	$0	
c. Install 48" I.D. Manhole	18	EA	$8,150.00	$146,700	
d. 18" RCP Pipe	11,272	LF	$130.00	$1,465,360	
DRAINAGE			TOTAL	$2,188,060	11%
3. Roadway and Sidewalks					
a. PCC Pavement, 10"	18,631	SY	$110.00	$2,049,422	
b. 2" Superpave, Type C Hot-MiX	1,467	TON	$100.00	$146,706	
c. 6" Graded Aggregate Base Course	18,631	SY	$30.00	$558,933	
d. Curb	10,480	LF	$35.00	$366,800	
e. Portland Cement Concrete Gutter	10,480	LF	$35.00	$366,800	
f. Sidewalk (6ft each side)	62,880	SF	$20.00	$1,257,600	
ROADWAY			TOTAL	$4,746,262	24%
Landscaping					
Planting area	32,704	SF	$15.00	$490,560	
Trees	262	EA	$3,100.00	$812,200	
LNDSCPG			TOTAL	$1,302,760	7%
Street lights and Traffic Control Devices					
Signing	72	EA	$500.00	$36,000	
Street Lights	105	EA	$8,000.00	$838,400	
Pavement Marking					
Thermoplastic Pavement Markings	15,720	LF	$3.00	$47,160	
Signals					
New Signals	18	EA	$200,000.00	$3,600,000	
Concrete Encased Multi Duct	5,240	LF	$100.00	$524,000	
ST LIGHTS & TRAFFIC DEVICES			TOTAL	$5,045,560	26%
Stormwater Management					

ponding (6")					
soil	2125	CY	$53.00	$112,631	
aggregate base	1,063	CY	$57.00	$60,566	
underdrain	10,480	LF	$18.00	$188,640	
Mulch	3,634	SY	$2.50	$9,084	
Planting area walls	8,176	LF	$35.00	$286,160	
STRMWTR MGMT			TOTAL	$657,081	3%
Other Engineering Costs					
MOT (10% of Rdwy cost)	10%	L.S	N/A	$474,626	
Preliminary Design (3% of total)	3%	L.S	N/A	$450,834	
Final Design (7% of total)	7%	L.S	N/A	$1,051,946	
Construction Management (10% of total)	5%	L.S	N/A	$751,390	
ENGG COSTS			TOTAL	$2,728,796	14%
PROJECT COST				**$17,756,595**	
CONTINGENCY	10%	L.S	N/A	$1,775,660	9%
TOTAL PROJECT COST				**$19,532,255**	

Resurfacing:

Description	Quantity	Unit	Unit Cost	Amount	% of
1. Grading					
Removal of Existing Surface Pavement	1035.06	CY	$60.00	$62,104	
Removal of Existing base Pavement		CY	$60.00		
Removal of Existing Sidewalk	0.00	CY	$60.00	$0	
Removal of curb and gutter	0.00	CY	$60.00	$0	
Excavation	0.00	CY	$40.00	$0	
Excavation landscaping	0.00	CY	$40.00	$0	
Borrow	0.00	CY	$50.00	$0	
GRADING			TOTAL	$62,104	18%
2. Drainage					
a. Install WQ Inlet	0.00	EA	$16,000.00	$0	
b. Remove Existing Inlet	0.00	EA	$2,000.00	$0	
c. Install 48" I.D. Manhole	0.00	EA	$8,150.00	$0	
d. 18" RCP Pipe	0.00	LF	$130.00	$0	
DRAINAGE			TOTAL	$0	0%
3. Roadway and Sidewalks					
a. PCC avement, 10"	0.00	SY	$110.00	$0	
b. 2" Superpave, Type C Hot-MiX	1467.06	TON	$100.00	$146,706	
c. 6" Graded Aggregate Base Course	0.00	SY	$30.00	$0	
d. Curb	0.00	LF	$35.00	$0	
e. Portland Cement Concrete Gutter	0.00	LF	$35.00	$0	
f. Sidewalk (6ft each side)	0.00	SF	$20.00	$0	
ROADWAY			TOTAL	$146,706	43%
Landscaping					
Planting area	0.00	SF	$15.00	$0	
	0.00	CY			
Trees	0.00	EA	$3,100.00	$0	
LNDSCPG			TOTAL	$0	0%
Street lights/Traffic Control					
Signing	0.00	EA	$500.00	$0	
Street Lights	0.00	EA	$8,000.00	$0	
Pavement Marking					
Thermoplastic Pavement Markings	15720.00	LF	$3.00	$47,160	
Signals					
New Signals	0.00	EA	$200,000.00	$0	
Concrete Encased Multi Duct	0.00	LF	$100.00	$0	
ST LIGHTS & TRAFFIC DEVICES			TOTAL	$47,160	14%
Stormwater Management					

ponding (6")					
soil					
aggregate base	0.00	SF	$20.00	$0	
underdrain	0.00	SF	$8.00	$0	
Mulch					
Planting area walls					
STRMWTR MGMT			TOTAL	$0	0%
Utility Work					
1. Water	0.00	LF	$138.00	$0	
2. Gas	0.00	LF	$150.00	$0	
3. Power	0.00	LF	$150.00	$0	
4. Communication	0.00	LF	$100.00	$0	
UTILITY			TOTAL	$0	0%
Other Engineering Costs					
MOT (10% of Rdwy cost)	10%	L.S	N/A	$14,671	
Preliminary Design/Engineering (3% of	3%	L.S	N/A	$7,679	
Final Design (7% of total)	7%	L.S	N/A	$17,918	
Construction Management (10% of	5%	L.S	N/A	$12,798	
ENGG COSTS			TOTAL	$53,066	16%
PROJECT COST				$309,036	
CONTINGENCY	0.10	L.S	N/A	$30,904	9%
Ops cost ($ 23,054 / lane mile)					
TOTAL PROJECT COST				$339,940	100%

Reconstruction:

Description	Quantity	Unit	Unit Cost	Amount	% of
1. Grading					
Removal of Existing Surface Pavement	1,035	CY	$60.00	$62,104	
Removal of Existing base Pavement	5,175	CY	$60.00	$310,519	
Removal of Existing Sidewalk	1,164	CY	$60.00	$69,867	
Removal of curb and gutter	320	CY	$60.00	$19,213	
Excavation		CY	$40.00	$0	
Excavation landscaping		CY	$40.00	$0	
Borrow	0	CY	$50.00	$0	
GRADING			TOTAL	$461,702	5%
2. Drainage					
a. Install WQ Inlet	9	EA	$16,000.00	$144,000	
b. Remove Existing Inlet	9	EA	$2,000.00	$18,000	
c. Install 48" I.D. Manhole	5	EA	$8,150.00	$36,675	
d. 18" RCP Pipe	2,818	LF	$130.00	$366,340	
DRAINAGE			TOTAL	$565,015	6%
3. Roadway and Sidewalks					
a. PCC avement, 10"	9,316	SY	$110.00	$1,024,711	
b. 2" Superpave, Type C Hot-MiX	1,467	TON	$100.00	$146,706	
c. 6" Graded Aggregate Base Course	0	SY	$30.00	$0	
d. Curb	10,480	LF	$35.00	$366,800	
e. Portland Cement Concrete Gutter	10,480	LF	$35.00	$366,800	
f. Sidewalk (6ft each side)	62,880	SF	$20.00	$1,257,600	
ROADWAY			TOTAL	$3,162,617	34%
Landscaping					
Planting area	41,920	SF	$15.00	$628,800	
	9,316	CY			
Trees	66	EA	$3,100.00	$203,050	
LNDSCPG			TOTAL	$831,850	9%
Street lights/Traffic Control					
Signing	18	EA	$500.00	$9,000	
Street Lights	26	EA	$8,000.00	$209,600	
Pavement Marking					
Thermoplastic Pavement Markings	15,720	LF	$3.00	$47,160	
Signals					
New Signals	5	EA	$200,000.00	$900,000	
Concrete Encased Multi Duct	1,310	LF	$100.00	$131,000	
ST LIGHTS & TRAFFIC DEVICES			TOTAL	$1,296,760	14%
Stormwater Management					
ponding (6")					

soil	2125	CY	$53.00	$112,631	
aggregate base	1,063	CY	$57.00	$60,566	
underdrain	10,480	LF	$18.00	$188,640	
Mulch	3,634	SY	$2.50	$9,084	
Planting area walls	8,176	LF	$35.00	$286,160	
STRMWTR MGMT			TOTAL	$657,081	7%
Utility Work					
1. Water	0	LF	$138.00	$0	
2. Gas	0	LF	$150.00	$0	
3. Power	0	LF	$150.00	$0	
4. Communication	0	LF	$100.00	$0	
UTILITY			TOTAL	$0	0%
Other Engineering Costs					
MOT (10% of Rdwy cost)	10%	L.S	N/A	$316,262	
Preliminary Design/Engineering (3% of	3%	L.S	N/A	$209,251	
Final Design (7% of total)	7%	L.S	N/A	$488,252	
Construction Management (10% of	5%	L.S	N/A	$348,751	
ENGG COSTS			TOTAL	$1,362,516	15%
PROJECT COST				$8,337,541	
CONTINGENCY	0	L.S	N/A	$833,754	9%
Ops cost ($ 23,054 / lane mile)					
TOTAL PROJECT COST				$9,171,295	100%

LCCA:

Description	Construction	Resurfacing	Reconstruction	Energy	Salvage Value	TOTAL LCCA
1. Grading						
Removal of Existing Surface	$0	$62,104	$62,104		$51,753.09	134,558.02
Removal of Existing base			$310,519		$258,765.43	51,753.09
Removal of Existing	$0	$0	$69,867		$58,222.22	11,644.44
Removal of curb and gutter	$0	$0	$19,213		$16,011.11	3,202.22
Excavation	$734,376	$0	$0		$0.00	734,376.30
Excavation landscaping	$124,207	$0	$0		$0.00	124,207.41
Borrow	$229,493	$0	$0		$0.00	229,492.59
GRADING	$1,088,076	$62,104	$461,702		$384,751.85	1,289,234.07
2. Drainage						
a. Install WQ Inlet	$576,000	$0	$144,000		$120,000.00	600,000.00
b. Remove Existing Inlet	$0	$0	$18,000		$15,000.00	3,000.00
c. Install 48" I.D. Manhole	$146,700	$0	$36,675		$30,562.50	152,812.50
d. 18" RCP Pipe	$1,465,360	$0	$366,340		$305,283.33	1,526,416.67
DRAINAGE	$2,188,060	$0	$565,015		$470,845.83	2,282,229.17
3. Roadway and Sidewalks						
a. PCC Pavement, 10"	$2,049,422	$0	$1,024,711		$853,925.93	2,220,207.41
b. 2" Superpave, Type C	$146,706	$146,706	$146,706		$122,255.16	464,569.61
c. 6" Graded Aggregate Base	$558,933	$0	$0		$0.00	558,933.33
d. Curb	$366,800	$0	$366,800		$305,666.67	427,933.33
e. Portland Cement Concrete	$366,800	$0	$366,800		$305,666.67	427,933.33
f. Sidewalk (6ft each	$1,257,600	$0	$1,257,600		$1,048,000.00	1,467,200.00
ROADWAY	$4,746,262	$146,706	$3,162,617		$2,635,514.42	5,566,777.02
Landscaping						
Planting area	$490,560	$0	$628,800		$524,000.00	595,360.00
					$0.00	0.00
Trees	$812,200	$0	$203,050		$169,208.33	846,041.67
LNDSCPG	$1,302,760	$0	$831,850		$693,208.33	1,441,401.67
Street lights/Traffic						
Signing	$36,000	$0	$9,000		$7,500.00	37,500.00
					$0.00	0.00
Street Lights	$838,400	$0	$209,600	$388,808	$174,666.67	1,262,141.33
Pavement Marking					$0.00	0.00
Thermoplastic Pavement	$47,160	$47,160	$47,160		$39,300.00	149,340.00
Signals					$0.00	0.00
New Signals	$3,600,000	$0	$900,000	$393,750	$750,000.00	4,143,750.00
Concrete Encased Multi Duct	$524,000	$0	$131,000		$109,166.67	545,833.33
ST LIGHTS & TRAFFIC DEVICES	$5,045,560	$47,160	$1,296,760	$782,558	$1,080,633.33	6,138,564.67
Stormwater Management						
ponding (6")					$0.00	0.00

soil	$112,631		$112,631		$93,859.07	131,402.70
aggregate base	$60,566	$0	$60,566		$50,471.39	70,659.94
underdrain	$188,640	$0	$188,640		$157,200.00	220,080.00
Mulch	$9,084		$9,084		$7,570.37	10,598.52
Planting area walls	$286,160		$286,160		$238,466.67	333,853.33
STRMWTR MGMT	$657,081	$0	$657,081		$547,567.50	766,594.50
Utility Work						
1. Water	$0	$0	$0		$0.00	0.00
2. Gas	$0	$0	$0		$0.00	0.00
3. Power	$0	$0	$0		$0.00	0.00
4. Communication	$0	$0	$0		$0.00	0.00
UTILITY	$0	$0	$0		$0.00	0.00
Other Engineering Costs						
MOT (10% of Rdwy cost)	$474,626	$14,671	$316,262	$0	$263,551.44	556,677.70
Preliminary	$450,834	$7,679	$209,251	$23,477	$174,375.64	524,544.03
Final Design (7% of total)	$1,051,946	$17,918	$488,252	$54,779	$406,876.49	1,223,936.08
Construction Management (10%	$751,390	$12,798	$348,751	$39,128	$290,626.06	874,240.05
ENGG COSTS	$2,728,796	$53,066	$1,362,516	$117,384	$1,135,429.63	3,179,397.87
PROJECT COST	$17,756,595	$309,036	$8,337,541	$899,942	$6,947,950.90	20,664,198.96
CONTINGENCY	$1,775,660	$30,904	$833,754	$0	$694,795.09	1,976,425.73
Ops cost ($ 23,054 / lane						713,838.30
TOTAL PROJECT COST	$19,532,255	$339,940	$9,171,295	$899,942	$7,642,745.99	23,354,462.98

LCA:

Construction:

Description	lb CO2/lb	Density lb/CF	Quantity (lb)	Quantity (tons)	tons CO2	% of total	COST OF CO2 $	Waste (tons)
1. Grading								
Removal of Existing Surface Pavement	0.14	106.25	0.00	0	0		$0.00	0.00
Removal of Existing base Pavement	0.127	150.00	0.00	0				0.00
Removal of Existing Sidewalk	0.127	150.00	0.00	0	0		$0.00	0.00
Removal of curb and gutter	0.127	150.00	0.00	0				0.00
Excavation	0.127	150.00	74,355,600.00	36,737	845		$16,899.00	36,736.96
Excavation landscaping	0.023	91.25	7,650,400.00	3,780				3,779.84
Borrow	0.023	91.25	11,308,247.50	5,587	129		$2,570.06	5,587.08
								0.00
GRADING			93,314,247.50	46,104	973	26.53%	$19,469.06	46,103.88
2. Drainage								
a. Install WQ Inlet	0.127	150.00	399,600.00	197	25		$501.47	
b. Remove Existing Inlet	0.127	150.00	0.00	0	0		$0.00	0.00
c. Install 48" I.D. Manhole	0.127	150.00	86,400.00	43	5		$108.43	
d. 18" RCP Pipe	0.127	150.00	1,437,180.00	710	90		$1,803.58	
DRAINAGE			1,923,180.00	950	121	3.29%	$2,413.48	
3. Roadway and Sidewalks								
a. PCC avement, 10"	0.127	150.00	20,960,000.00	10,356	1,315		$26,303.56	
b. 2" Superpave, Type C Hot-MiX	0.14	106.25	2,969,333.33	1,467	205		$4,107.77	
c. 6" Graded Aggregate Base Course	0.017	140.00	11,737,600.00	5,799	99		$1,971.73	
d. Curb	0.127	150.00	1,048,000.00	518	66		$1,315.18	
e. Portland Cement Concrete Gutter	0.127	150.00	1,572,000.00	777	99		$1,972.77	
f. Sidewalk (6ft each side)	0.127	150.00	4,716,000.00	2,330	296		$5,918.30	
ROADWAY			43,002,933.33	21,247	2,079	56.67%	$41,589.31	
Landscaping								
Planting area	0.023	91.25	5,968,480.00	2,949	68		$1,356.47	
Trees			0.00	0	0		$0.00	
LNDSCPG			5,968,480.00	2,949	68	1.85%	$1,356.47	
Street lights/Traffic Control								
Signing	2.53	86.25	1,043.28	1	1		$26.08	
Street Lights	2.7	490.63	89,003.69	44	119		$2,374.60	
Pavement Marking								
Thermoplastic Pavement Markings	3.56	75.00	24,759.00	12	44		$870.97	

Signals								
New Signals	2.7	490.63	15,286.89	8	20		$407.85	
Concrete Encased Multi Duct	0.127	150.00	907,830.00	449	57		$1,139.27	
ST LIGHTS & TRAFFIC DEVICES			1,037,922.87	513	241	6.57%	$4,818.78	
Stormwater Management								
ponding (6")								
soil	0.023	91.25	5,235,742.50	2,587	59.497		$1,189.94	
aggregate base	0.017	140.00	4,016,460.00	1,984	33.735		$674.70	
underdrain	2.5	86.25	19,840.61	10	24.507		$490.13	
Mulch	0.02	31.50	171,696.00	85	1.697		$33.93	
Planting area walls	0.127	65.63	1,073,100.00	530	67.334		$1,346.68	
STRMWTR MGMT			10,516,839.11	5,196	187	5.09%	$3,735.39	
TOTAL PROJECT			**155,763,602.80**	**76,958**	**3,669**		**$73,382.48**	**46,103.88**

Resurfacing:

Description	**lb CO2/lb**	**Density lb/CF**	Quantity(lb)	Quantity (tons)	tons CO2	% of total	COST OF CO2 $	Waste (tons)
1. Grading								
Removal of Existing Surface Pavement	0.14	106.25	2,969,333.33	1,467.06	205.389		$4,107.77	1,467.06
Removal of Existing base Pavement	0.127	150.00	0.00	0.00	0.000		$0.00	0.00
Removal of Existing Sidewalk	0.127	150.00	0.00	0.00	0.000		$0.00	0.00
Removal of curb and gutter	0.127	150.00	0.00	0.00	0.000		$0.00	0.00
Excavation	0.127	150.00	0.00	0.00	0.000		$0.00	0.00
Excavation landscaping	0.023	91.25	0.00	0.00	0.000		$0.00	0.00
Borrow	0.023	91.25	0.00	0.00	0.000		$0.00	0.00
GRADING			2,969,333.33	1,467.06	205.389	45.21%	$4,107.77	1,467.06
2. Drainage								
a. Install WQ Inlet	0.127	150.00	0.00	0.00	0.000		$0.00	
b. Remove Existing Inlet	0.127	150.00	0.00	0.00	0.000		$0.00	
c. Install 48" I.D. Manhole	0.127	150.00	0.00	0.00	0.000			
d. 18" RCP Pipe	0.127	150.00	0.00	0.00	0.000		$0.00	
DRAINAGE			0.00	0.00	0.000	0.00%	$0.00	
3. Roadway and Sidewalks								
a. PCC avement, 10"	0.127	150.00	0.00	0.00	0.000		$0.00	
b. 2" Superpave, Type C Hot-MiX	0.14	106.25	2,969,333.33	1,467.06	205.389		$4,107.77	
c. 6" Graded Aggregate Base Course	0.017	140.00	0.00	0.00	0.000		$0.00	
d. Curb	0.127	150.00	0.00	0.00	0.000		$0.00	
e. Portland Cement Concrete Gutter	0.127	150.00	0.00	0.00	0.000		$0.00	
f. Sidewalk (6ft each side)	0.127	150.00	0.00	0.00	0.000		$0.00	
ROADWAY			2,969,333.33	1,467.06	205.389	45.21%	$4,107.77	
Landscaping								
Planting area	0.023	91.25	0.00	0.00	0.000		$0.00	
				0.00				
Trees			0.00	0.00	0.000		$0.00	
LNDSCPG			0.00	0.00	0.000	0.00%	$0.00	
Street lights/Traffic Control								
Signing	2.53	86.25	0.00	0.00	0.000		$0.00	
				0.00				
Street Lights	2.7	490.63	0.00	0.00	0.000		$0.00	
Pavement Marking				0.00				
Thermoplastic Pavement Markings	3.56	75.00	24,759.00	12.23	43.548		$870.97	12.23
Signals				0.00				
New Signals	2.7	490.63	0.00	0.00	0.000		$0.00	
Concrete Encased Multi Duct	0.127	150.00	0.00	0.00	0.000		$0.00	
ST LIGHTS & TRAFFIC DEVICES			24,759.00	12.23	43.548	9.59%	$870.97	12.23

Stormwater Management

ponding (6")								
soil	0.023	91.25	0.00	0	0.000		$0.00	0.00
aggregate base	0.017	140.00	0.00	0	0.000		$0.00	
underdrain	2.5	86.25	0.00	0	0.000		$0.00	
Mulch	0.02	31.50	0.00	0	0.000		$0.00	0.00
Planting area walls	0.127	65.63	0.00	0	0.000		$0.00	
STRMWTR MGMT			0.00	0.00	0.000	0.00%	$0.00	0.00
TOTAL PROJECT			5,963,425.67	2,946.36	454.326		$9,086.52	1,479.29

Reconstruction:

Description	lb CO2/lb	Density lb/CF	Quantity(lb)	Quantity (tons)	tons CO2	% of total	COST OF CO2 $	Waste (tons)
1. Grading								
Removal of Existing Surface Pavement	0.14	106.25	2,969,333.33	1,467.06	205.389		$4,107.77	1,467.06
Removal of Existing base Pavement	0.127	150.00	20,960,000.00	10,355.73	1315.178		$26,303.56	10,355.73
Removal of Existing Sidewalk	0.127	150.00	4,716,000.00	2,330.04	295.915		$5,918.30	2,330.04
Removal of curb and gutter	0.127	150.00	1,296,900.00	640.76	81.377		$1,627.53	640.76
Excavation	0.127	150.00	0.00	0.00	0.000		$0.00	0.00
Excavation landscaping	0.023	91.25	0.00	0.00	0.000		$0.00	0.00
Borrow	0.023	91.25	0.00	0.00	0.000		$0.00	0.00
GRADING			29,942,233.33	14,793.59	1897.858	53.36%	$37,957.16	14,793.59
2. Drainage								
a. Install WQ Inlet	0.127	150.00	99,900.00	49.36	6.268		$125.37	
b. Remove Existing Inlet	0.127	150.00	99,900.00	49.36	6.268		$125.37	49.36
c. Install 48" I.D. Manhole	0.127	150.00	21,600.00	10.67	1.355		$27.11	10.67
d. 18" RCP Pipe	0.127	150.00	359,295.00	177.52	22.545		$450.89	177.52
DRAINAGE			580,695.00	286.90	36.437	1.02%	$728.74	237.55
3. Roadway and Sidewalks								
a. PCC avement, 10"	0.127	150.00	10,480,000.00	5,177.87	657.589		$13,151.78	
b. 2" Superpave, Type C Hot-MiX	0.14	106.25	2,969,333.33	1,467.06	205.389		$4,107.77	
c. 6" Graded Aggregate Base Course	0.017	140.00	0.00	0.00	0.000		$0.00	
d. Curb	0.127	150.00	1,048,000.00	517.79	65.759		$1,315.18	
e. Portland Cement Concrete Gutter	0.127	150.00	1,572,000.00	776.68	98.638		$1,972.77	
f. Sidewalk (6ft each side)	0.127	150.00	4,716,000.00	2,330.04	295.915		$5,918.30	
ROADWAY			20,785,333.33	10,269.43	1323.290	37.20%	$26,465.80	0.00
Landscaping								
Planting area	0.023	91.25	7,650,400.00	3,779.84	86.936		$1,738.73	3,779.84
				0.00				
Trees			0.00	0.00	0.000		$0.00	0.00
LNDSCPG			7,650,400.00	3,779.84	86.936	2.44%	$1,738.73	3,779.84
Street lights/Traffic Control								
Signing	2.53	86.25	260.82	0.13	0.326		$6.52	0.13
				0.00				
Street Lights	2.7	490.63	22,250.92	10.99	29.683		$593.65	10.99
Pavement Marking				0.00				
Thermoplastic Pavement Markings	3.56	75.00	24,759.00	12.23	43.548		$870.97	12.23
Signals				0.00				
New Signals	2.7	490.63	3,821.72	1.89	5.098		$101.96	1.89
Concrete Encased Multi Duct	0.127	150.00	226,957.50	112.13	14.241		$284.82	112.13
ST LIGHTS & TRAFFIC DEVICES			278,049.97	137.38	92.896	2.61%	$1,857.92	137.38

Stormwater Management								
ponding (6")								
soil	0.023	91.25	5,235,742.50	2,586.83	59.497		$1,189.94	2,586.83
aggregate base	0.017	140.00	4,016,460.00	1,984.42	33.735		$674.70	1,984.42
underdrain	2.5	86.25	19,840.61	9.80	24.507		$490.13	9.80
Mulch	0.02	31.50	171,696.00	84.83	1.697		$33.93	84.83
Planting area walls	0.127	65.63	0.00	0.00	0.000		$0.00	0.00
STRMWTR MGMT **TOTAL PROJECT**			9,443,739.11	4,665.88	119.435	3.36%	$2,388.71	4,665.88

LCA:

Description	Total LCA CO2 (tons)	CO2 ($)	MG	Cost $	Quantity (tons)	Cost $	TOTAL LCA COST ($)
1. Grading							
Removal of Existing Surface	445.01	$8,900.18			4,401.19	$233,262.85	$242,163.02
Removal of Existing base	219.20	$4,383.93			10,355.73	$548,853.75	$553,237.68
Removal of Existing Sidewalk	49.32	$986.38			2,330.04	$123,492.09	$124,478.48
Removal of curb and gutter	13.56	$271.26			640.76	$33,960.33	$34,231.58
Excavation	844.95	$16,899.00			36,736.96	$1,947,058.70	$1,963,957.70
Excavation landscaping	0.00	$0.00			3,779.84	$200,331.62	$200,331.62
Borrow	128.50	$2,570.06			5,587.08	$296,115.18	$298,685.23
		$0.00					
GRADING	1,700.54	$34,010.80			63,831.59	$3,383,074.51	$3,417,085.31
2. Drainage							
a. Install WQ Inlet	26.12	$522.37			0.00	$0.00	$522.37
b. Remove Existing Inlet	1.04	$20.89			49.36	$2,615.96	$2,636.85
c. Install 48" I.D. Manhole	5.65	$112.94			10.67	$565.61	$678.56
d. 18" RCP Pipe	93.94	$1,878.72			177.52	$9,408.42	$11,287.14
DRAINAGE	126.75	$2,534.93			237.55	$12,589.99	$15,124.92
3. Roadway and Sidewalks							
a. PCC avement, 10"	1,424.78	$28,495.52	139.0123	$910,530.63	0.00	$0.00	$939,026.15
b. 2" Superpave, Type C Hot-MiX	650.40	$13,007.95	0.0000	$0.00	0.00	$0.00	$13,007.95
c. 6" Graded Aggregate Base	98.59	$1,971.73	0.0000	$0.00	0.00	$0.00	$1,971.73
d. Curb	76.72	$1,534.37	8.6883	$56,908.16	0.00	$0.00	$58,442.54
e. Portland Cement Concrete	115.08	$2,301.56	8.6883	$56,908.16	0.00	$0.00	$59,209.73
f. Sidewalk (6ft each side)	345.23	$6,904.68	52.1296	$341,448.98	0.00	$0.00	$348,353.67

ROADWAY	2,710.79	$54,215.82	208.5185	$1,365,795.94	0.00	$0.00	$1,420,011.76
Landscaping							
Planting area	82.31	$1,646.26	0.0000		3,779.84	$200,331.62	$201,977.88
	0.00				0.00	$0.00	$0.00
Trees	0.00	$0.00			0.00	$0.00	$0.00
LNDSCPG	82.31	$1,646.26	0.0000		3,779.84	$200,331.62	$201,977.88
Street lights/Traffic Control							
Signing	1.36	$27.17			0.13	$6.83	$34.00
	0.00				0.00		
Street Lights	4,670.37	$93,407.47			10.99	$582.66	$93,990.13
Pavement Marking	0.00				0.00		
Thermoplastic Pavement Markings	137.90	$2,758.07			36.70	$1,945.00	$4,703.07
Signals	0.00				0.00		
New Signals	802.16	$16,043.27			1.89	$100.07	$16,143.34
Concrete Encased Multi Duct	59.34	$1,186.74			112.13	$5,943.06	$7,129.80
ST LIGHTS & TRAFFIC DEVICES	5,671.14	$113,422.72			161.84	$8,577.62	$122,000.34
Stormwater Management							
ponding (6")	0.00				0.00		
soil	69.41	$1,388.27			2,586.83	$137,101.95	$138,490.22
aggregate base	39.36	$787.15			1,984.42	$496.10	$1,283.26
underdrain	28.59	$571.82			9.80	$343.09	$914.92
Mulch	1.98	$39.59			84.83	$555,636.76	$555,676.35
Planting area walls	67.33	$1,346.68			0.00	$0.00	$1,346.68
STRMWTR MGMT	206.68	$4,133.50			4,665.88	$247,291.59	$251,425.09
TOTAL PROJECT	10,498.20	$209,964.03	208.5185	$1,365,795.94	2,676.70	$3,851,865.33	
$5,247625.30							

ILCA2

Description	LCCA	LCA	TOTAL
1. Grading			
Removal of Existing Surface Pavement	$134,558.02	$242,163.02	$376,721.05
Removal of Existing base Pavement			
Removal of Existing Sidewalk	$11,644.44	$124,478.48	$136,122.92
Removal of curb and gutter			
Excavation(2sw+2g+2c+bike+lne)	$734,376.30	$1,963,957.70	$2,698,333.99
Excavation landscaping			
Borrow	$229,492.59	$298,685.23	$528,177.83
	$0.00	$0.00	
GRADING	$1,289,234.07	$3,417,085.31	$4,706,319.39
2. Drainage (chap 33)	$0.00	$0.00	
a. Install WQ Inlet (1 per block each side)	$600,000.00	$522.37	$600,522.37
b. Remove Existing Inlet	$3,000.00	$2,636.85	$5,636.85
c. Install 48" I.D. Manhole (1 per block)	$152,812.50	$678.56	$153,491.06
d. 18" RCP Pipe	$1,526,416.67	$11,287.14	$1,537,703.81
	$0.00	$0.00	
DRAINAGE	$2,282,229.17	$15,124.92	$2,297,354.09
3. Roadway and Sidewalks	$0.00	$0.00	
a. Portland Cement Concrete Pavement, 10"	$2,220,207.41	$939,026.15	$3,159,233.55
b. 2" Superpave, Type C Hot-MiX	$464,569.61	$13,007.95	$477,577.56
c. 6" Graded Aggregate Base Course	$558,933.33	$1,971.73	$560,905.06
d. Curb	$427,933.33	$58,442.54	$486,375.87
e. Portland Cement Concrete Gutter	$427,933.33	$59,209.73	$487,143.06
f. Sidewalk (6ft each side)	$1,467,200.00	$348,353.67	$1,815,553.67
	$0.00	$0.00	

ROADWAY	$5,566,777.02	$1,420,011.76	$6,986,788.78
Landscaping (chap 47)	$0.00	$0.00	
Planting area (4 ft wide)	$595,360.00	$201,977.88	$797,337.88
(2 ft depth)	$0.00	$0.00	
Trees (assume 6" caliper)	$846,041.67	$0.00	$846,041.67
Landscaping	$1,441,401.67	$201,977.88	$1,643,379.55
Street lights and Traffic Control Devices	$0.00	$0.00	
Signing	$37,500.00	$34.00	$37,534.00
Street Lights	$0.00	$0.00	
Sidewalk (Washington Globe twin-20 19' pole)	$1,262,141.33	$93,990.13	$1,356,131.46
Pavement Marking	$0.00	$0.00	
Thermoplastic Pavement Markings	$149,340.00	$4,703.07	$154,043.07
Signals	$0.00	$0.00	
New Signals	$4,143,750.00	$16,143.34	$4,159,893.34
Concrete Encased Multi Duct (4)	$545,833.33	$7,129.80	$552,963.13
	$0.00	$0.00	
Street Lights & Traffic Devices	$6,138,564.67	$122,000.34	$6,260,565.00
Stormwater Management			
ponding (6")			
soil	$131,402.70	$138,490.22	$269,892.92
aggregate base	$70,659.94	$1,283.26	$71,943.20
underdrain	$220,080.00	$914.92	$220,994.92
Mulch	$10,598.52	$555,676.35	$566,274.86
Planting area walls	$333,853.33	$1,346.68	$335,200.01
LID	$766,594.50	$251,425.09	$1,018,019.59
TOTAL PROJECT COST	**$23,354,462.98**	**$5,427,625.30**	**$28,782,088.28**

STIP:

Project Name	**Lanes**	**Length**	**Bike Lanes**	**Cost**	**LCCA Cost**	**LCA Cost**	**ILCA2 Cost**
	number	**Miles**	**number**	**$**	**$**	**$**	**$**
CONSTRUCTION							
Project 1	2	1	2	$19,532,254.58	$23,354,462.98	$5,427,625.30	$28,782,088.28
Project 2	8	1.3	0	$45,286,530.28	$65,094,717.26	$21,092,212.50	$86,186,929.76
MAINTENANCE/RESURFACING							
Project 3	6	115	2	$92,560,144.79	$3,994,580,026.31	$1,170,422,524.78	$5,165,002,551.10
Project 4	6	20.2	2	$16,258,390.65	$701,656,665.49	$205,587,260.87	$907,243,926.37
RECONSTRUCTION							
Project 5	4	10.8	2	$116,028,869.96	$313,685,683.94	$84,268,147.35	$397,953,831.30
Project 6	6	0.75	0	$8,725,358.75	$24,751,002.13	$6,824,877.03	$31,575,879.16
Project 7	5	0.25	2	$2,882,368.31	$7,972,556.15	$2,247,524.18	$10,220,080.33
Project 8	6	0.853	2	$10,505,149.29	$29,629,363.15	$8,681,481.86	$38,310,845.01
Project 9	4	0.21	2	$2,256,116.92	$6,099,443.85	$1,638,547.31	$7,737,991.16
Project 10	4	4.2	0	$42,259,110.52	$114,705,479.35	$28,244,391.43	$142,949,870.78
Project 11	8	0.5	2	$6,943,825.63	$20,212,993.12	$6,276,284.05	$26,489,277.18
Project 12	4	1.5	2	$16,115,120.83	$43,567,456.10	$11,703,909.35	$55,271,365.46
Project 13	4	0.7	2	$7,520,389.72	$20,331,479.51	$5,461,824.37	$25,793,303.88
Project 14	6	1.12	2	$13,793,396.49	$38,903,735.91	$11,398,897.63	$50,302,633.54
TOTAL	5.5	158.383		$400,667,026.72	$5,404,545,065.27	$1,569,275,508.03	$6,973,820,573.30

Project Name	CO2 EQ Tons	LCA CO2 EQ Tons	LCA CO2 Cost $	LCA STRMWTR MG	LCA STRMWTR Cost $	LID COST $	DRAINAGE COST $
CONSTRUCTION							
Project 1	3,669.12	10,498.20	$209,964.03	208.52	1,365,795.94	766,594.50	2,282,229.17
Project 2	14,437.56	28,721.03	$574,420.52	835.81	5,474,565.39	1,369,149.04	3,664,022.92
MAINTENANCE/RESURFACING							
Project 3	123,879.06	1,791,728.56	$35,834,571.13	45,960.94	301,044,188.27	102,660,179.14	287,123,854.17
Project 4	21,759.63	314,721.02	$6,294,420.32	8,073.14	52,879,066.11	18,032,483.64	50,433,929.17
RECONSTRUCTION							
Project 5	56,921.17	140,823.63	$2,816,472.59	3,284.17	21,511,286.04	8,960,175.23	25,806,375.00
Project 6	4,664.33	10,852.52	$217,050.40	267.16	1,749,926.05	648,028.13	1,872,546.88
Project 7	1,531.82	3,577.43	$71,548.68	87.97	576,195.16	215,292.88	610,776.04
Project 8	5,957.44	13,289.95	$265,799.04	340.91	2,232,962.54	761,470.72	2,129,709.98
Project 9	1,106.80	2,738.24	$54,764.74	63.86	418,275.01	174,225.63	501,790.63
Project 10	18,922.99	50,101.81	$1,002,036.28	1,094.72	7,170,428.68	3,364,141.82	10,035,812.50
Project 11	4,348.87	9,060.64	$181,212.72	247.62	1,621,882.68	477,874.28	1,301,989.58
Project 12	7,905.72	19,558.84	$391,176.75	456.13	2,987,678.62	1,244,468.78	3,584,218.75
Project 13	3,689.34	9,127.46	$182,549.15	212.86	1,394,250.02	580,752.10	1,672,635.42
Project 14	7,822.20	17,449.88	$348,997.56	447.62	2,931,908.62	999,820.88	2,796,336.67
TOTAL	276,616.04	2,422,249.20	$48,444,983.92	61,581.44	$403,358,409.12	$140,254,656.77	$393,816,226.85

Project Name	STIP WASTE MAT TONS	LCA WASTE MAT TONS	LCA WASTE Cost $	LCA Energy CO2	LCA Energy Cost $
CONSTRUCTION					
Project 1	46,103.88	72,676.70	3,851,865.33	5,327.62	106,552.35
Project 2	176,259.03	283,834.46	15,043,226.59	6,925.90	138,518.05
MAINTENANCE/RESURFACING					
Project 3	403,973.73	15,727,240.86	833,543,765.39	612,675.99	12,253,519.85
Project 4	70,958.86	2,762,524.05	146,413,774.44	107,617.87	2,152,357.40
RECONSTRUCTION					
Project 5	366,509.62	1,130,950.73	59,940,388.72	57,538.27	1,150,765.34
Project 6	29,681.66	91,658.50	4,857,900.58	3,995.71	79,914.26
Project 7	9,774.25	30,184.53	1,599,780.33	1,331.90	26,638.09
Project 8	37,752.00	116,655.10	6,182,720.28	4,544.46	90,889.15
Project 9	7,126.58	21,990.71	1,165,507.56	1,118.80	22,375.99
Project 10	122,865.57	378,715.59	20,071,926.47	22,375.99	447,519.86
Project 11	27,289.88	84,399.79	4,473,188.66	2,663.81	53,276.17
Project 12	50,904.11	157,076.49	8,325,053.99	7,991.43	159,828.52
Project 13	23,755.25	73,302.36	3,885,025.19	3,729.33	74,586.64
Project 14	49,568.86	153,169.65	8,117,991.45	5,966.93	119,338.63
TOTAL	1,422,523.27	21,084,379.53	$1,117,472,114.9 9	843,804.02	$16,876,080.31

Appendix 3

Integrated Life Cycle Analysis Approach ($ILCA^2$) Tool

User Manual

TABLE OF CONTENTS

Glossary:

EC	Energy Costs
Eq.	Equivalent
CO_2	Carbon Dioxide
CFC	Carbon footprint Costs
GWP	Global Warming Potential
JDK	Java Development Kit
IC	Initial Capital Cost
IDE	Integrated Development Environment
$ILCA^2$	Integrated Life Cycle Analysis Approach
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
RSC	Resurfacing Costs
RCC	Reconstruction Costs
OC	Operation Costs
SWC	Solid Wastes Costs
SRC	Storm water runoff Costs

1 Introduction:

Integrated life cycle analysis approach ($ILCA^2$) is a methodology that integrates life cycle impacts and life cycle costs for transportation projects. $ILCA^2$ establishes a common set of characteristics which include the scope, temporal boundary, and spatial boundary. The scope includes construction, resurfacing and reconstruction of urban streets. The temporal scope is the life cycle of the roadway which is defined as 35 years. The spatial boundary includes both length and cross section. $ILCA^2$ is illustrated in Figure 1.

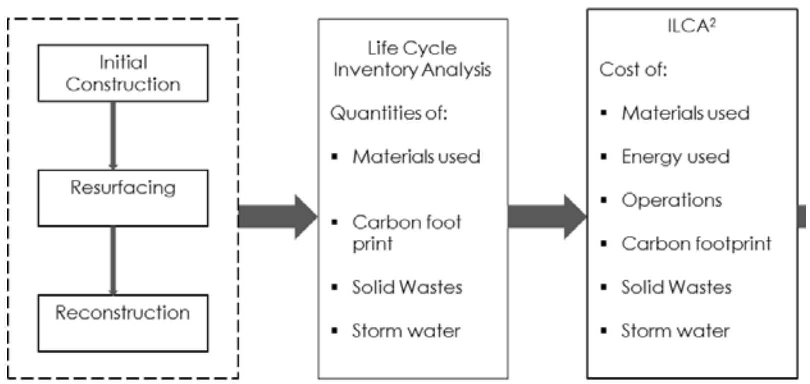


Figure 1: Integrated Life cycle Analysis Approach ($ILCA^2$)

The integrated life cycle costs are calculated as:

$$ILCA^2 = \Sigma CFC + \Sigma SWC + \Sigma SRC + IC + \Sigma\ RSC + \Sigma\ RCC + \Sigma\ OC + \Sigma\ EC - SV \qquad (8)$$

Where,
CFC = Carbon footprint costs
SWC = Solid Wastes costs
SRC = Storm water runoff costs
IC= Initial Capital Cost which includes planning, design and construction cost
RSC = Resurfacing Costs
RCC = Reconstruction Costs
OC = Operation Costs
EC = Energy Costs
SV = Salvage Value

The material quantities are calculated by using the standard materials needed for roadway construction, resurfacing and reconstruction. The life cycle impact costs are based on the costs of the carbon foot print of the materials used as tons of CO_2 equivalent, Storm water runoff from the facility and Solid waste materials. The life cycle costs are calculated for initial construction, resurfacing and construction based on the quantities of the materials, energy used for streetlights and signal for 35 years. $ILCA^2$ does not include the user costs.

2 ILCA² tool overview:

ILCA² was used to develop a decision support tool in Java programming with a user interface. This tool requires length of the project in miles, number of vehicle lanes and the number of bicycle lanes as inputs. These inputs are used by this tool to perform integrated life cycle analysis to provide:

- Carbon foot print of the roadway as tons of CO2 equivalent
- Storm water runoff as million gallons
- Solid wastes as tons of solid wastes
- Costs of Carbon foot print, Storm water runoff, and Solid wastes in dollars
- Life cycle costs in dollars
- Integrated life cycle costs in dollars

The output of the tool also includes the estimates of the quantities of the materials needed for roadway construction, resurfacing and reconstruction. The outputs also give the results for construction, resurfacing and reconstruction separately as well as for the life cycle to provide comparison.

3 System Requirements:

The ILCA2 tool has been developed using a Java Development Kit (JDK) called NetBeans Integrated Development Environment (IDE) 7.3 by Sun Microsystems. The NetBeans development tool has a compiler and its source code editor function was used as the text editor (source code editor). Use of NetBeans development tool provides several benefits such as line numbering, line indenting, error resolution hints, error highlights, color highlights, and simple and easy to use text editor.

NetBeans IDE runs on operating systems that support the Java VM (Virtual Machine) which include Microsoft Windows XP Professional SP3/Vista SP1/Windows 7 Professional, Macintosh OS X 10.6 Intel and Solaris OS version 11 Express. The NetBeans IDE supported Operating Systems with minimum hardware configurations are given below:

Microsoft Windows XP Professional SP3/Vista SP1/Windows 7 Professional:
Processor: 800MHz Intel Pentium III or equivalent
Memory: 512 MB
Disk space: 750 MB of free disk space

Solaris OS version 11 Express (SPARC):
Processor: UltraSPARC II 450 MHz
Memory: 512 MB
Disk space: 650 MB of free disk space

Macintosh OS X 10.6 Intel:
Processor: Dual-Core Intel (32 or 64-bit)
Memory: 1 GB
Disk space: 650 MB of free disk space

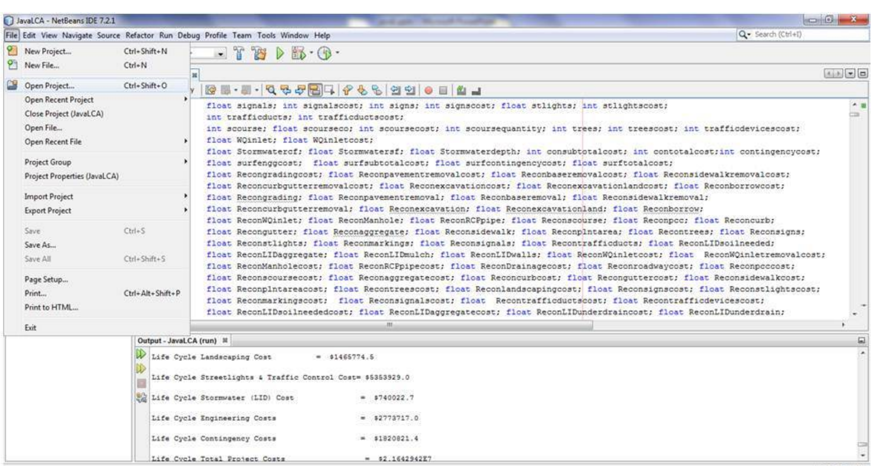
4 Getting Started:

In order to install and run ILCA2 tool, NetBeans IDE by Sun Microsystems is needed. NetBeans IDE can be downloaded free of cost from the NetBeans website: www.netbeans.org. Follow the instructions on the website for download. The systems requirements are given in the section 3. Once NetBeans has been installed on the computer, ILCA^2 tool programming code can be saved in the editor function.

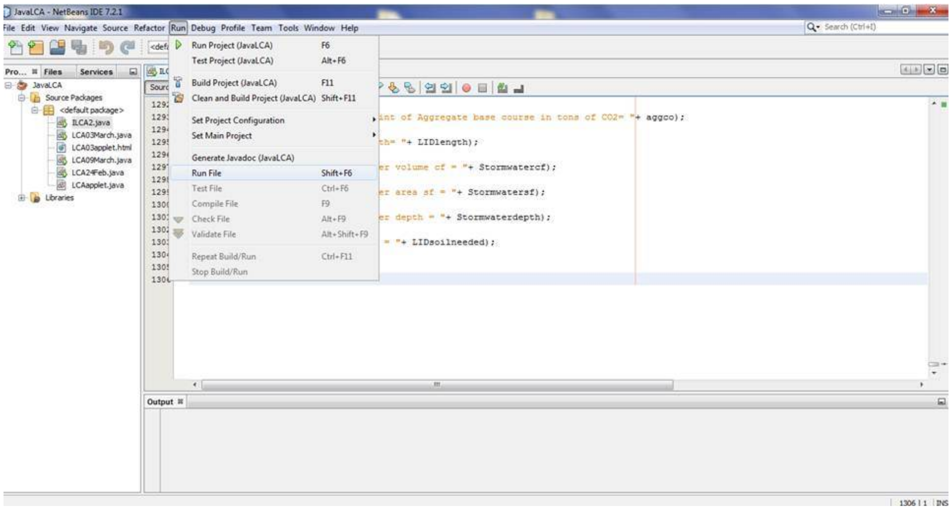
5 Running ILCA2 tool:

In order to run the tool, follow the steps given below:

1. Install NetBeans IDE 7.3 or later version
2. Open NetBeans IDE tool kit
3. Open the ILCA^2 program code by clicking “File” and then “open project”.



4. Select ILCA2.java and Open
5. Click “Run” tab and then select “Run File”



6. Computer screen shows “Welcome to ILCA2”
7. Enter the number of lanes
8. Enter number of miles
9. Enter number of bike lanes

The program runs after number of bike lanes are entered and shows results on the screen.

6 Outputs:

The outputs include:

1. Carbon foot print: tons of CO2 equivalent
2. Storm water runoff: million gallons
3. Solid wastes: tons of solid wastes
4. Costs of: Carbon foot print, Storm water runoff
5. Life cycle costs
6. Integrated life cycle costs

7 References:

NetBeans IDE 7.3 Release Notes:
https://netbeans.org/community/releases/73/relnotes.html#system_requirements

Appendix 4

Java code for ILCA^2

```
import java.util.Scanner;

 //Integrated Life Cycle Analysis Approach (ILCA2)MODEL
//Developed by Faisal Hameed

class ILCA2userinput
{
   public static void main(String args[])
   {
      float area; float areasqy; float blanes; float aggbase; int
aggregatecost; int Conexcavation; int Conexcavationcost; int
Conexcavationland; int Conexcavationlandcost;
      int Conborrow; int Conborrowcost; int Congradingcost; int curbvol; int
curb; int curbcost; int Drainagecost; int enggcost; int gutter;
      int guttervol; int guttercost; float aggco; float intersections; float
lanes; float length; int LIDcost; int LIDlength; int landscapingcost;
      int LIDsoilneeded; int LIDaggregate; int LIDunderdrain; int LIDmulch;
int LIDwalls;
      int LIDsoilneededcost; int LIDaggregatecost; int LIDunderdraincost; int
LIDmulchcost; int LIDwallscost;
      int Manhole;int Manholecost ; int markings; int markingscost; float
miles; float pcc; float pccmat; float pccco; int pcccost; int pccquantity;
int pccquantitySY; int plntarea; int plntareacost;
      float Resurpavementremovalcost; float Resurpavementremoval;
      int RCPpipe; int RCPpipecost; int roadwaycost; int sidewalk; int
sidewalkvol; int sidewalkcost;
      float signals; int signalscost; int signs; int signscost; float
stlights; int stlightscost;
      int trafficducts; int trafficductscost;
      int scourse; float scourseco; int scoursecost; int scoursequantity; int
trees; int treescost; int trafficdevicescost;
      float WQinlet; float WQinletcost;
      float Stormwatercf; float Stormwatersf; float Stormwaterdepth; int
consubtotalcost; int contotalcost;int contingencycost;
      float surfenggcost;  float surfsubtotalcost; float surfcontingencycost;
float surftotalcost;
      float Recongradingcost; float Reconpavementremovalcost; float
Reconbaseremovalcost; float Reconsidewalkremovalcost;
      float Reconcurbgutterremovalcost; float Reconexcavationcost; float
Reconexcavationlandcost; float Reconborrowcost;
      float Recongrading; float Reconpavementremoval; float Reconbaseremoval;
float Reconsidewalkremoval;
```

```
	float Reconcurbgutterremoval; float Reconexcavation; float
Reconexcavationland; float Reconborrow;
	float ReconWQinlet; float ReconManhole; float ReconRCPpipe; float
Reconscourse; float Reconpcc; float Reconcurb;
	float Recongutter; float Reconaggregate; float Reconsidewalk; float
Reconplntarea; float Recontrees; float Reconsigns;
	float Reconstlights; float Reconmarkings; float Reconsignals; float
Recontrafficducts; float ReconLIDsoilneeded;
	float ReconLIDaggregate; float ReconLIDmulch; float ReconLIDwalls;
float ReconWQinletcost; float  ReconWQinletremovalcost;
	float ReconManholecost; float ReconRCPpipecost; float
ReconDrainagecost; float Reconroadwaycost; float Reconpcccost;
	float Reconscoursecost; float Reconaggregatecost; float Reconcurbcost;
float Recongguttercost; float Reconsidewalkcost;
	float Reconplntareacost; float Recontreescost; float
Reconlandscapingcost; float Reconsignscost; float Reconstlightscost;
	float Reconmarkingscost;  float Reconsignalscost; float
Recontrafficductscost; float Recontrafficdevicescost;
	float ReconLIDsoilneededcost; float ReconLIDaggregatecost; float
ReconLIDunderdraincost; float ReconLIDunderdrain;
	float ReconLIDmulchcost; float ReconLIDwallscost; float ReconLIDcost;
float Reconenggcost; float Reconsubtotalcost;
	float Reconcontingencycost; float Recontotalcost; float Energycost;
float Energylightscost; float Energysignalscost;
	float LifeEnergytotalcost; float  Energyenggcost; float
SVRecongradingcost; float SVReconpavementremovalcost;
	float SVReconbaseremovalcost; float SVReconsidewalkremovalcost; float
SVReconcurbgutterremovalcost; float SVReconexcavationcost;
	float SVReconexcavationlandcost; float SVReconborrowcost; float
SVReconDrainagecost; float SVReconWQinletcost;
	float SVReconWQinletremovalcost; float SVReconManholecost; float
SVReconRCPpipecost; float SVReconroadwaycost;
	float SVReconpcccost; float SVReconscoursecost; float
SVReconaggregatecost; float SVReconcurbcost; float SVRecongguttercost;
	float SVReconsidewalkcost;float SVReconlandscapingcost; float
SVReconplntareacost; float SVRecontreescost;
	float SVRecontrafficdevicescost; float SVReconsignscost; float
SVReconstlightscost; float SVReconmarkingscost;
	float SVReconsignalscost; float SVRecontrafficductscost; float
SVReconLIDcost; float SVReconLIDsoilneededcost;
	float SVReconLIDaggregatecost; float SVReconLIDunderdraincost; float
SVReconLIDmulchcost; float SVReconLIDwallscost;
	float SVRecontotalcost; float SVReconsubtotalcost; float
RSVeconcontingencycost; float SVReconcontingencycost;
	float SVReconenggcost; float LCCAtotalcosttest; float LCCAgradingcost;
float LCCADrainagecost; float LCCAroadwaycost;
	float LCCAlandscapingcost; float LCCAtrafficdevicescost; float
LCCALIDcost; float LCCAenggcost; float LCCAcontingencycost;
	float LCCAtotalcost; float plntmat; float plntco;
	float Congradmat; float Conexcavationmat; float Conexcavationlandmat;
float Conborrowmat; float Congradco;
	float Conexcavationco; float Conexcavationlandco; float Conborrowco;
float  Drainagemat; float WQinletmat;
	float Manholemat; float RCPpipemat; float Drainageco; float WQinletco;
float Manholeco; float RCPpipeco;
	float roadwaymat; float scoursemat; float aggbasemat; float curbmat;
float guttermat; float sidewalkmat;
```

```
      float roadwayco; float aggbaseco; float curbco; float gutterco; float 
sidewalkco;
      float LIDsoilneededmat; float LIDaggregatemat; float LIDunderdrainmat; 
float LIDmulchmat; float LIDmat;
      float LIDco; float LIDsoilneededco; float LIDaggregateco; float 
LIDunderdrainco; float LIDmulchco; float LIDwallsco; float LIDwallsmat;
      float Stlightssignalsmat; float signsmat; float stlightsmat; float 
markingsmat; float signalsmat; float trafficductsmat;
      float Stlightssignalsco; float signsco; float stlightsco; float 
markingsco; float signalsco; float trafficductsco;
      float contotalmat; float contotalco; float resurftotalmat; float 
Resurpavementremovalmat; float resurftotalco;
      float Resurpavementremovalco;float Reconpavementremovalmat; float 
Reconpavementremovalco;
      float Reconbaseremovalco; float Reconbaseremovalmat; float 
Reconsidewalkremovalmat; float Reconsidewalkremovalco;
      float Recongradingmat; float Reconcurbgutterremovalmat; float 
Recongradingco; float Reconcurbgutterremovalco;
      float Recondrainagemat; float ReconWQinletmat; float ReconManholemat; 
float ReconRCPpipemat;
      float Recondrainageco; float ReconWQinletco;  float ReconManholeco; 
float ReconRCPpipeco;
      float Reconroadwaymat; float Reconscoursemat; float Reconpccmat; float 
Reconcurbmat; float Recongruttermat;
      float Reconsidewalkmat; float Reconroadwayco;  float Reconscourseco; 
float Reconpccco; float Reconcurbco;
      float Recongutterco; float Reconsidewalkco; float Reconplntmat; float 
Reconplntco;
      float Reconstlightssignalsmat; float Reconsignsmat; float 
Reconstlightsmat; float Reconmarkingsmat;
      float Reconsignalsmat; float Recontrafficductsmat; float 
Reconstlightssignalsco; float Reconsignsco;
      float Reconstlightsco; float Reconmarkingsco; float Reconsignalsco; 
float Recontrafficductsco;
      float ReconLIDmat; float ReconLIDsoilneededmat; float 
ReconLIDaggregatemat; float ReconLIDunderdrainmat;
      float ReconLIDmulchmat; float ReconLIDco; float ReconLIDsoilneededco; 
float ReconLIDaggregateco;
      float ReconLIDunderdrainco; float ReconLIDmulchco; float 
Reconcontotalmat; float Reconcontotalco;
      float  Lifeenergy; float Lifeenergyco;
      float LCAmat; float LCAco;float LCAcocost;float contotalcocost; float 
resurftotalcocost;
      float Reconcontotalcocost; float Lifeenergycocost; float 
LCAstormwatercost; float LCAstormwater;
      float   runoffarea; float runoffareagallonconversion; float 
totalILCA2cost; float totalLCAcost;
      float LCAwastematerials; float conswastematerial; float 
resurfwastematerial; float Reconwastematerial;
      float LCAwastematerialscost; float conswastematerialcost; float 
resurfwastematerialcost; float Reconwastematerialcost;

      Scanner in = new Scanner(System.in);

      System.out.println("Welcome to Integrated Life Cycle Analysis 
Approach(ILCA2)MODEL");
      System.out.println("");
```

```
      System.out.println("Enter number of vehicular lanes");
      lanes = in.nextInt();
      System.out.println("Enter number of miles");
      miles = in.nextInt();
      System.out.println("Enter number of Bike lanes");
      blanes = in.nextInt();
      area = (lanes *11 + blanes * 5) * miles * 5240;
      areasqy = area/9;
      length = miles*5240;
      intersections = miles*18;
      LIDlength = (int) ((float) length - (intersections* (lanes *11 + blanes
* 5 + 12 ) + intersections * 20 ));
      Stormwatercf = (float)((1.2/12)*(((0.95*((lanes *11) + (blanes * 5) +
12))+(0.25*8))* miles* 5240));
      Stormwatersf = 8*LIDlength;
      Stormwaterdepth= (float) (Stormwatercf/Stormwatersf)*1;

      //CONSTRUCTION
      //Grading
      Conexcavation = (int)((lanes *11 + blanes * 5 + 12 + 2 + 1.3)* miles*
5240 * 2)/27;
      Conexcavationmat= (float)((Conexcavation*27*150)/2024);
      Conexcavationco= (float)(float)(Conexcavationmat*0.023);
      Conexcavationland = (int)(8* miles* 5240 * 2)/27;
      Conexcavationlandmat=
(float)(float)((Conexcavationland*27*91.50)/2024);
      Conexcavationlandco= (float)(float)(Conexcavationlandmat*0.023);
      Conborrow = (int)((lanes *11 + blanes * 5 + 12 + 2 + 1.3)* miles* 5240
* 0.5)/27;
      Conborrowmat= (float)(float)((Conborrow*27*91.50)/2024);
      Conborrowco= (float)(float)(Conborrowmat*0.023);
      Congradmat =
(float)(Conexcavationmat+Conexcavationlandmat+Conborrowmat);
      Congradco=(float) (Conexcavationco+Conborrowco);


      //Draiange
      WQinlet = 18*2*miles;
      WQinletmat = (float) ((WQinlet*74*150)/2024);
      WQinletco = (float) (WQinletmat*0.127);
      Manhole = (int)(float)(18*miles);
      Manholemat = (float) ((Manhole *32*150)/2024);
      Manholeco = (float) (Manholemat*0.127);
      RCPpipe= (int)(float)(float) ((miles*5240*2)+(WQinlet*lanes*11));
      RCPpipemat = (float)((RCPpipe*0.85*150)/2023);
      RCPpipeco = (float)(RCPpipemat*0.127);
      Drainagemat = (float)(WQinletmat + Manholemat + RCPpipemat);
      Drainageco = (float) (WQinletco + Manholeco +  RCPpipeco);
      //Roadway
      //Surface course
      scourse = (int) (area * 2 / 12);
      scoursequantity = (int) (scourse * 106.25)/2024;
      scoursemat = scoursequantity;
      scourseco = (float) (scoursemat * 0.14);
      //PCC base
      pcc = (float) (area * 10/12);
      pccquantity = (int)(float)((pcc * 150)/2024);
```

```
	pccmat=pccquantity;
	pccco = (float) (pccmat * 0.127);
	//Aggregate base
	aggbase = area * 6/12;
	aggbasemat = (float) ((aggbase*140)/2024);
	aggco = (float) (aggbasemat * 0.017);
	//Curb
	curb = (int) (length * 2);
	curbvol = curb * 8 / 12;
	curbmat = (float)((curbvol*150)/2024);
	curbco= (float)(curbmat*0.127);
	//Gutter
	gutter = (int) (length * 2);
	guttervol = gutter * 1;
	guttermat = (float)((guttervol*150)/2024);
	gutterco= (float)(guttermat*0.127);
	//Sidewalk
	sidewalk = (int) (length * 2 * 6);
	sidewalkvol = sidewalk * 6 / 12;
	sidewalkmat = (float)((sidewalkvol*150)/2024);
	sidewalkco= (float)(sidewalkmat*0.127);
	//total
	roadwaymat =
(float)(scoursemat+pccmat+aggbasemat+curbmat+guttermat+sidewalkmat);
	roadwayco = (float)(scourseco+pccco+aggco+curbco+gutterco+sidewalkco);


	//Landscaping
	plntarea= LIDlength * 2 * 4;
	plntmat=(float)((plntarea*2*91.5)/2024);
	plntco= (float)(plntmat*0.023);
	trees=(int) (length*2/40);

	//Streetlights and signals
	signs = (int) (miles * 18 * 4);
	signsmat = (float)((signs * 0.168 * 86.25)/2024);
	signsco = (float)(signsmat*2.53);
	stlights = (float) length *2 / 100;
	stlightsmat = (float)((stlights * 1.7318 * 490.63)/2024);
	stlightsco = (float)(stlightsmat*2.7);
	markings = (int) ((lanes + 1)* length);
	markingsmat = (float)((markings * 0.021 * 75)/2024);
	markingsco = (float)(markingsmat*3.56);
	signals = 18 * miles;
	signalsmat = (float)((signals * 1.7318 * 490.63)/2024);
	signalsco = (float)(signalsmat*2.7);
	trafficducts = (int) (1 * length);
	trafficductsmat = (float)((trafficducts * 1.155 * 150.0)/2024);
	trafficductsco = (float)(trafficductsmat*0.127);
	Stlightssignalsmat = (float)(signsmat + stlightsmat + markingsmat +
signalsmat + trafficductsmat);
	Stlightssignalsco = (float)(signsco + stlightsco + markingsco +
signalsco + trafficductsco);


	//LID
	//ponding = 6inch
```

```
      LIDsoilneeded= (int)(Stormwatercf/0.4/27);
      LIDsoilneededmat = (float)((LIDsoilneeded*27*91.25)/2024);
      LIDsoilneededco = (float)(LIDsoilneededmat*0.023);
      LIDaggregate= LIDsoilneeded/2;
      LIDaggregatemat=(float)((LIDaggregate*27*140)/2024);
      LIDaggregateco=(float)(LIDaggregatemat*0.017);
      LIDunderdrain= (int) ((float) miles*5240*2);
      LIDunderdrainmat=(float)((LIDunderdrain*0.02195*86.25)/2024);
      LIDunderdrainco=(float)(LIDunderdrainmat*2.5);
      LIDmulch= (int) Stormwatersf/9;
      LIDmulchmat = (float)((LIDmulch*1.5*31.50)/2024);
      LIDmulchco =(float)(LIDmulchmat*0.02);
      LIDwalls= LIDlength*2;
      LIDwallsmat = (float)((LIDwalls*2*65.63)/2024);
      LIDwallsco = (float)(LIDwallsmat*0.127);
      LIDmat= (float) (LIDsoilneededmat + LIDaggregatemat + LIDunderdrainmat
+ LIDmulchmat + LIDwallsmat);
      LIDco = (float) (LIDsoilneededco + LIDaggregateco + LIDunderdrainco +
LIDmulchco + LIDwallsco);

      //RESURFACING
      Resurpavementremovalmat = scoursemat;
      Resurpavementremovalco = scourseco;

      //Energy
      Lifeenergy= (float)(float)((stlights+signals)*(4.8*35*365));
      Lifeenergyco= (float)((Lifeenergy*1.432)/2024);


      System.out.println("---------------------------Life Cycle Costs--------
-------------------");
      System.out.println("");
      System.out.println("CONSTRUCTION: Material Quantities and Costs");
      System.out.println("");
      System.out.println("Element               Quantity
Cost");
      System.out.println("");
      System.out.println("Grading:");

      //Grading
      Conexcavationcost = Conexcavation*40;
      System.out.println("Excavation             = "+ Conexcavation+"  CY;
$" + Conexcavationcost);
      Conexcavationlandcost = Conexcavationland*40;
      System.out.println("Excavation Landscaping= "+ Conexcavationland+"  CY;
$" + Conexcavationlandcost);
      Conborrowcost = Conborrow*50;
      System.out.println("Borrow                = "+ Conborrow+"  CY;
$" + Conborrowcost);
      Congradingcost = Conexcavationcost + Conexcavationlandcost +
Conborrowcost;
      System.out.println("Total Grading Cost                           =  $"
+ Congradingcost);
      System.out.println("");

      //Drainage
      WQinletcost = WQinlet*16000;
```

```
      System.out.println("Install Water Quality inlets= "+ WQinlet+"  ;
$" + WQinletcost);
      Manholecost = Manhole*8150;
      System.out.println("Install Manholes            = "+ Manhole+"  ;
$" + Manholecost);
      RCPpipecost = RCPpipe*130;
      System.out.println("RCP pipe                   = "+ RCPpipe+"  LF;
$" + RCPpipecost);
      Drainagecost = (int) (WQinletcost + Manholecost + RCPpipecost);
      System.out.println("Total Drainage Cost                       =  $" +
Drainagecost);
      System.out.println("");

      //Roadway
      System.out.println("");
      System.out.println("Roadway:");
      pcccost = (int) (areasqy*110);
      System.out.println("PCC pavement          = "+ areasqy+"  SY;       $"
+ pcccost);
      scoursecost = scoursequantity*100;
      System.out.println("Surfacecourse         = "+ scoursequantity+"  tons;
$" + scoursecost);
      aggregatecost = (int) (areasqy*30);
      System.out.println("Aggregate Base        = "+ areasqy+"  SY;       $"
+ aggregatecost);
      curbcost = curb*35;
      System.out.println("Curb (both sides)     = "+ curb+"  LF;       $" +
curbcost);
      guttercost = gutter*35;
      System.out.println("Gutter (both sides)   = "+ gutter+"  LF;       $" +
guttercost);
      sidewalkcost = sidewalk*20;
      System.out.println("Sidewalk (both sides) = "+ sidewalk+"  SF;       $"
+ sidewalkcost);
      roadwaycost = pcccost + scoursecost + aggregatecost + curbcost +
guttercost + sidewalkcost;
      System.out.println("Total Roadway Section Cost     =  $" +
roadwaycost);
      System.out.println("");

      //Landscaping
      System.out.println("Lanscaping:");
      System.out.println("");
      plntareacost = plntarea*15;
      System.out.println("Planting area          = "+ plntarea+"  SF;
$" + plntareacost);
      treescost = trees*3100;
      System.out.println("No. of Trees                 = "+ trees+"       $"
+ treescost);
      landscapingcost = plntareacost + treescost;
      System.out.println("Total Landscaping Cost   =                   $" +
landscapingcost);
      System.out.println("");

      //Streetlights
      System.out.println("Streetlights & Traffic Control Devices:");
      System.out.println("");
```

```
      signscost = signs * 500;
      System.out.println("Signs                  = "+ signs+"       ;      $"
+ signscost);
      stlightscost = (int) stlights * 8000;
      System.out.println("Streetlights           = "+ stlights+"     ;
$" + stlightscost);
      markingscost = markings*3;
      System.out.println("Pavement Markings      = "+ markings+"  LF;      $"
+ markingscost);
      signalscost = (int) (signals*200000);
      System.out.println("Signals                = "+ signals+"     ;
$" + signalscost);
      trafficductscost =trafficducts * 100;
      System.out.println("Ducts                  = "+ trafficducts+"  LF;
$" + trafficductscost);
      trafficdevicescost = signscost + stlightscost + markingscost +
signalscost + trafficductscost;
      System.out.println("Total Streetlights & Traffic Devices Cost  =    $"
+ trafficdevicescost);
      System.out.println("");

      //Stormwater
      System.out.println("Stormwater Management:");
      System.out.println("");
      LIDsoilneededcost = LIDsoilneeded*53;
      System.out.println("Soil                         = "+ LIDsoilneeded +"
CY;       $" + LIDsoilneededcost);
      LIDaggregatecost= LIDaggregate*57;
      System.out.println("LID aggregate base           = "+ LIDaggregate +"
CY;       $" + LIDaggregatecost);
      LIDunderdraincost= LIDunderdrain*18;
      System.out.println("Underdrain                   = "+ LIDunderdrain+"
LF;       $" + LIDunderdraincost);
      LIDmulchcost= (int) (LIDmulch*2.5);
      System.out.println("Mulch                        = "+ LIDmulch+" SY;
$" + LIDmulchcost);
      LIDwallscost= LIDwalls*35;
      System.out.println("LID Walls                   = "+ LIDwalls+" LF;
$" + LIDwallscost);
      LIDcost = LIDsoilneededcost + LIDaggregatecost + LIDunderdraincost +
LIDmulchcost + LIDwallscost;
      System.out.println("Total Stormwater (LID) Cost
=  $" + LIDcost);

      System.out.println("");

      //Engineering costs
      System.out.println("Engineering Costs:");

      System.out.println("");
      enggcost = (int) ((roadwaycost/10)+((Congradingcost + Drainagecost +
landscapingcost + roadwaycost + trafficdevicescost + LIDcost)/6.66));
      System.out.println("Engineering Costs                            =  $"
+ enggcost);
      System.out.println("");
      consubtotalcost =  Congradingcost + Drainagecost + roadwaycost +
landscapingcost + trafficdevicescost + LIDcost + enggcost;
```

```
      System.out.println("Project Costs                                =  $"
+ consubtotalcost);
      System.out.println("");
      contingencycost = (int)consubtotalcost/10;
      contotalcost =  consubtotalcost + contingencycost;
      System.out.println("Total Project Costs                            =
$" + contotalcost);
      System.out.println("");
      System.out.println("");System.out.println("");
      System.out.println("");

      //Resurfacing
     //Grading
      Resurpavementremoval = (float) ((float)(((lanes *11 + blanes * 5)*
miles* 5240)/9)*(0.0556));
      System.out.println("");
      System.out.println("RESURFACING: Material Quantities and Costs");
      System.out.println("");
      System.out.println("Element               Quantity
Cost");
      System.out.println("");
      System.out.println("Grading:");

      //Grading
      Resurpavementremovalcost = Resurpavementremoval*60;
      System.out.println("Pavement Excavation           = "+
Resurpavementremoval+"  CY;       $" + Resurpavementremovalcost);
      System.out.println("Total Grading Cost                           =  $"
+ Resurpavementremovalcost);
      System.out.println("");

      //Roadway
      System.out.println("");
      System.out.println("Roadway:");
      scoursecost = scoursequantity*100;
      System.out.println("Surfacecourse         = "+ scoursequantity+"  tons;
$" + scoursecost);
      System.out.println("Total Roadway Section Cost     =  $" +
scoursecost);
      System.out.println("");

      //Streetlights
      System.out.println("Streetlights & Traffic Control Devices:");
      System.out.println("");
      markingscost = markings*3;
      System.out.println("Pavement Markings     = "+ markings+"  LF;      $"
+ markingscost);
      System.out.println("Total Streetlights & Traffic Devices Cost  =    $"
+ markingscost);
      System.out.println("");

      //Engineering costs
      System.out.println("Engineering Costs:");
      System.out.println("");
      surfenggcost = (int) ((scoursecost/10)+((Resurpavementremovalcost +
scoursecost + markingscost)/6.66));
```

```
      System.out.println("Engineering Costs                              =  $"
+ surfenggcost);
      System.out.println("");

      surfsubtotalcost =  surfenggcost + Resurpavementremovalcost +
scoursecost + markingscost;
      System.out.println("Project Costs                                  =  $"
+ surfsubtotalcost);
      System.out.println("");

      surfcontingencycost = (int)surfsubtotalcost/10;
      surftotalcost =  surfsubtotalcost + surfcontingencycost;
      System.out.println("Total Project Costs                           =
$" + surftotalcost);
      System.out.println("");
      System.out.println("");System.out.println("");
      System.out.println("");

      //
      //Reconstruction
      //Grading
      Reconpavementremoval= Resurpavementremoval;
      Reconbaseremoval = (float)(0.278* areasqy);
      Reconsidewalkremoval = (float)((sidewalk * 0.5)/27);
      Reconcurbgutterremoval= (float)((3.3* miles*5240 *0.5)/27);

      //Draiange
      ReconWQinlet = (float) 0.25*WQinlet;
      ReconManhole = (float) 0.25*Manhole;
      ReconRCPpipe= (float) 0.25*RCPpipe;

      //Roadway
      Reconscourse = scoursequantity;
      Reconpcc = (float) (areasqy*0.5);
      Reconcurb = curb;
      Recongutter = gutter;
      Reconsidewalk = sidewalk;

      //Landscaping
      Reconplntarea= 4*2*5240*miles;
      Recontrees= (float) 0.25*trees;

      //Streetlights and signals
      Reconsigns = signs/4;
      Reconstlights = stlights/4;
      Reconmarkings = markings;
      Reconsignals = (float) signals/4;
      Recontrafficducts = trafficducts/4;

      //LID
      //ponding = 6inch

      ReconLIDsoilneeded = LIDsoilneeded;
      ReconLIDaggregate =  LIDaggregate;
      ReconLIDunderdrain = LIDunderdrain;
      ReconLIDmulch = LIDmulch;
      ReconLIDwalls = LIDwalls;
```

```
      System.out.println("");

      System.out.println("RECONSTRUCTION: Material Quantities and Costs");
      System.out.println("");
      System.out.println("Element               Quantity
Cost");
      System.out.println("");
      System.out.println("Grading:");

      //Grading
      Reconpavementremovalcost = Reconpavementremoval*60;
      System.out.println("Existing Sur Pavement Removal= "+
Reconpavementremoval+"  CY;       $" + Reconpavementremovalcost);
      Reconbaseremovalcost = Reconbaseremoval*60;
      System.out.println("Existing PCC Pavement Removal= "+
Reconbaseremoval+"  CY;       $" + Reconbaseremovalcost);
      Reconsidewalkremovalcost = Reconsidewalkremoval*60;
      System.out.println("Existing Sidewalk Removal    = "+
Reconsidewalkremoval+"  CY;       $" + Reconsidewalkremovalcost);
      Reconcurbgutterremovalcost = Reconcurbgutterremoval*60;
      System.out.println("Existing curb/gutter Removal = "+
Reconcurbgutterremoval+"  CY;       $" + Reconcurbgutterremovalcost);
      Reconexcavationcost = Conexcavation*0;
      System.out.println("Excavation                    = "+ 0 +"  CY;
$" + Reconexcavationcost);
      Reconexcavationlandcost = Conexcavationland*0;
      System.out.println("Excavation Landscaping         = "+ 0 +"  CY;
$" + Reconexcavationlandcost);
      Reconborrowcost = Conborrow*0;
      System.out.println("Borrow                          = "+ 0 +"  CY;
$" + Reconborrowcost);
      Recongradingcost = Reconpavementremovalcost + Reconbaseremovalcost +
Reconsidewalkremovalcost + Reconcurbgutterremovalcost + Reconexcavationcost +
Reconexcavationlandcost + Reconborrowcost;
      System.out.println("Total Grading Cost                           =  $"
+ Recongradingcost);
      System.out.println("");

      //Drainage
      ReconWQinletcost = ReconWQinlet*16000;
      System.out.println("Install Water Quality inlets= "+ ReconWQinlet+"  ;
$" + ReconWQinletcost);
      ReconWQinletremovalcost = ReconWQinlet*2000;
      System.out.println("Install Water Quality inlets= "+ ReconWQinlet+"  ;
$" + ReconWQinletremovalcost);
      ReconManholecost = ReconManhole*8150;
      System.out.println("Install Manholes            = "+ ReconManhole+"  ;
$" + ReconManholecost);
      ReconRCPpipecost = ReconRCPpipe*130;
      System.out.println("RCP pipe                  = "+ ReconRCPpipe+"  LF;
$" + ReconRCPpipecost);
      ReconDrainagecost = ReconWQinletcost + ReconWQinletremovalcost +
ReconManholecost + ReconRCPpipecost;
      System.out.println("Total Drainage Cost                        =  $" +
ReconDrainagecost);
      System.out.println("");
```

```
      //Roadway
      System.out.println("");
      System.out.println("Roadway:");
      Reconpcccost = Reconpcc*110;
      System.out.println("PCC pavement          = "+ Reconpcc+"  SY;       $"
+ Reconpcccost);
      Reconscoursecost = Reconscourse*100;
      System.out.println("Surfacecourse         = "+ Reconscourse+"  tons;
$" + Reconscoursecost);
      Reconaggregatecost = areasqy*0;
      System.out.println("Aggregate Base        = "+ 0+"  SY;       $" +
Reconaggregatecost);
      Reconcurbcost = Reconcurb*35;
      System.out.println("Curb (both sides)     = "+ Reconcurb+"  LF;
$" + Reconcurbcost);
      Reconguttercost = Recongutter*35;
      System.out.println("Gutter (both sides)   = "+ Recongutter+"  LF;
$" + Reconguttercost);
      Reconsidewalkcost = Reconsidewalk*20;
      System.out.println("Sidewalk (both sides) = "+ Reconsidewalk+"  SF;
$" + Reconsidewalkcost);
      Reconroadwaycost = Reconpcccost + Reconscoursecost + Reconaggregatecost
+ Reconcurbcost + Reconguttercost + Reconsidewalkcost;
      System.out.println("Total Roadway Section Cost     =  $" +
Reconroadwaycost);
      System.out.println("");

      //Landscaping
      Reconplntarea= 4*2*5240*miles;
      Recontrees= (float) 0.25*trees;
      System.out.println("Lanscaping:");
      System.out.println("");
      Reconplntareacost = Reconplntarea*15;
      System.out.println("Planting area          = "+ Reconplntarea+"  SF;
$" + Reconplntareacost);
      Recontreescost = Recontrees*3100;
      System.out.println("No. of Trees                   = "+ Recontrees+"
$" + Recontreescost);
      Reconlandscapingcost = Reconplntareacost + Recontreescost;
      System.out.println("Total Landscaping Cost   =                   $" +
Reconlandscapingcost);
      System.out.println("");

      //Streetlights
      System.out.println("Streetlights & Traffic Control Devices:");
      System.out.println("");
      Reconsignscost = Reconsigns * 500;
      System.out.println("Signs                = "+ Reconsigns+"       ;
$" + Reconsignscost);
      Reconstlightscost = Reconstlights * 8000;
      System.out.println("Streetlights          = "+ Reconstlights+"     ;
$" + Reconstlightscost);
      Reconmarkingscost = Reconmarkings*3;
      System.out.println("Pavement Markings     = "+ Reconmarkings+"  LF;
$" + Reconmarkingscost);
      Reconsignalscost = Reconsignals*200000;
```

```
      System.out.println("Signals               = "+ Reconsignals+"     ;
$" + Reconsignalscost);
      Recontrafficductscost =Recontrafficducts * 100;
      System.out.println("Ducts                 = "+ Recontrafficducts+"  LF;
$" + Recontrafficductscost);

      Recontrafficdevicescost = Reconsignscost + Reconstlightscost +
Reconmarkingscost + Reconsignalscost + Recontrafficductscost;

      System.out.println("Total Streetlights & Traffic Devices Cost  =    $"
+ Recontrafficdevicescost);

      System.out.println("");

      //Stormwater

      System.out.println("Stormwater Management:");
      System.out.println("");
      ReconLIDsoilneededcost = ReconLIDsoilneeded*53;
      System.out.println("Soil                        = "+ ReconLIDsoilneeded
+"  CY;       $" + ReconLIDsoilneededcost);
      ReconLIDaggregatecost= ReconLIDaggregate*57;
      System.out.println("LID aggregate base          = "+ ReconLIDaggregate
+"  CY;       $" + ReconLIDaggregatecost);
      ReconLIDunderdraincost= ReconLIDunderdrain*18;
      System.out.println("Underdrain                  = "+
ReconLIDunderdrain+" LF;       $" + ReconLIDunderdraincost);
      ReconLIDmulchcost= (int) (ReconLIDmulch*2.5);
      System.out.println("Mulch                       = "+ ReconLIDmulch+"
SY;       $" + ReconLIDmulchcost);
      ReconLIDwallscost= ReconLIDwalls*35;
      System.out.println("LID Walls                  = "+ ReconLIDwalls+" LF;
$" + ReconLIDwallscost);
      ReconLIDcost = ReconLIDsoilneededcost + ReconLIDaggregatecost +
ReconLIDunderdraincost + ReconLIDmulchcost + ReconLIDwallscost;

      System.out.println("Total Stormwater (LID) Cost
=  $" + ReconLIDcost);
      System.out.println("");

      //Engineering costs
      System.out.println("Engineering Costs:");
      System.out.println("");
      Reconenggcost = (int) ((Reconroadwaycost/10)+((Recongradingcost +
ReconDrainagecost + Reconlandscapingcost + Reconroadwaycost +
Recontrafficdevicescost + ReconLIDcost)/6.66));
      System.out.println("Engineering Costs                            =  $"
+ Reconenggcost);

      System.out.println("");
      Reconsubtotalcost =  Recongradingcost + ReconDrainagecost +
Reconlandscapingcost + Reconroadwaycost + Recontrafficdevicescost +
ReconLIDcost + Reconenggcost;
      System.out.println("Project Costs                                =  $"
+ Reconsubtotalcost);
      System.out.println("");
```

```
      Reconcontingencycost = (float)(Reconsubtotalcost * 0.10);
      Recontotalcost =  Reconsubtotalcost + Reconcontingencycost;
      System.out.println("Total Project Costs                            =
$" + Recontotalcost);
      System.out.println("");
      System.out.println("");System.out.println("");
      System.out.println("");


      //Energy
      //Streetlights and signals
      Energylightscost= stlights*106*35;
      Energysignalscost = signals*625*35;

      System.out.println("");

      System.out.println("Energy: Quantities and Costs");
      System.out.println("");
      System.out.println("Element               Quantity
Cost");
      System.out.println("");

      //Streetlights
      System.out.println("Streetlights & Traffic Control Devices:");
      System.out.println("");
      System.out.println("Streetlights energy                       = $" +
Energylightscost);
      System.out.println("Signals energy                            = $" +
Energysignalscost);
      Energycost = Energylightscost + Energysignalscost;
      System.out.println("Total Streetlights & Traffic Devices Energy Cost  =
$" + Energycost);
      System.out.println("");

      //Engineering costs
      System.out.println("Engineering Costs:");
      System.out.println("");
      Energyenggcost = (int) (Energycost/6.66);
      System.out.println("Engineering Costs                              =  $"
+ Energyenggcost);

      System.out.println("");
      Reconsubtotalcost =  Recongradingcost + ReconDrainagecost +
Reconlandscapingcost + Reconroadwaycost + Recontrafficdevicescost +
ReconLIDcost + Reconenggcost;
      System.out.println("Project Costs                                 =  $"
+ Reconsubtotalcost);

      LifeEnergytotalcost =  Energycost + Energyenggcost;
      System.out.println("Life Cycle Energy Costs                       =  $"
+ LifeEnergytotalcost);
      System.out.println("");
      System.out.println("");



      //Salvage Value
```

```
	System.out.println("");

	System.out.println("Salvage Value:");
	System.out.println("");
	System.out.println("Element                        Cost");
	System.out.println("");
	System.out.println("Grading:");

	//Grading
	SVReconpavementremovalcost = (float) (float)
(Reconpavementremoval*60*0.83);
	System.out.println("Existing Sur Pavement Removal= $" +
SVReconpavementremovalcost);
	SVReconbaseremovalcost = (float) (float)(Reconbaseremoval*60*0.83);
	System.out.println("Existing PCC Pavement Removal= $" +
SVReconbaseremovalcost);
	SVReconsidewalkremovalcost = (float) (float)
(Reconsidewalkremoval*60*0.83);
	System.out.println("Existing Sidewalk Removal    = $" +
SVReconsidewalkremovalcost);
	SVReconcurbgutterremovalcost = (float)
(float)(Reconcurbgutterremoval*60*0.83);
	System.out.println("Existing curb/gutter Removal = $" +
SVReconcurbgutterremovalcost);
	SVReconexcavationcost = Conexcavation*0;
	System.out.println("Excavation                    = $" +
SVReconexcavationcost);
	SVReconexcavationlandcost = Conexcavationland*0;
	System.out.println("Excavation Landscaping        = $" +
SVReconexcavationlandcost);
	SVReconborrowcost = Conborrow*0;
	System.out.println("Borrow                         = $" +
SVReconborrowcost);
	SVRecongradingcost = SVReconpavementremovalcost +
SVReconbaseremovalcost + SVReconsidewalkremovalcost +
SVReconcurbgutterremovalcost + SVReconexcavationcost +
SVReconexcavationlandcost + SVReconborrowcost;
	System.out.println("Total Grading Cost                           =  $"
+ SVRecongradingcost);
	System.out.println("");

	//Drainage
	SVReconWQinletcost = (float) (float) (ReconWQinlet*16000*0.83);
	System.out.println("Install Water Quality inlets= "+ ReconWQinlet+"  ;
$" + ReconWQinletcost);
	SVReconWQinletremovalcost = (float) (float) (ReconWQinlet*2000*0.83);
	System.out.println("Install Water Quality inlets= "+ ReconWQinlet+"  ;
$" + ReconWQinletremovalcost);
	SVReconManholecost = (float) (float)(ReconManhole*8150*0.83);
	System.out.println("Install Manholes           = "+ ReconManhole+"  ;
$" + ReconManholecost);
	SVReconRCPpipecost = (float) (float) (ReconRCPpipe*130*0.83);
	System.out.println("RCP pipe                  = "+ ReconRCPpipe+"  LF;
$" + ReconRCPpipecost);
	SVReconDrainagecost = SVReconWQinletcost + SVReconWQinletremovalcost +
SVReconManholecost + SVReconRCPpipecost;
```

```
      System.out.println("Total Drainage Cost                        =  $" +
SVReconDrainagecost);
      System.out.println("");

      //Roadway
      System.out.println("");
      System.out.println("Roadway:");
      SVReconpcccost = (float)(float) (Reconpcc*110*0.83);
      System.out.println("PCC pavement          = $" + SVReconpcccost);
      SVReconscoursecost = (float)(float) (Reconscourse*100*0.83);
      System.out.println("Surfacecourse         = $" + SVReconscoursecost);
      SVReconaggregatecost = areasqy*0;
      System.out.println("Aggregate Base        = $" + SVReconaggregatecost);
      SVReconcurbcost = (float)(float) (Reconcurb*35*0.83);
      System.out.println("Curb (both sides)     = $" + SVReconcurbcost);
      SVRecongutercost = (float)(float) (Recongutter*35*0.83);
      System.out.println("Gutter (both sides)   = $" + SVRecongutercost);
      SVReconsidewalkcost = (float)(float) (Reconsidewalk*20*0.83);
      System.out.println("Sidewalk (both sides) = $" + SVReconsidewalkcost);
      SVReconroadwaycost = SVReconpcccost + SVReconscoursecost +
SVReconaggregatecost + SVReconcurbcost + SVRecongutercost +
SVReconsidewalkcost;
      System.out.println("Total Roadway Section Cost     =  $" +
SVReconroadwaycost);
      System.out.println("");

      //Landscaping
      Reconplntarea= 4*2*5240*miles;
      Recontrees= (float) 0.25*trees;
      System.out.println("Lanscaping:");
      System.out.println("");
      SVReconplntareacost = (float) (float) (Reconplntarea*15*0.83);
      System.out.println("Planting area          =  $" +
SVReconplntareacost);
      SVRecontreescost = (float) (float) (Recontrees*3100*0.83);
      System.out.println("No. of Trees                  = "+ Recontrees+"
$" + Recontreescost);
      SVReconlandscapingcost = SVReconplntareacost + SVRecontreescost;
      System.out.println("Total Landscaping Cost   =                   $" +
SVReconlandscapingcost);
      System.out.println("");

      //Streetlights
      System.out.println("Streetlights & Traffic Control Devices:");
      System.out.println("");
      SVReconsignscost = (float) (float) (Reconsigns * 500*0.83);
      System.out.println("Signs                 = $" + SVReconsignscost);
      SVReconstlightscost = (float) (float) (Reconstlights * 8000*0.83);
      System.out.println("Streetlights          = $" + SVReconstlightscost);
      SVReconmarkingscost = (float) (float) (Reconmarkings*3*0.83);
      System.out.println("Pavement Markings     = $" + SVReconmarkingscost);
      SVReconsignalscost = (float) (float) (Reconsignals*200000*0.83);
      System.out.println("Signals               = $" + SVReconsignalscost);
      SVRecontrafficductscost = (float) (float) (Recontrafficducts *
100*0.83);
      System.out.println("Ducts                 = $" +
SVRecontrafficductscost);
```

```
	SVRecontrafficdevicescost = SVReconsignscost + SVReconstlightscost + 
SVReconmarkingscost + SVReconsignalscost + SVRecontrafficductscost;
	System.out.println("Total Streetlights & Traffic Devices Cost  =    $"
+ SVRecontrafficdevicescost);

	System.out.println("");

	//Stormwater

	System.out.println("Stormwater Management:");
	System.out.println("");
	SVReconLIDsoilneededcost = (float) (float)
(ReconLIDsoilneeded*53*0.83);
	System.out.println("Soil                        = $" + 
SVReconLIDsoilneededcost);
	SVReconLIDaggregatecost= (float) (float) (ReconLIDaggregate*57*0.83);
	System.out.println("LID aggregate base          = $" + 
SVReconLIDaggregatecost);
	SVReconLIDunderdraincost= (float) (float) (ReconLIDunderdrain*18*0.83);
	System.out.println("Underdrain                  = $" + 
SVReconLIDunderdraincost);
	SVReconLIDmulchcost= (int) (ReconLIDmulch*2.5*0.83);
	System.out.println("Mulch                       = $" + 
SVReconLIDmulchcost);
	SVReconLIDwallscost= (float) (float) (ReconLIDwalls*35*0.83);
	System.out.println("LID Walls                   = $" + 
SVReconLIDwallscost);
	SVReconLIDcost = SVReconLIDsoilneededcost + SVReconLIDaggregatecost + 
SVReconLIDunderdraincost + SVReconLIDmulchcost + SVReconLIDwallscost;

	System.out.println("Total Stormwater (LID) Cost
=  $" + SVReconLIDcost);
	System.out.println("");

	//Engineering costs
	System.out.println("Engineering Costs:");
	System.out.println("");
	SVReconenggcost = (int) ((SVReconroadwaycost/10)+((SVRecongradingcost + 
SVReconDrainagecost + SVReconlandscapingcost + SVReconroadwaycost + 
SVRecontrafficdevicescost + SVReconLIDcost)/6.66));
	System.out.println("Engineering Costs                            =  $"
+ SVReconenggcost);

	System.out.println("");
	SVReconsubtotalcost =  SVRecongradingcost + SVReconDrainagecost + 
SVReconlandscapingcost + SVReconroadwaycost + SVRecontrafficdevicescost + 
SVReconLIDcost + SVReconenggcost;
	System.out.println("Project Costs                                =  $"
+ SVReconsubtotalcost);
	System.out.println("");

	SVReconcontingencycost = (float)(SVReconsubtotalcost * 0.10);
	SVRecontotalcost =  SVReconsubtotalcost + SVReconcontingencycost;
	System.out.println("Total Project Costs                          =  
$" + SVRecontotalcost);
	System.out.println("");
```

```
      System.out.println("");System.out.println("");
      System.out.println("");


      //Life Cycle Costs
      System.out.println("***********Life Cycle Costs******");
      System.out.println("");
      System.out.println("Life Cycle: Material Quantities and Costs");
      System.out.println("");
      System.out.println("Element               Quantity
Cost");
      System.out.println("");
      System.out.println("Grading:");

      //Grading
      LCCAgradingcost = Congradingcost+ (2*Resurpavementremovalcost)+
Recongradingcost -SVRecongradingcost;
      System.out.println("Life Cycle Grading Cost                           =
$" + LCCAgradingcost);
      System.out.println("");

      //Drainage
      LCCADrainagecost = Drainagecost+ ReconDrainagecost -
SVReconDrainagecost;
      System.out.println("Life Cycle Drainage Cost                        =
$" + LCCADrainagecost);
      System.out.println("");

      //Roadway
      System.out.println("");
      LCCAroadwaycost = roadwaycost+ (2*scoursecost)+ Reconroadwaycost -
SVReconroadwaycost;
      System.out.println("Life Cycle Roadway Section Cost     =  $" +
LCCAroadwaycost);
      System.out.println("");

      //Landscaping
      LCCAlandscapingcost = landscapingcost+ Reconlandscapingcost -
SVReconlandscapingcost;
      System.out.println("Life Cycle Landscaping Cost          =  $" +
LCCAlandscapingcost);
      System.out.println("");

      //Streetlights
      LCCAtrafficdevicescost = trafficdevicescost+ (2*markingscost)+
Recontrafficdevicescost -SVRecontrafficdevicescost;
      System.out.println("Life Cycle Streetlights & Traffic Control Cost= $"
+ LCCAtrafficdevicescost);
      System.out.println("");

      //Stormwater
      LCCALIDcost = LIDcost+ ReconLIDcost -SVReconLIDcost;
      System.out.println("Life Cycle Stormwater (LID) Cost               =
$" + LCCALIDcost);
      System.out.println("");

      //Engineering costs
```

```
      LCCAenggcost = enggcost+ (2*surfenggcost)+ Reconenggcost -
SVReconenggcost;
      System.out.println("Life Cycle Engineering Costs                   =
$" + LCCAenggcost);
      System.out.println("");
      LCCAcontingencycost = contingencycost+ (2*surfcontingencycost)+
Reconcontingencycost -SVReconcontingencycost;
      System.out.println("Life Cycle Contingency Costs                   =
$" + LCCAcontingencycost);
      System.out.println("");
      LCCAtotalcost = contotalcost+ (2*surftotalcost)+ Recontotalcost -
SVRecontotalcost + LifeEnergytotalcost+713838;
      LCCAtotalcosttest = 713838+LCCAgradingcost
+LCCADrainagecost+LCCAroadwaycost+LCCAlandscapingcost+LCCAtrafficdevicescost+
LCCALIDcost+LCCAenggcost+LCCAcontingencycost+LifeEnergytotalcost;
      System.out.println("Life Cycle Total Project Costs                  =
$" + LCCAtotalcost);
      System.out.println("Life Cycle Total Project Costs      (check)     =
$" + LCCAtotalcosttest);
      System.out.println("");
      System.out.println("");System.out.println("");
      System.out.println("");



      //LCA


      System.out.println("--------------------------Life Cycle Impacts -----
---------------------");
      System.out.println("");
      System.out.println("CONSTRUCTION: ");
      System.out.println("");
      System.out.println("Element               MatQuantity                CO
Waste");
      System.out.println("");
      System.out.println("Grading:");

      //Grading
      System.out.println("Excavation material                     = "+
Conexcavationmat+" Tons;    CO=" + Conexcavationco+" Tons");
      System.out.println("Borrow     material                     = "+
Conborrowmat+" Tons;    CO=" + Conborrowco+" Tons");
      System.out.println("Total Grading material                  = "+
Congradmat+" Tons;    CO=" + Congradco+" Tons");
      System.out.println("");

      //Drainage
      System.out.println("");
      System.out.println("Drainage:");
      System.out.println("Install Water Quality inlets material= "+
WQinletmat+" Tons;    CO=" + WQinletco+" Tons");
      System.out.println("Install Manhole  material               = "+
Manholemat+" Tons;    CO=" + Manholeco+" Tons");
      System.out.println("Install RCP pipe  material              = "+
RCPpipemat+" Tons;    CO=" + RCPpipeco+" Tons");
```

```
      System.out.println("Total Drainage Materials              = "+
Drainagemat+" Tons;    CO=" + Drainageco+" Tons");
      System.out.println("");

      //Roadway
      System.out.println("");
      System.out.println("Roadway:");
      System.out.println("PCC pavement          material= "+ pccmat+" Tons;
CO=" + pccco+" Tons");
      System.out.println("Surfacecourse         material= "+ scoursemat+"
Tons;    CO=" + scourseco+" Tons");
      System.out.println("Aggregate Base        material= "+ aggbasemat+"
Tons;    CO=" + aggco+" Tons");
      System.out.println("Curb                  material= "+ curbmat+" Tons;
CO=" + curbco+" Tons");
      System.out.println("Gutter                material= "+ guttermat+"
Tons;    CO=" + gutterco+" Tons");
      System.out.println("Sidewalk              material= "+ sidewalkmat+"
Tons;    CO=" + sidewalkco+" Tons");
      System.out.println("Total Roadway         material= "+ roadwaymat+"
Tons;    CO=" + roadwayco+" Tons");
      System.out.println("");


      System.out.println("");
      System.out.println("Lanscaping:");
      System.out.println("");
      System.out.println("Planting area            material= "+ plntmat+"
Tons;    CO=" + plntco+" Tons");
      System.out.println("Total Planting area      material= "+ plntmat+"
Tons;    CO=" + plntco+" Tons");
      System.out.println("");

      //Streetlights

      System.out.println("Streetlights & Traffic Control Devices:");
      System.out.println("");
      System.out.println("Signs                        material= "+ signsmat+"
Tons;    CO=" + signsco+" Tons");
      System.out.println("Streetlights                 material= "+
stlightsmat+" Tons;    CO=" + stlightsco+" Tons");
      System.out.println("Pavement Markings            material= "+
markingsmat+" Tons;    CO=" + markingsco+" Tons");
      System.out.println("Signals                      material= "+ signalsmat+"
Tons;    CO=" + signalsco+" Tons");
      System.out.println("Trafficducts                 material= "+
trafficductsmat +" Tons;    CO=" + trafficductsco+" Tons");
      System.out.println("Total Streelight & Traffic material= "+
Stlightssignalsmat+" Tons;    CO=" + Stlightssignalsco+" Tons");
      System.out.println("");

      //Stormwater

      System.out.println("Stormwater Management:");
      System.out.println("");
      System.out.println("Soil                         material= "+
LIDsoilneededmat+" Tons;    CO=" + LIDsoilneededco+" Tons");
```

```
      System.out.println("LID aggregate             material= "+
LIDaggregatemat+" Tons;    CO=" + LIDaggregateco+" Tons");
      System.out.println("Underdrain                material= "+
LIDunderdrainmat+" Tons;    CO=" + LIDunderdrainco+" Tons");
      System.out.println("Mulch                     material= "+
LIDmulchmat+" Tons;    CO=" + LIDmulchco+" Tons");
      System.out.println("LID walls                 material= "+
LIDwallsmat+" Tons;    CO=" + LIDwallsmat+" Tons");
      System.out.println("Total Stormwater (LID)    material= "+ LIDmat+"
Tons;    CO=" + LIDco+" Tons");

      System.out.println("");

      contotalmat = (float)
(Congradmat+Drainagemat+roadwaymat+plntmat+Stlightssignalsmat+ LIDmat);
      contotalco = (float)
(Congradco+Drainageco+roadwayco+plntco+Stlightssignalsco + LIDco);
      System.out.println("Total Construction              material= "+
contotalmat+" Tons;    CO=" + contotalco+" Tons");
      System.out.println("");System.out.println("");System.out.println("");
      //construction waste material
      conswastematerial= Congradmat;



      //Resurfacing
     //Grading
      Resurpavementremoval = (float) ((float)(((lanes *11 + blanes * 5)*
miles* 5240)/9)*(0.0556));
      System.out.println("");
      System.out.println("RESURFACING:");
      System.out.println("");
      System.out.println("");
      System.out.println("Grading:");

      //Grading
      System.out.println("Total (Pavement excavation)     material= "+
Resurpavementremovalmat+" Tons;    CO=" + Resurpavementremovalco+" Tons");

      System.out.println("");

      //Roadway
      System.out.println("");
      System.out.println("Roadway:");
      System.out.println("Total Roadway (Surface Course)   material= "+
scoursemat+" Tons;    CO=" + scourseco+" Tons");
      System.out.println("");

      //Streetlights
      System.out.println("Streetlights & Traffic Control Devices:");
      System.out.println("");
      System.out.println("Total Streetlights & Traffic control
(markings)material= "+ markingsmat+" Tons;    CO=" + markingsco+" Tons");
      System.out.println("");

      //Total
```

```
	resurftotalmat = (float)
(Resurpavementremovalmat+scoursemat+markingsmat);
	resurftotalco = (float) (Resurpavementremovalco+scourseco+markingsco);
	System.out.println("Total Resurfacing              material= "+
resurftotalmat+" Tons;    CO=" + resurftotalco+" Tons");
	System.out.println("");System.out.println("");System.out.println("");
	//waste material
	resurfwastematerial= resurftotalmat;


	//
	//Reconstruction
	//Grading
	Reconpavementremoval= Resurpavementremoval;
	Reconpavementremovalmat= Resurpavementremovalmat;
	Reconpavementremovalco= Resurpavementremovalco;
	Reconbaseremoval = (float)(0.278* areasqy);
	Reconbaseremovalmat = (float)((Reconbaseremoval * 27 * 150)/2024);
	Reconbaseremovalco = (float)(Reconbaseremovalmat*0.127);
	Reconsidewalkremoval = (float)((sidewalk * 0.5)/27);
	Reconsidewalkremovalmat = (float)((Reconsidewalkremoval *
27*150)/2024);
	Reconsidewalkremovalco = (float)(Reconsidewalkremovalmat*0.127);
	Reconcurbgutterremoval= (float)((3.3* miles*5240 *0.5)/27);
	Reconcurbgutterremovalmat = (float)((Reconcurbgutterremoval
*27*150)/2024);
	Reconcurbgutterremovalco = (float)(Reconcurbgutterremovalmat*0.127);
	Recongradingmat =
(float)(Reconpavementremovalmat+Reconbaseremovalmat+Reconsidewalkremovalmat+R
econcurbgutterremovalmat);
	Recongradingco =
(float)(Reconpavementremovalco+Reconbaseremovalco+Reconsidewalkremovalco+Reco
ncurbgutterremovalco);


	//Drainage
	ReconWQinlet = (float) 0.25*WQinlet;
	ReconWQinletmat= (float) 0.25*WQinletmat;
	ReconWQinletco = (float) 0.25*WQinletco;
	ReconManhole = (float) 0.25*Manhole;
	ReconManholemat = (float) 0.25*Manholemat;
	ReconManholeco = (float) 0.25*Manholeco;
	ReconRCPpipe= (float) 0.25*RCPpipe;
	ReconRCPpipemat= (float) 0.25*RCPpipemat;
	ReconRCPpipeco= (float) 0.25*RCPpipeco;
	//WQ inlet removal is equal to WQ installation. hence WQ inlets are
added twice to get the value for WQ removal
	Recondrainagemat = (float)
(ReconWQinletmat+ReconWQinletmat+ReconManholemat+ReconRCPpipemat);
	Recondrainageco = (float)
(ReconWQinletco+ReconWQinletco+ReconManholeco+ReconRCPpipeco);


	//Roadway
	Reconscoursemat = scoursemat;
	Reconscourseco = scourseco;
	Reconpccmat = (float) 0.5* pccmat;
```

```
	Reconpccco = (float) 0.5* pccco;
	Reconcurbmat = curbmat;
	Reconcurbco = curbco;
	Reconguttermat = guttermat;
	Recongutterco = gutterco;
	Reconsidewalkmat = sidewalkmat;
	Reconsidewalkco = sidewalkco;
	Reconroadwaymat = 
(float)(Reconscoursemat+Reconpccmat+Reconcurbmat+Reconguttermat+Reconsidewalk
mat);
	Reconroadwayco = 
(float)(Reconscourseco+Reconpccco+Reconcurbco+Recongutterco+Reconsidewalkco);

	//Landscaping
	Reconplntarea= 4*2*5240*miles;
	Reconplntmat=(float)((Reconplntarea*2*91.5)/2024);
	Reconplntco= (float)(Reconplntmat*0.023);


	//Streetlights and signals
	Reconsignsmat= (float) (signsmat/4);
	Reconsignsco = (float)(signsco/4);
	Reconstlightsmat = (float)(stlightsmat/4);
	Reconstlightsco = (float)(stlightsco/4);
	Reconmarkingsmat = markingsmat;
	Reconmarkingsco = markingsco;
	Reconsignalsmat = (float)(signalsmat/4);
	Reconsignalsco = (float)(signalsco/4);
	Recontrafficductsmat = (float)(trafficductsmat/4);
	Recontrafficductsco = (float)(trafficductsco/4);
	Reconstlightssignalsmat = 
(float)(Reconsignsmat+Reconstlightsmat+Reconmarkingsmat+Reconsignalsmat+Recon
trafficductsmat);
	Reconstlightssignalsco = 
(float)(Reconsignsco+Reconstlightsco+Reconmarkingsco+Reconsignalsco+Recontraf
ficductsco);


	//LID
	//ponding = 6inch
	ReconLIDsoilneeded = LIDsoilneeded;
	ReconLIDaggregate =  LIDaggregate;
	ReconLIDunderdrain = LIDunderdrain;
	ReconLIDmulch = LIDmulch;
	ReconLIDwalls = LIDwalls;

	LIDsoilneeded= (int)(Stormwatercf/0.4/27);
	ReconLIDsoilneededmat = LIDsoilneededmat;
	ReconLIDsoilneededco = LIDsoilneededco;
	ReconLIDaggregatemat = LIDaggregatemat;
	ReconLIDaggregateco = LIDaggregateco;
	ReconLIDunderdrainmat = LIDunderdrainmat;
	ReconLIDunderdrainco = LIDunderdrainco;
	ReconLIDmulchmat = LIDmulchmat;
	ReconLIDmulchco = LIDmulchco;
	ReconLIDmat= (float) (ReconLIDsoilneededmat + ReconLIDaggregatemat + 
ReconLIDunderdrainmat + ReconLIDmulchmat);
```

```
	ReconLIDco = (float) (ReconLIDsoilneededco + ReconLIDaggregateco +
ReconLIDunderdrainco + ReconLIDmulchco);
	//wastematerial
	Reconwastematerial= (float) (Recongradingmat+(Recondrainagemat-
ReconWQinletmat)+ Reconplntmat+Reconstlightssignalsmat+ ReconLIDmat);


	System.out.println("");

System.out.println("RECONSTRUCTION: ");
	System.out.println("");
	System.out.println("Element               MatQuantity                CO
Waste");
	System.out.println("");
	System.out.println("Grading:");


	System.out.println("Existing Sur Pavement Removal material= "+
Reconpavementremovalmat+" Tons;    CO=" + Reconpavementremovalco+" Tons");
	System.out.println("Existing PCC Pavement Removal material= "+
Reconbaseremovalmat+" Tons;    CO=" + Reconbaseremovalco+" Tons");
	System.out.println("Existing Sidewalk Removal     material= "+
Reconsidewalkremovalmat+" Tons;    CO=" + Reconsidewalkremovalco+" Tons");
	System.out.println("Existing curb/gutter Removal  material= "+
Reconcurbgutterremovalmat+" Tons;    CO=" + Reconcurbgutterremovalco+"
Tons");
	System.out.println("Total Grading                 material= "+
Recongradingmat+" Tons;    CO=" + Recongradingco+" Tons");
	System.out.println("");

	//Drainage

	System.out.println("");
	System.out.println("Drainage:");
	System.out.println("Install Water Quality inlets material= "+
ReconWQinletmat+" Tons;    CO=" + ReconWQinletco+" Tons");
	System.out.println("Install Manhole  material             = "+
ReconManholemat+" Tons;    CO=" + ReconManholeco+" Tons");
	System.out.println("Install RCP pipe  material            = "+
ReconRCPpipemat+" Tons;    CO=" + ReconRCPpipeco+" Tons");
	System.out.println("Total Drainage Materials              = "+
Recondrainagemat+" Tons;    CO=" + Recondrainageco+" Tons");
	System.out.println("");

	//Roadway
	System.out.println("");
	System.out.println("Roadway:");
	System.out.println("PCC pavement          material= "+ Reconpccmat+"
Tons;    CO=" + Reconpccco+" Tons");
	System.out.println("Surfacecourse         material= "+
Reconscoursemat+" Tons;    CO=" + Reconscourseco+" Tons");
	System.out.println("Aggregate Base        material= "+ Reconpccmat+"
Tons;    CO=" + Reconpccco+" Tons");
	System.out.println("Curb                  material= "+ Reconcurbmat+"
Tons;    CO=" + Reconcurbco+" Tons");
	System.out.println("Gutter                material= "+ Reconguttermat+"
Tons;    CO=" + Recongutterco+" Tons");
```

```
	System.out.println("Sidewalk              material= "+
Reconsidewalkmat+" Tons;    CO=" + Reconsidewalkco+" Tons");
	System.out.println("Total Roadway         material= "+
Reconroadwaymat+" Tons;    CO=" + Reconroadwayco+" Tons");
	System.out.println("");


	System.out.println("");
	System.out.println("Lanscaping:");
	System.out.println("");
	System.out.println("Planting area            material= "+
Reconplntmat+" Tons;    CO=" + Reconplntco+" Tons");
	System.out.println("Total Planting area      material= "+
Reconplntmat+" Tons;    CO=" + Reconplntco+" Tons");
	System.out.println("");

	//Streetlights

	System.out.println("Streetlights & Traffic Control Devices:");
	System.out.println("");
	System.out.println("Signs                     material= "+
Reconsignsmat+" Tons;    CO=" + Reconsignsco+" Tons");
	System.out.println("Streetlights              material= "+
Reconstlightsmat+" Tons;    CO=" + Reconstlightsco+" Tons");
	System.out.println("Pavement Markings         material= "+
Reconmarkingsmat+" Tons;    CO=" + Reconmarkingsco+" Tons");
	System.out.println("Signals                   material= "+
Reconsignalsmat+" Tons;    CO=" + Reconsignalsco+" Tons");
	System.out.println("Trafficducts              material= "+
Recontrafficductsmat +" Tons;    CO=" + Recontrafficductsco+" Tons");
	System.out.println("Total Streelight & Traffic material= "+
Reconstlightssignalsmat+" Tons;    CO=" + Reconstlightssignalsco+" Tons");
	System.out.println("");

	//Stormwater

	System.out.println("Stormwater Management:");
	System.out.println("");
	System.out.println("Soil                      material= "+
ReconLIDsoilneededmat+" Tons;    CO=" + ReconLIDsoilneededco+" Tons");
	System.out.println("LID aggregate             material= "+
ReconLIDaggregatemat+" Tons;    CO=" + ReconLIDaggregateco+" Tons");
	System.out.println("Underdrain                material= "+
ReconLIDunderdrainmat+" Tons;    CO=" + ReconLIDunderdrainco+" Tons");
	System.out.println("Mulch                     material= "+
ReconLIDmulchmat+" Tons;    CO=" + ReconLIDmulchco+" Tons");
	System.out.println("Total Stormwater (LID)    material= "+
ReconLIDmat+" Tons;    CO=" + ReconLIDco+" Tons");

	System.out.println("");

	Reconcontotalmat = (float)
(Recongradingmat+Recondrainagemat+Reconroadwaymat+Reconplntmat+Reconstlightss
ignalsmat+ ReconLIDmat);
	Reconcontotalco = (float)
(Recongradingco+Recondrainageco+Reconroadwayco+Reconplntco+Reconstlightssigna
lsco + ReconLIDco);
```

```
      System.out.println("Total Construction               material= "+
contotalmat+" Tons;    CO=" + contotalco+" Tons");
      System.out.println("");System.out.println("");System.out.println("");


      System.out.println("Life Cycle Energy            = "+ Lifeenergy+"
Tons;    CO=" + Lifeenergyco+" Tons");
      System.out.println("");
      System.out.println("");

     //life cycle


      LCAmat = (float) (contotalmat + (2*resurftotalmat)+ Reconcontotalmat);
      LCAco = (float) ((float)(float)(contotalco + (2*resurftotalco)+
Reconcontotalco+ Lifeenergyco) - (0.833*Reconcontotalco)) ;
      runoffarea = (float)(((lanes *11) + (blanes * 5) + (12+ 4)) * miles *
5240);
      runoffareagallonconversion = (float) (3.17*35*7.48);
      LCAstormwater = (float)((runoffarea *
runoffareagallonconversion)/1000000);
      LCAstormwatercost = (float) (LCAstormwater*6550);
      LCAwastematerials = (float) (conswastematerial +
(2*resurfwastematerial)+Reconwastematerial);

      System.out.println("LCA                     material= "+ LCAmat+"
Tons;    CO=" + LCAco+" Tons");
      System.out.println("");System.out.println("");
      System.out.println("Stormwater Runoff                         = "+
LCAstormwater+"  MG");
      System.out.println("");System.out.println("");

      System.out.println("Life Cycle Impact Costs:");
      System.out.println("");

      contotalcocost = contotalco * 20;
      resurftotalcocost = resurftotalco *20;
      Reconcontotalcocost = Reconcontotalco *20;
      Lifeenergycocost = Lifeenergyco * 20;
      LCAcocost = LCAco*20;
      conswastematerialcost = conswastematerial*53;
      resurfwastematerialcost =  resurfwastematerial*53;
      Reconwastematerialcost = Reconwastematerial *53;
      LCAwastematerialscost =  LCAwastematerials *53;

      System.out.println("Construction  Carbon footprint Cost      = $"+
contotalcocost);
      System.out.println("Resurfacing  Carbon footprint Cost       = $"+
resurftotalcocost);
      System.out.println("Reconstruction Carbon footprint Cost     = $"+
Reconcontotalcocost);
      System.out.println("Energy Carbon footprint Cost             = $"+
Lifeenergycocost);
      System.out.println("LCA  Carbon footprint Cost               = $"+
LCAcocost);
      System.out.println("");System.out.println("");
```

```
      System.out.println("Stormwater Runoff  Cost                   = $ "+
LCAstormwatercost);
      System.out.println("");System.out.println("");
      LCAwastematerialscost = (float) (conswastematerialcost  +
resurfwastematerialcost + Reconwastematerialcost );

      totalLCAcost = LCAcocost + LCAstormwatercost + LCAwastematerialscost;
      System.out.println("LCA              Cost                  = $ "+
totalLCAcost);
      System.out.println("");System.out.println("");
      System.out.println("LCCA             Cost                  = $ "+
LCCAtotalcost);
      System.out.println("");System.out.println("");
      totalILCA2cost= totalLCAcost+LCCAtotalcost;

      System.out.println("Integrated Life Cycle Cost (ILCA2)       = $ "+
totalILCA2cost);
      System.out.println("");System.out.println("");



                    }
}
```