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RESEARCH REPORT

TOOLS TO SUPPORT GHG EMISSIONS REDUCTION: A REGIONAL EFFORT

Part 1 - Carbon Footprint Estimation and Decision Support

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16. Abstract

Tools are proposed for carbon footprint estimation of transportation construction projects and decision support for construction firms that must make equipment choice and usage decisions that affect profits, project duration and greenhouse gas emissions. These tools will enable responsible agencies and construction firms to predict and affect the impact of their construction-related decisions and investments.

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EXECUTIVE SUMMARY

The construction sector plays a significant role in worldwide greenhouse gas (GHG) emissions. The transportation construction industry contributes to these emissions through the burning of fossil fuels in the operation of heavy equipment, deforestation, and release of pollutants from on-site production and use of large quantities of off-gassing materials (e.g. asphalt and concrete). This study proposes tools for predicting or assessing the carbon footprint of construction and maintenance projects associated with roadways and other components of the transportation infrastructure. The developed tools will enable responsible agencies and construction firms to predict and affect the impact of their construction-related decisions and investments.

The first tool, the carbon footprint estimation tool (CFET), estimates the emissions footprint of construction projects in the transportation sector. This tool determines emissions from an inventory of equipment and construction processes, and credits efforts to reduce emissions through reforestation and equipment retrofit, while incorporating recent and future GHG policies on quantifying emissions. It was developed using the state-of-the-practice methodologies available nationally and is in accordance with global regulations under the IPCC Guidelines for National Greenhouse Gas Inventories. The benefits of this tool lie in its wide-applicability to a variety of users, as well as project sizes and types. Independently, this tool will enable construction companies to identify sources and reduce emissions, while also allowing state agencies to monitor these companies in accordance with GHG laws.

The ability to estimate emissions resulting from decisions related to equipment usage, material choice, and site preparation produced from CFET enables the development of an additional class of decision support tools. Specifically, an optimization-based methodology (a decision support tool) was developed that derives input from an emissions estimation tool to aid construction firms in making profitable decisions in terms of equipment choice and usage while simultaneously reducing project emissions or meeting relevant constraints imposed by recent emissions-related laws. A myriad of programs currently exist to support efforts toward reducing emissions from equipment use and materials production. However, it appears that no tools exist to aid

contractors in making optimal construction management plans with the goal of reducing emissions while minimizing the impact on costs. This methodology helps to fill that gap.

Given the high cost of new, more efficient equipment, older, more emissive equipment is often used on construction jobs. To encourage construction contractors to improve their fleet mix, new jobs undertaken in the United States often require that the equipment mix meet Environmental Protection Agency (EPA) Nonroad Diesel Tier System guidelines. These guidelines limit the number of older, less efficient equipment on a job site during specified periods of time. The proposed decision support tool permits a contractor to develop an equipment-usage plan that adheres to current environmental standards and anticipated new regulations, accounting for recent laws that might affect construction, and possible future carbon tax or cap and trade programs. Moreover, these tools assist contractors in trading off project cost, duration and resulting emissions in bid development and aid contractors in making green construction decisions. They will, likewise, allow transportation agencies to consider emissions as a factor in assessing bids. The techniques are designed to be generic and can be applied over varying geographic locations, site elevations, soil properties and other factors that affect equipment operation.

Collectively, the carbon footprint estimation and decision support tools were applied to data associated with the construction of the Inter-County Connector (ICC), a new roadway that will connect counties in Maryland. Application of the tools to this case study showed its utility and highlighted the need for reduction strategies.

CFET used estimates made from the data provided by the ICC Contract A as inputs and calculated the net emissions from the entire project over the duration of Contract A (2.5 years). The tool estimated emissions from each of the processes observed on the construction site, such as site preparation, operation of equipment and reforestation. Additionally, the tool was able to identify sources of high and low emissions, and quantify the sequestration capabilities attained by the ICC through reforestation efforts. Based on the inputs, the use of equipment on site proved to be the major GHG emitter, followed by deforestation; reforestation compensated for a small portion of the total emissions produced on-site. The tool also calculated the offsets that the project would require to purchase in order to achieve zero net emission status.

Analysis using the decision support tool showed that a substantial decrease in emissions can be achieved with a relatively small increase in equipment cost. For example, in the ICC case study, it was found that a savings of 12% in emissions can be achieved through a 0.95% increase in total cost with the use of more efficient, less emissive equipment. The tool further aids in establishing a reasonable cap on emissions for a given project so as to prevent excessive strain on a budget.

This work supports both local and worldwide efforts, such as those of the 193 countries that participated in the United Nations Conference on Climate Change in 2009 in Copenhagen, Denmark to reduce regional and national emissions and limit the rise of global temperatures.

This work is part of a larger regional effort to develop tools to support GHG emissions reduction. The regional effort is funded by the Mid-Atlantic University Transportation Center, Maryland State Highway Administration and NAVTEQ.

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Acronym	
ACES	American Clean Energy and Security Act
ARB	Air and Resource Board (under U.S. state of California)
ARRA	American Recovery and Reinvestment Act of 2009
BOF	Basic Oxygen Furnace
C stock	Carbon stock
CDM	Clean Development Mechanism
CAR	Climate Action Report (developed by U.S. Government)
CCSP	Climate Change Science Program
CCTP	Climate Change Technology Program
CCX	Chicago Climate Exchange
C-density	Carbon density
CEMS	Continuous emission monitoring system
CER	Certified Emissions Reduction
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
COP15	United Nations Conference on Climate Change
CORINAIR	Core Inventory of Air Emissions in Europe
DOE	Department of Energy (under U.S. Government)
DOT	Department of Transportation (under U.S. Government)
EAF	Electric Arc Furnace
ECMT	European Conference of Ministers of Transport
EF	Emission factor
EFDB	Emission factor database (by IPCC)
EIIP	Emissions Inventory Improvement Program (by EPA)
EPA	Environmental Protection Agency (under U.S. Government)
FIADB	Forest Inventory and Analysis Database (by USDA)
GHG	Greenhouse Gas
GWP	Global warming potential
ha	Hectare
hp	Horsepower
ICC	Inter County Connector
IPCC	International Panel on Climate Changes (under UNFCCC)
kg	Kilogram

L	Liters
LSD	Low sulfur diesel (550 ppm)
M2M	Methane to Markets
MC	Medium cure asphalt
MD	State of Maryland
MMT	Million metric tons
MT	Metric tons
N	Nitrogen
N_2O	Nitrous dioxide
NASA	National Aeronautics and Space Administration (under the U.S. Government)
NCDC	National Clean Diesel Campaign by EPA
NO	Nitric oxide
NOx	Nitrogen oxides
O_2	Oxygen
O_3	Ozone
OHF	Open Hearth Furnace
OTAQ	Office of Transportation and Air Quality (under U.S. Government)
PM	Particulate matter
ppm	Parts per million
RC	Rapid cure asphalt
RGGI	Regional Greenhouse Gas Initiative
ROG	Reactive organic gas
SC	Slow cure asphalt
SHA	State Highway Administration (of MD)
SOC	Soil organic carbon
SOx	Sulfur oxides
U.S.	United States of America
ULSD	Ultra low sulfur diesel (15 ppm)
UNFCCC	United Nations Framework Convention on Climate Change
USDA	Unites States Department of Agriculture
VOC	Volatile organic content
WHO	World Health Organization (under United Nations)

Chapter 1. Introduction

The turn of the 21st Century saw the world population rise to approximately 6.7 billion, of which the United States accounts for almost five percent [U.S Census Bureau, 2009]. This exponential growth has created an increased demand on energy and other natural resources, resulting in wide-spread impact on the environment. Growing awareness of the impact of greenhouse gas (GHG) emissions produced by humans on climate change has brought critical attention towards developing strategies to identify their sources, and to estimate and reduce their magnitude. This project aids in the estimation and reduction of GHG emissions in construction projects associated with roadways and other components of the transportation infrastructure. The objective was to conceptualize and build tools that will enable responsible agencies to assess and predict the impact of their construction-related decisions and investments. Specifically, an emissions estimation tool was developed to quantify the carbon footprint of these construction efforts. In addition, optimization-based techniques that derive input from this emissions assessment tool were created to aid construction firms in making profitable decisions in terms of equipment choice and usage while simultaneously meeting relevant constraints imposed by recent emissions-related laws.

While GHGs are vital to life on earth to help regulate surface temperatures and the climate, constant deposition through human activities in the past decades has resulted in excessive concentrations in the atmosphere causing global warming. Global warming is known to have several environmental (e.g. melting of polar ice, increased frequency of severe weather events, etc.,) and health effects. With the intention of reversing the effects of climate change, global and national agencies have developed and continue to develop regulatory policies, such as the Kyoto Protocol and the American Recovery and Reinvestment Act, to reduce emissions. Chapter 2 presents an overview of GHGs, its sources and the general effects of climate change. Current and future polices in relation to GHG reduction are also discussed in this chapter.

The common methods of calculating GHG emissions are based on an emission factor and conversion to carbon dioxide equivalents (CO_2e). They are presented in Chapter 3. Existing models employed in carbon emissions estimation are also reviewed.

Chapter 4 focuses on emissions in the construction industry in the United States (U.S.) and the impact of specific governmental emissions reduction strategies on the industry. Many of these strategies, like the U.S. Environmental Protection Agency's (EPA) Clean Air Nonroad Diesel Rule, have already been implemented and are establishing standards for the management of construction projects. This chapter introduces the motivation behind this research and project, since construction agencies will be required to evolve in their methods to meet these strict standards.

Chapter 5 describes in detail the methodologies and assumptions used to develop the carbon footprint estimation tool proposed herein. The carbon estimation tool will determine emissions from operation of an inventory of applicable equipment (type, brand and age), and construction processes (site preparation, materials productions, etc.), while crediting any efforts to reduce GHG emissions through reforestation or equipment retrofit. The tool also incorporates recent and future GHG policies on quantifying emissions.

In Chapter 6, optimization-based techniques are proposed that derive input from the emissions estimation model presented in Chapter 5. Mathematical models were formulated to generate optimal or Pareto-optimal decisions in terms of equipment choice and usage simultaneous with reducing project emissions or meeting relevant constraints imposed by recent emissions-related laws. These models are intended for use by construction firms in making profitable, but green decisions.

The tools were applied to data obtained from the Intercounty Connector (ICC) project as a case study to evaluate their utility and efficiency in Chapter 7.

The developed tools enable construction companies to actively reduce emissions and optimize the construction process and costs. Simultaneously, these tools will allow state agencies to monitor these companies in accordance with recent GHG reduction laws at both state and federal levels. These and other benefits are described in Chapter 8. A discussion of potential uses of the developed tools beyond transportation infrastructure construction is also provided.

Chapter 2. Background

2.1 Overview of Greenhouse Gas Emissions

Greenhouse effect is a natural phenomenon that is induced when atmospheric gases trap the ultraviolet rays from the sun within the earth's atmosphere. It is therefore essential in maintaining the earth's temperature and climatic conditions. Naturally occurring atmospheric gases such as water vapor, carbon-dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), ozone (O_3) and, anthropogenic-produced gases such as halocarbons, nitric oxide (NO), carbon-monoxide (CO), aerosols, and fluorinated gases are collectively classified as greenhouse gases (GHGs). Additionally, other air pollutants such as sulfur oxides (SO_x), reactive organic gases (ROG) and particulate matter (PM) also indirectly affect greenhouse gas effect [USEPA, 2010c].

CO_2 is produced primarily from the combustion of fossil fuels, like petroleum, diesel and biofuels, and biomass, such as trees and solid wastes as a result of their high carbon content. It is also formed naturally during biological respiration and artificially during the production of materials, like cement, steel, asphalt and chemicals. CO_2 is sequestered through the natural carbon cycle by forests and oceans. CH_4 is emitted from the burning of fuels as well, in addition to being produced from livestock, agricultural practices and decay of organic material [USEPA, 2010c]. NO and NO_2, the primary constituents of NO_x emissions, are formed when nitrogen (N), either in the air or in fuel, combines with oxygen (O_2) at high temperatures. Other pollutants, such as PM and CO, are formed as a result of incomplete combustion of fuel; whereas, SO_x are formed from the sulfur content in the fuel [USEPA, 2009b].

Although the earth produces GHGs through natural processes, such as respiration of plants and animals, volcanic eruptions and regular changes in temperatures, the concentration of these gases in the atmosphere is maintained through natural absorption by forests and oceans. However, since the industrial revolution, anthropogenic activities, such as use of fossil fuels, and deforestation for urbanization and agriculture, have resulted in an increased deposition of these gases into the atmosphere [IPCC, 2007]. The International Panel on Climate Change (IPCC) has established a strong correlation between the anthropogenic deposition of GHGs and global warming resulting in climate change. Due to its large volumetric prevalence, CO_2 is considered a major player in elevating greenhouse effect, and accounts for approximately 86% of all U.S. emissions. CO_2 emissions are increasing at a rate of about 0.3% per year, resulting in almost a 36% total increase since the Industrial Revolution [USEPA, 2009a]. The excessive presence of GHGs, further worsened by the constant growth in population, magnifies the greenhouse effect, thereby raising the earth's temperature and bringing about 'global warming'. Global warming is a result of the exacerbation of the earth's greenhouse effect.

Some of the observed effects of climate change include increase in the earth's temperatures, melting of the glacial ice-caps, rise in sea level, and variations in the length of seasons. Recent years (1995 to 2006) have been recorded to be the warmest years since 1850. The warmer temperatures are known to cause changes in regional precipitation, later freezing and earlier break-up of ice on rivers and lakes, lengthening of growing seasons, shifts in plant and animal ranges, and earlier flowering of trees. The sea level has been predicted to rise between seven and twenty-three inches by 2080, posing increased risk of loss of land and habitats, and danger to human population in coastal areas. Moreover, the changes in climatic conditions have increased the probability and intensity of extreme climatic events, such as hurricanes, droughts, wildfires and other natural disasters, resulting in damage to human lives, property and the nation's economy [IPCC, 2007].

Beside the environmental effects, climate change is also known to affect human health directly from exposure to heat-waves or cold fronts, and the lengthening of transmission seasons of vector borne diseases that thrive in warm temperatures. Decreased air quality has contributed to increased incidence of respiratory diseases and damage to lung tissue [WHO, 2003].

Although each of the GHGs have varying effects on the environment and human health, it is critical that their concentrations in the atmosphere be reduced to curb climate change and, therefore, preserve the earth for future generations.

2.2 Greenhouse Gas Policies and Regulations: Global and National

The United Nations Framework Convention on Climate Change (UNFCCC) was developed in 1994 to address the urgent need to reduce GHG emissions and, thus, curb climate change. 193 nations collectively established the Framework's objective of "…stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" [ECMT, 2007]. In 1997, the UNFCCC members drew up the Kyoto Protocol, an international binding agreement signed by 37 industrialized countries and ratified by 55 nations (not including the U.S.), all committing to reduce GHG emissions to 5% below their 1990 levels by 2012. The Framework presents market-based strategies, such as emission trading, clean development mechanisms and joint implementation to help participants implement the Protocol. Although the Framework provides these global options, it strongly encourages that national measures be taken [UNFCCC, 2010].

Under its commitment to the UNFCCC, the U.S. government develops a national emissions inventory annually, recording sources and sinks of emissions from various sectors of the economy. These inventories are developed in accordance with the guidelines established by the IPCC. Additionally, the State Department authors the annual Climate Action Report documenting current climatic conditions, GHG emissions, policies and regulations [U.S. Department of State, 2006].

Within the U.S., the government collaborates with several federal agencies, such as the Environmental Protection Agency (EPA), Department of Energy (DOE), Department of Transportation (DOT), Department of Agriculture (USDA) and National Aeronautics and Space Administration (NASA), in efforts to monitor and reduce emissions. However, most of these efforts are executed under the close guidance of the USEPA.

In its efforts to abate emissions, the government has developed initiatives/programs, some of which facilitate technological and informational exchange, while others provide financial incentives. One of the notable informational exchange initiatives is the Climate VISION Partnership established between major industrial sectors (e.g. oil and gas, transportation, electricity generation, mining, manufacturing and forestry products) and four U.S agencies (DOE, EPA, USDA, and DOT) to reduce GHG emissions in the next decade.

Similarly, the Clean Energy-Environment State Partnership Program and the Climate Leaders program are collaborations between EPA and states, and private companies, respectively, to encourage goals and establish concrete strategies towards emissions reduction. Other initiatives, like ENERGYSTAR buildings and Green Power Partnerships, deal with reduction of emissions through improving energy efficiency. The Climate Change Technology Program (CCTP) and the Climate Change Science Program (CCSP) are initiatives that revolve around the development of clean technology and the improvement in the understanding of the science behind climate change [USEPA, 2010c].

2.3 Emissions reductions: The Future

As the awareness of global warming continues to grow, political and public sentiments have been increasing towards employing strategies that promote clean development and, thereby, reduce national emissions. Being the North American country that ranks as the top emitter per capita worldwide, the U.S. contributes almost 19.4% of global emissions but only accounts for 5% of global population [IPCC, 2007]. This has resulted in a watchful eye towards U.S. efforts in reducing its emissions. Moreover, in the recent 2009 United Nations Conference on Climate Change (COP15), the U.S. developed the Copenhagen Change Accord in collaboration with other top emitters in the world (China, Brazil, India and South Africa) to set forth the groundwork for global action against climate change. According to the Accord, the U.S. pledged a 17% decrease of its 2005 levels by 2020.

Already under the Obama Administration, the energy provisions of the American Recovery and Reinvestment Act of 2009 (ARRA) promotes emissions reduction through energy efficiency. The $787 billion Act not only provides tax incentives for use of renewable energy and energy-efficient technologies, but also grants, contracts and loans for programs in energy-efficiency. Under this act, with approximately $300 million in financial assistance, the EPA strengthened the National Clean Diesel Campaign (NCDC) [ARRA, 2009]. Therefore, the U.S. government is exploring various federal and state legislative options towards wide-spread emissions reduction. These include, but are not restricted to, enforcing a carbon tax and/ or carbon trading system, and carbon allowances [UNFCC COP15, 2009].

Besides technological advancement in carbon reduction, governments are considering instituting limitations, in the form of caps, on carbon emissions. Such caps, once enforced, will require companies to either comply with national or regional regulations, and/or pay a penalty for noncompliance or excessive GHG emissions production. National efforts to reduce emissions include the set-up of partnerships to implement cap-and-trade programs. Seven U.S. states in the Northeast and Mid-Atlantic regions have set up a regional mandatory cap-and-trade market system called Regional Greenhouse Gas Initiative (RGGI) that aims to reduce emissions from the power sector by 10% by 2018 and sell carbon offsets. Proceeds from this effort are channeled to various clean energy projects [RGGI, 2009]. Several U.S. states have since established local carbon markets that allow individuals and businesses to purchase and sell carbon offsets. The Maryland Terrapass and Chicago Climate Exchange (CCX) are two examples of state based carbon trading programs [MD Terrapass, 2010 & CCX, 2010]. Other market-based emissions reductions programs include the Methane to Markets (M2M) initiative chaired by the EPA. This global program focuses on the recovery and sale of CH_4 as clean energy [USEPA, 2010b]. While carbon markets that permit the buying and selling of carbon allowances between companies, industries and countries successfully exist internationally, the wide-spread establishment of such markets in the U.S. is likely to have a significant effect on all sectors of the economy.

With several of these global and national policies as a foundation, the world has begun to set the stage to develop stringent programs to combat climate change. This in turn will have an effect on the future functioning of business across the world.

Chapter 3. Greenhouse Gas Emissions Calculations

3.1 Emission Factor (EF)

The quantification of emissions is vital in the management of air quality. Emissions estimates help identify key sources and enable the development of strategic tools to combat poor air quality. Emissions are determined via the use of an appropriate emission factor (EF). An EF is "a representative value that relates the quantity of pollutant released to the atmosphere with an activity associated with the release of that pollutant" [USEPA, 2010c].

EFs are typically long-term averages developed from published technical data, documentation from emission tests or continuous emission monitoring systems (CEMS) and personal communication. Since the development of EFs is dependent on the data available, their accuracy is sometimes imperfect. Hence, the use of an EF in quantifying emissions is at best an approximation unless based on long-term empirical data [USEPA, 1997]. Table 3-1 lists well known EFs for a variety of fuels used in transportation.

Several EF databases are maintained globally and nationally to facilitate agencies, industries, consultants, and other users in estimating emissions. The IPCC manages an EF database (EFDB) library based on The Core Inventory of Air Emissions in Europe (CORINAIR). The EFDB allows the user to obtain EFs based on IPCC source/sink categories, which include energy, land use change, solvents, industries, etc. [IPCC-NGGIP, 2009].

EPA's AP-42 document is a compilation of EFs for air pollutants used within the U.S. Several website databases, such as CHIEF and FIRE, access EFs from the AP-42 and related documents. Many U.S. states have also developed similar software models and documents for the purpose of producing state emissions inventories [USEPA, 2010c].

EFs are ranked based on their methods and the expanse of the data used in their development. The EPA AP-42 EF ratings are assigned as in Table 3-2.

Table 3-1. Carbon dioxide emission factors of transportation fuels.

Source: EIA, 2010

Transportation Fuel	Emission Factors	
	Pounds CO_2 per Unit of Volume	Kilograms CO_2 Per Million BTU
Aviation Gasoline	18.33 per gallon	69.16
Biodiesel		
▪ B100	0 per gallon	0.00
▪ B20	17.89 per gallon	59.44
▪ B10	20.13 per gallon	66.35
▪ B5	21.25 per gallon	69.76
▪ B2	21.92 per gallon	71.8
Diesel Fuel (No.1 and No.2)	22.37 per gallon	73.15
Ethanol/Ethanol Blends		
▪ E100	0 per gallon	0.00
▪ E85	2.93 per gallon	14.71
▪ E10 (Gasohol)	17.59 per gallon	65.94
Methanol/Methanol Fuels		
▪ M85	10.68 per gallon	64.01
Motor Gasoline	19.54 per gallon	70.88
Jet Fuel, Kerosene	21.09 per gallon	70.88
Natural Gas	120.36 per 1000 cubic feet	53.06
Propane	12.67 per gallon	63.07
Residual Fuel (No.5 and No.6 Fuel Oil)	26.00 per gallon	78.8

Table 3-2. AP-42 ratings of emission factors established by USEPA.

Source: USEPA, 2009b

Rating	Quality	Assignment Analysis
A	Excellent	Excellent. Emission factor is developed primarily from A and B rated source test data taken from many randomly chosen facilities in the industry population. The source category population is sufficiently specific to minimize variability.
B	Above Average	Emission factor is developed primarily from A or B rated test data from a moderate number of facilities. Although no specific bias is evident, is not clear if the facilities tested represent a random sample of the industry. As with the A rating, the source category population is sufficiently specific to minimize variability.
C	Average	Emission factor is developed primarily from A, B, and C rated test data from a reasonable number of facilities. Although no specific bias is evident, it is not clear if the facilities tested represent a random sample of the industry. As with the A rating, the source category population is sufficiently specific to minimize variability.
D	Below Average	Emission factor is developed primarily from A, B and C rated test data from a small number of facilities, and there may be reason to suspect that these facilities do not represent a random sample of the industry. There also may be evidence of variability within the source population.
E	Poor	Factor is developed from C and D rated test data from a very few number of facilities, and there may be reason to suspect that the facilities tested do not represent a random sample of the industry. There also may be evidence of variability within the source category population.
U	Unrated	Unrated (only used in the L&E documents). Emission factor is developed from source tests which have not been thoroughly evaluated, research papers, modeling data, or other sources that may lack supporting documentation. The data are not necessarily "poor," but there is not enough information to rate the factors according to the rating protocol. "U" ratings are commonly found in L&E documents and FIRE rather than in AP 42.

3.2 Carbon Density (C-density)

CO_2 is constantly cycled between the atmosphere and forest systems. Trees continually absorb CO_2 from the atmosphere via photosynthesis to grow and store it in the form of carbon in the biomass of the tree (leaves, trunk, roots, etc.). CO_2 is also stored as carbon in soil, which accumulates when organic matter decomposes. Most soil organic carbon (SOC) is stored within the first meter depth from the soil surface. The amount of CO_2 absorbed and therefore the carbon stored, depends on the tree type, age, and size, as well as climatic conditions of the region. Together, the amount of carbon stored in the biomass and the soil is termed the carbon stock (C-stock) of that ecosystem and is quantified by the carbon density (C-density) of that system. C-density is, therefore, defined as the average mass of carbon stored in the biomass of a living system per area of that system. Table 3-3 lists the C-density of the various forests types (where non-soil refers to the carbon stored in tree parts, and soil refers to that stored in the soil) in the northeast region of the U.S. [USEPA, 2009a].

Table 3-3. Carbon density values for various forest types in the northeast region of the U.S. *Source: USEPA, 2009a*

Region	Forest Type	Carbon Density (MT/ha)	
		Non-Soil	Soil
Northeast (CT,DE,MA,MD,ME, NH,NJ,NY,OH,PA,RI, VT,WV)	White/Red/Jack Pine	135.8	78.1
	Spruce/Fir	104.2	98
	Oak/Pine	127.1	66.9
	Oak/Hickory	115	53.1
	Elm/Ash/Cottonwood	96.2	111.7
	Maple/Beech/Birch	129.4	69.6
	Aspen/Birch	72.6	87.4
	Minor Types & Nonstocked	80.1	82.7
	All	118.2	69.7

3.3 Measuring Greenhouse Gases: GWP and Units

3.3.1 Global Warming Potential (GWP)

GHGs are measured qualitatively through the intensity of their effect on the earth's atmosphere. This intensity is determined by the GHG's global warming potential (GWP). GWP is defined as "the ratio of radioactive force absorbed by one unit mass of the greenhouse gas to that of one unit mass of reference gas over a specified time period". CO_2 is the globally accepted reference gas with a GWP of one, and GWP is typically measured for 1-, 20-, 50-, and 100-year time periods [USEPA, 2006 & IPCC, 2007]. For example, the GHG CH_4 with a 100-year GWP of 21 has 21 times the effect on the atmosphere as compared to CO_2. Table 3-4 lists the GWP values of some common GHGs. The GWPs for all species of air pollutants as mandated by the IPCC can be found in Appendix A.

Table 3-4. GWP Values for some common GHGs. *Source: IPCC, 2007*

Species	Chemical Formula	Lifetime (Years)	Global Warming Potential (Time Horizon)		
			20 years	100 years	500 years
Carbon Dioxide	CO_2	Variable	1	1	1
Methane	CH_4	12±3	56	21	6.5
Nitrous Oxide	N_2O	120	280	310	170
HFC-23	CHF_3	264	9100	11700	9800
Perfluoromethane	CF_4	50,000	4400	6500	10,000
Sulphur hexafluoride	SF_6	3200	16,300	23,900	34,900

In addition to being a measure of a GHG's effect on the atmosphere, GWPs are used to convert GHGs into carbon-dioxide equivalents (CO_2e). This allows for the use of an easy and standard unit for reporting quantities of GHGs being measured. Mass units of GHG are converted to CO_2e by multiplying the amount by its GWP. For example, 50 pounds of CH_4 = 50 pounds x 21= 1,050 pounds CO_2e [IPCC, 2007].

3.3.2 Units of Measurement

The units of measurement are typically recorded in teragrams (Tg) or million metric tons (MT). Common units of measurement and their conversions are listed in Table 3-5.

Table 3-5. Common units of measurement of GHGs & their conversions.
Source: USEPA, 2005a

From		To
1 metric ton of carbon equivalent	=	3.667 metric tons CO_2e
1 metric ton of CO_2e	=	0.2727 metric tons of carbon equivalent
1 teragram	=	1 million metric tons
1 kilogram	=	2.205 pounds
1 pound	=	0.000454 metric ton
1 metric ton	=	1.102 tons

The U.S. Inventory of GHGs typically accounts for CO_2, CH_4, CO, NO_2 and fluorinated gases emitted from various sources, while estimating GHGs in Tg CO_2e. However, since these GHGs contribute towards air pollution, several inventories of emission estimates, especially those from vehicles, also include other pollutants, such as SOx and PM.

3.4 Overview of Existing Estimation Models of Greenhouse Gases in the U.S.

Several models currently exist that enable the quantification of GHGs and the subsequent development of emissions inventories. Under the Clean Air Act, the EPA creates models that estimate emissions from various sources. The NONROAD2008 model helps in the inventory of emissions from non-road vehicles and diesel equipment whereas the recent MOVES2010 model estimates on-road and highway vehicle emissions. On the other hand, GLOBEIS estimates the volatile organic content (VOC), CO and soil NOx emissions from biogenic sources [USEPA, 2010c]. The USDA developed two models, the Carbon Online Estimator (COLE) and Carbon Calculation Tool (CCT), which estimate C-stocks and measure carbon flux for regions in the U.S. based on forest inventory data, respectively [USDA NRS, 2010].

Additionally, many states and private agencies develop models to estimate emissions.

The state of California's Air and Resource Board (ARB) is a pioneer in developing specific strategies and regulations towards emissions reduction. The EMFAC2007 model is one such model that calculates emission rates from all on-road vehicles operating on the state's roads [ARB, 2007]. The OFFROAD2007 model, on the other hand, estimates the contribution of emissions due to agricultural, construction, lawn and garden equipment, as well as recreation vehicles [ARB, 2009]. California's URBEMIS2007 model calculates project-specific air pollution emissions for a variety of urban land-use projects. Specifically, the model estimates NOx, ROG, CO, CO2 and PM emissions from the operation of equipment for the construction of an urban area (e.g. residential or educational areas) and use of associated materials (i.e. asphalt and natural gas) [Rimpo, 2007]. Table 3-6 provides a summary of the existing GHG estimation models.

Table 3-6. Summary of current models in emissions estimation & their uses.

Emissions Type	Model Name	Source	Air Pollutant/ GHGs Estimated	Utility
	NONROAD2008	EPA	CO, CO_2, NOx, SOx, HC, PM	Non-road vehicles and diesel equipment.
	URBEMIS	AQMD	CO, CO_2 , NOx, PM, ROG	Air pollutants from construction of urban projects.
	EMFAC2007	California ARB	CO, CO_2, NOx, SOx, HC, PM, Lead	On-road vehicles in California.
	OFFROAD2007	California ARB	CO, CO_2, NOx, SOx, HC, PM	Agricultural, construction, lawn and garden equipment, and recreation vehicles.
Biogenic	GLOBEIS	EPA	VOC, CO and soil NOx	Emissions from biogenic sources.
	COLE	USDA	Carbon	Tool for forest carbon analysis.
	CCT	USDA	Carbon Stock	State-level annualized estimates of carbon stocks on forestland.

The majority of these models determine individual source emissions (e.g. passenger cars) and rarely determine comprehensive emissions for a source category (e.g. transportation). Therefore, there exists a need for an all-encompassing emissions estimation model that will enable users to quantify emissions from various sources simultaneously. This, in turn, will encourage and support proactive efforts in GHG emission reduction.

Chapter 4. Emissions in Construction

4.1 Emissions in the Construction Sector

The 873.1 billion U.S. dollar construction industry (2003) in the U.S. ranks first among 55 nations globally [USEPA, 2008]. The industry is vital in the development of the nation's infrastructure, which includes construction of residential and industrial buildings, roads, bridges and other long-standing structures. Within the U.S., this industry permeates both the transportation and industrial sectors as it involves the use of non-road vehicles and equipment, like excavators and cranes, and supports large construction-based industries, like cement and chemicals. The transportation and industry sectors contribute almost 28% and 33% to U.S. national emissions, respectively. Collectively, emissions from the construction industry amount to nearly 2% (~131 MMT CO_2e) of the total U.S. emissions (Figure 4-1) [USEPA, 2008]. Despite the economic recession, it has been estimated that by 2030, about half of the buildings in America will have been built after 2000, implying that half the volume of urban structures will be constructed within 25 years just to support population growth [Nelson, 2004]. While each individual construction project may not produce large quantities of GHGs compared with operations in other sectors, because there are consistently a large number of on-going construction projects, the aggregate product of these projects is large [Truitt, 2009]. The construction industry is the third largest industrial emitter of CO_2 (Figure 4-1) [USEPA, 2008].

A majority of construction emissions result from either the use of fuel for operating equipment and vehicles, or production of electricity in the transportation segment of the construction sector [USEPA, 2009d].

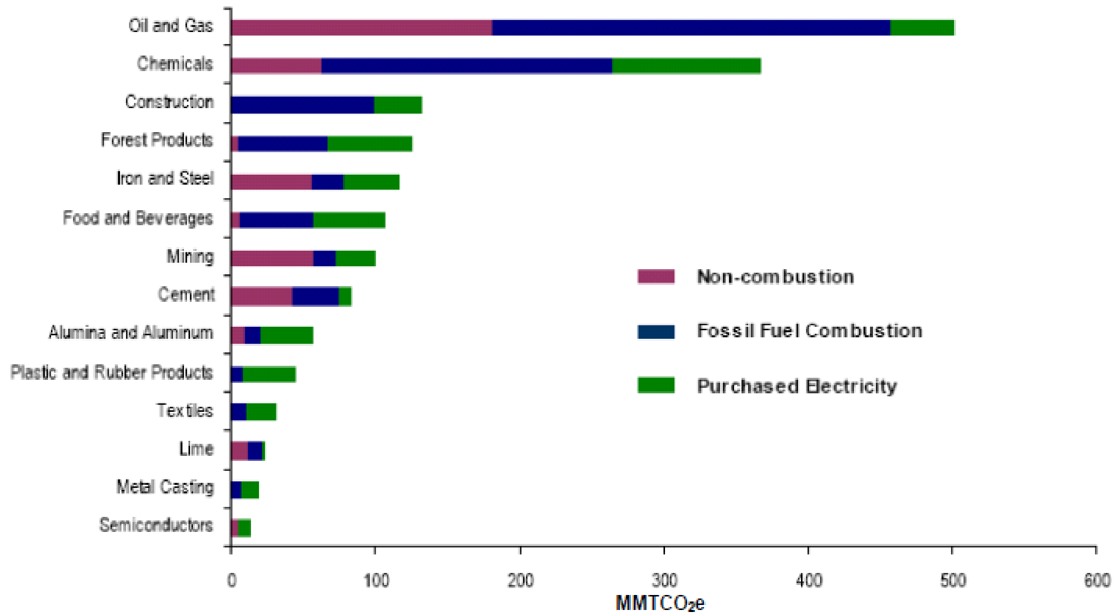

Figure 4-1. Construction industry as the 3rd largest emitter amongst all U.S. industries.
Source: USEPA, 2009d

The transportation sector in the U.S. is divided into transportation vehicles (on– and non-road) and non-transportation vehicles. Transportation vehicles include cars, motorcycles, light and heavy trucks, buses, ships and aircraft, among others; non-transportation vehicles include construction, agricultural and commercial equipment, generators and recreational vehicles [USEPA, 2009e]. The construction industry's contribution to GHG emissions within this sector is, in large part, like on-road traffic, due to its dependence on fossil fuel for energy required to operate heavy equipment. However, the average rate of production of emissions is much greater for construction equipment (i.e. non-road vehicles) as compared to passenger vehicles (see Report MS-12 1997 for more detail) due to differences in fuel type (i.e. diesel versus gasoline), engine technology, and horse power. For example, one can estimate that a typical excavator produces 454 pounds of CO_2e per hour of operation, while a typical medium-size passenger vehicle (or sports utility vehicle) produces 55 (or 78.5) pounds of CO_2e per hour of operation. With continuing demand for fossil fuel, sustained increase in GHG emissions is predicted [USEPA, 2010c]. As seen in Figure 4-2, construction equipment contributes significantly towards the emissions from non-transportation vehicles, resulting in 2% or approximately 59.7 MMT CO_2e of the transportation emissions [OTAQ, 2006].

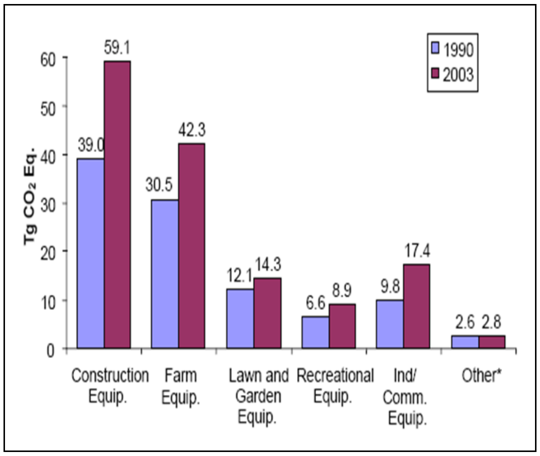

Figure 4-2. Construction equipment as leading emitter among non-transportation sources.
Source: OTAQ, 2006

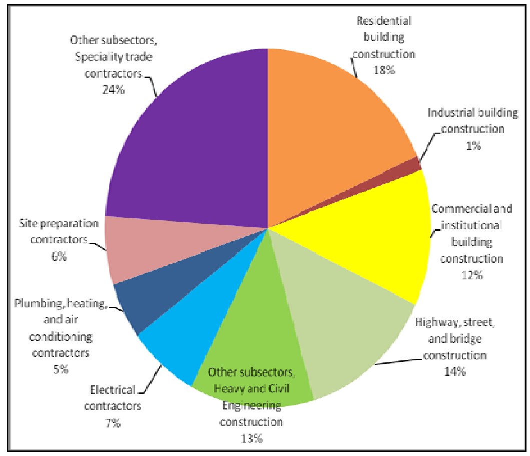

Figure 4-3. Division of emissions from construction industry by sub-sectors.
Source: USEPA, 2009d

The remainder of the 131 MMT CO_2e of the total construction emissions stems from the use of electricity and off-gassing from industrial processes in the construction industry, including cement and materials production, and use of chemicals and steel. These processes are particularly important while considering emissions due to the construction of buildings, and heavy and civil engineering subsectors of the industry (Figure 4-3) [USEPA, 2009d].

In addition, the construction industry reduces emission sinks as building of structures often call for deforestation of standing forests, which are important sources of atmospheric carbon sequestration.

4.2 Emission Reduction Polices in Construction

To foster mitigation efforts to reduce industrial and construction-related environmental impact associated with GHG emissions, improvements in technologies to aid in monitoring, and methods to encourage individual and institutional accountability towards emissions reductions, are being developed. The Office of Transportation and Air Quality (OTAQ) has established programs that have already produced wide-scale reductions. Some of these programs directly impact or regulate the construction industry. The most evident of these is the National Clean Diesel Campaign (NCDC) that promotes immediate improvement in air quality from diesel engines through various regulatory and voluntary strategies. The voluntary Diesel Retrofit Technology Verification Program provides agencies a list of retrofit technologies approved by the EPA. The technologies typically enable reductions of emissions between 20 and 90%. However, it is the NCDC regulatory programs that have had the most impact. The Clean Air Nonroad Diesel Rule establishes a set of standards mandated by the EPA towards reductions of emissions from diesel engines by almost 90%. The EPA has also established a tier system, and enforces the use of low sulfur diesel in heavy-duty engines.

The EPA's tier system regulates emissions from diesel engines based on the equipment age and horsepower (Appendix B). The system has four levels: tier 1, 2, 3 and 4. Conceptually, a tier 1 level vehicle would be older and produce greater emissions as compared to a tier 4 level vehicle. Although not strictly mandated, EPA strongly encourages construction projects to utilize higher tiered equipment so as to reduce construction emissions. This would imply that either the construction equipment fleet should be relatively new or the older equipment must be retrofit with reduction technologies. Also, according to these standards, manufacturers would be required to meet the most recent set of emissions standards put forth by the EPA. The ultra-low sulfur diesel (ULSD) produces a 99% reduction of the sulfur content in the fuel, reducing from current levels of 3300 parts per million (ppm) to 15 ppm. The most updated tier system took effect in 2008; the diesel fuel rule will be executed starting in 2010 [USEPA, 2009c].

4.3 Project Motivation

Currently, construction emissions are only calculated to develop state and national inventories. Also, traditional approaches for construction planning do not consider emissions as a decision factor. Studies have shown that almost 53% of survey respondents do not employ any form of emissions reduction strategies (Figure 4-4) [USEPA, 2008]. This is mainly because the development and installation of lower emitting vehicle technology is time-consuming, expensive, and sometimes creates unfavorable trade-offs between cost, productivity and emissions. Similarly, green efforts or environmental restoration involves permitting processes that are tedious and expensive. Therefore, the present sentiment in the construction industry towards emissions reduction is for the most part negative or neutral [USEPA, 2009d].

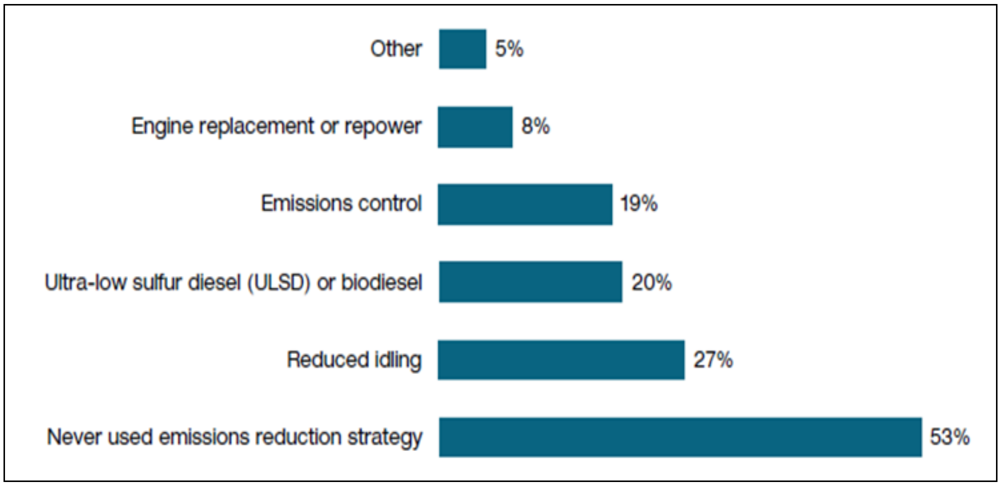

Figure 4-4. Industry survey of construction firms that use emissions reduction strategies. *Source: USEPA, 2008*

However, future implementation of carbon reduction programs (e.g. cap, tax, or imposition of stricter standards) will define how contractors bid on jobs and implement their construction plans to meet these standards while remaining profitable. Numerous works such as Toenjes [Toenjes, 2010], proclaim the need for emissions reduction in the transportation construction sector and explicitly recognize the need for construction firms to prepare for changes in local and national clean-air regulations. This project and research seeks to aid in filling the gap that currently exists to specifically offer emissions estimation and decision analysis pertaining to construction of transportation infrastructure. A set of tools is thus proposed herein for this purpose.

Firstly, a carbon footprint estimation tool (CFET) was developed to facilitate these companies in identifying sources and quantifying emissions from their projects, thereby aiding their efforts in emissions reduction. Secondly, decision support techniques were developed using an optimization-based methodology to permit a construction firm to assess its equipment needs while accounting for the GHG emissions resulting from equipment use and policy makers to set carbon price, caps and penalties for noncompliance. The details of the proposed tools, their development, uses, and benefits are discussed in the following chapters.

Chapter 5. Carbon Footprint Estimation Tool (CFET) for Construction Projects

5.1 Description of CFET

The state-of-the-art and state-of-the-practice in relevant carbon footprint computation used nationally and around the globe were reviewed. Various estimation models (Table 3-6), the IPCC Guidelines, and EPA best-practice methodologies were evaluated for their potential to aid in GHG emissions estimation for activities on individual construction projects. Although models currently exist that estimate construction-related emissions from equipment, land-use change or carbon stocks of forests, there does not exist a tool that estimates the net emissions from all major activities undertaken during a construction project. The carbon footprint estimation tool (CFET) was therefore developed to address the need for a calculator to estimate emissions from all major processes observed during the course of a construction project, from site preparation to landscaping.

The proposed tool aims to measure production of emissions from the operation of an inventory of applicable equipment, quantify the loss in carbon sinks from deforestation and soil movement, and include the amount of sequestration of CO_2 achieved from reforestation efforts. Moreover, the model integrates key GHG reduction policies that impact construction, like the EPA Tier System and the NCDC.

CFET and its interface were constructed on MYSQL and Visual Basic to produce a tool that is both user-friendly and portable. The interface was created with drop-down menus and integrated instructions such that it would require minimum effort by the user to input the required data. The output of the tool is showcased in a way that clearly defines the amount of GHG (in MT CO_2e) and other related air pollutants associated with each process, and the total net emission of the project to aid the user in the decision-making process to achieve their goals of emissions reduction.

5.2 Components of CFET

The components of the CFET were developed based on the four major processes in construction projects: site preparation, operation of construction equipment, materials production and environmental impact mitigation (Figure 5-1).

The site preparation component quantifies the amount of CO_2 absorbed by forests and the organic soil layer that is lost during deforestation from clearing and grubbing processes, and movement of existing forest soil. The equipment component estimates emissions produced during the operation of all equipment on site for the duration of the project. The materials production component computes emissions from on-site production of concrete, and asphalt, and off-gassing from the use of chemical solvents, like surface coatings and fertilizers. Additionally, due to the extensive use of cement and steel on-site, this component also allows users to estimate emissions from the production of these materials at off-site facilities should they so choose. The environmental impact mitigation component determines the amount of CO_2 absorbed through the re-plantation of trees that help abate the emissions produced during construction.

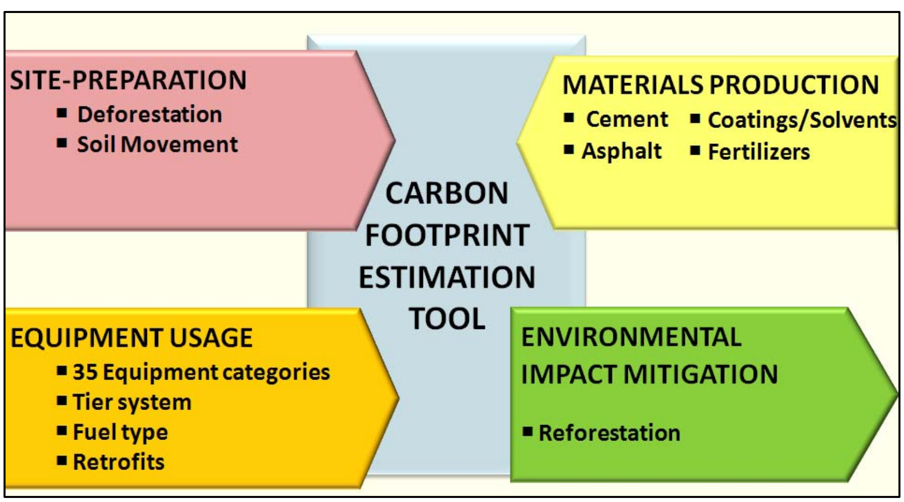

Figure 5-1. Diagram illustrating the various components of CFET.

5.3. Methodology of Emissions Estimation of Components

Each component in the tool performs calculations based on a set of data input by the user using a database of EFs specifically created for each component and a mathematical relationship converting input data and appropriate EF to the amount of CO_2e produced/sequestered by that activity. Subsections 5.3.1-5.3.5 list the input data, EF database used, assumptions, and equations used to estimate emissions for each component of CFET.

To develop the tool, high ranking EFs, i.e. AP-42 Type A or B (see Section 3.1), were either obtained and adapted from various sources, or estimated directly through stoichiometric relationships of the processes that each of the components captures. Moreover, all equations and methodologies used to estimate emissions are in accordance with the most recent IPCC guidelines [IPCC, 2006]. The IPCC guidelines categorize methodologies into various tiers: Tier 1 being the lowest level and Tier 3 being the highest level. These tiers rank emissions estimation methodologies based on the amount of data available for calculations. Basic equations obtained from extensive study of literature in the area were tailored to incorporate details of each construction process based on studies of the best practice guidelines for emissions estimation, policy trends and statistical analysis. Hence, the proposed tool provides a detailed quantitative estimation of net emissions from a construction project.

5.3.1 Site-Preparation: Deforestation & Soil Movement

The Site-Preparation component focuses on accounting for the CO_2 that would normally be sequestered by growing trees or forests and in the primary layer of the soil (humus or organic layer) that is lost when a construction site is cleared.

Input Data

Since the amount of carbon sequestered in forest trees is dependent on the region within the U.S. and the type of forests in each region, the site-preparation component of CFET classifies the vegetation on the construction-site prior to construction in the same manner. Users must specify the location of their construction site within the U.S. and also the forest types within their construction site. In addition, the user must manually enter the extent of the area of each type of forestland that the construction project would clear. A screenshot of the user-interface illustrating these categories of input data as required from the user is shown in Figure 5-2. For example, as shown in the figure, if the construction site is located in the state of Maryland and the construction project would require the deforestation of 1,000 acres of Jack Pine trees and 700 acres of Elm trees, the user would choose from the tool's drop-down menu: 'Northeast' under Regions, then 'White/Red/Jack Pine' under Forest Types and enter 1,000 acres under Area of Tree Cleared. Similarly, the user would enter the information for other tree types on-site.

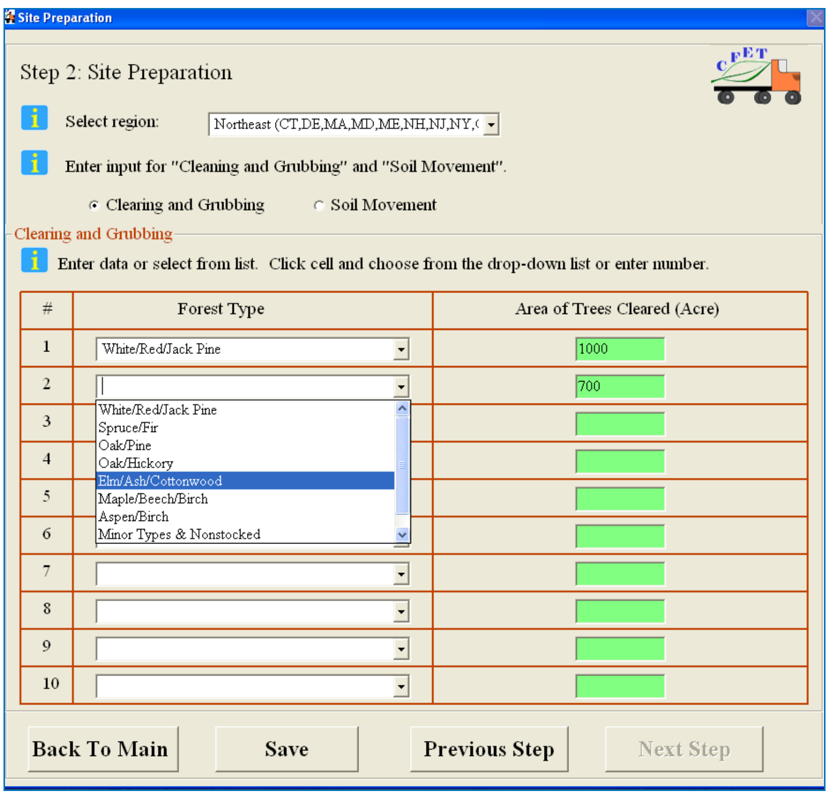

Figure 5-2. Screenshot of the user-interface for site-preparation component.

Database

The database for the site-preparation component of CFET was built based on data obtained directly from the latest Inventory of U.S. Greenhouse Gas Sources and Sinks: 1990-2007. According to the region and forest types, the Inventory lists C-density values by various carbon pools in forest ecosystems, namely above-ground biomass, below-ground biomass, dead wood, litter and soil organic carbon. The categories in the database and the C-density values reflect USDA's most recent inventory by state as in the Forest Inventory and Analysis Database (FIADB) and is in accordance with the IPCC guidelines.

This component's database lists the C-density (MT/ha) of major forest types in each region of the U.S. The classification of regions and the forest types per region in this component are consistent with those in the Inventory. Thus, the database categorizes 49 U.S. states into 11 regions based on their geographic locations: Northeast (CT,DE,MA,MD,ME,NH,NJ,NY,OH,PA,RI,VT,WV), Northern Lake States (MI,MN,WI), Northern Prairie States (IA,IL,IN,KS,MO,ND,NE,SD), South Central (AL,AR,KY,LA,MS,OK,TN,TX), Southeast (FL,GA,NC,SC,VA), Pacific Northwest-Westside (Western OR & WA), Pacific Northwest-Eastside (Eastern OR & WA), Pacific Southwest (CA), Rocky Mountain-North (ID,MT), and Rocky Mountain-South (AZ,CO,NM,NV,UT,WY) [USEPA, 2009a].

Although the C-density data in the Inventory is listed by carbon pool, the C-density values of the forest types under each region that are used in this component are summarized into just two categories: Non-soil and Soil C-density. The non-soil C-density values were obtained by summing all carbon pools related to tree parts (live and dead), i.e. above-ground biomass, below-ground biomass, dead wood and litter; whereas, the soil C-density is only the soil organic carbon values. Tables 5-1 and 5-2 demonstrate a sample conversion of the Inventory data into the site-preparation component's database. Appendix C contains the site-preparation database as used in the tool.

Assumptions

This component was developed under the assumption that the construction site to be cleared is primarily forestland. Additionally, sites that are mostly grasslands or ground vegetation would be covered under the 'Minor types and non-stocked' forest type category in the database. If the site is on urban land, or has previously built structures, then this component will not be used in the tool under the assumption that no sequestration capabilities that previously existed would be lost by subsequent construction in the area.

Table 5-1. Original data with C-density values for all carbon pools in the northeast region. Source: USEPA, 2009a

Region	Forest Type	Carbon Density (MT C/ha)				
		Above-ground Biomass	Below-ground Biomass	Dead Wood	Litter	Soil Organic Carbon
Northeast (CT,DE,MA,MD,ME,NH, NJ,NY,OH,PA,RI,VT,WV)	White/Red/Jack Pine	91.8	19.0	11.2	13.8	78.1
	Spruce/Fir	51.1	10.8	11.7	30.6	98.0
	Oak/Pine	75.7	15.0	9.1	27.3	66.9

Table 5-2. Database constructed for site-preparation component of CFET from original data with soil & non-soil carbon pools. *Source: USEPA, 2009a*

Region	Forest Type	Carbon Density (MT C/ha)	
		Non-Soil	Soil
Northeast (CT,DE,MA,MD,ME,NH,NJ,NY,OH,PA,RI,VT, WV)	White/Red/Jack Pine	135.8	78.1
	Spruce/Fir	104.2	98.0
	Oak/Pine	127.1	66.9

Due to the lack of a comprehensive statistical database of soil carbon and since the first meter of soil typically accounts for the highest concentration of carbon [Francek, 2009], the sequestration capacity lost due to movement of soil is assumed to be from the loss of the soil organic content within each forest and region. Also, biological activity in the soil produces NOx (primarily N_2O) emissions. However, the N_2O emissions from forest soil as summarized in Table 5-3 are typically small compared to soil organic carbon (as shown previously) [USEPA, 2009b]. Due to this reason, and since during site-preparation soil is being removed from the site, natural NOx emissions are considered to be negligible and, hence, are not accounted for in this component.

Table 5-3. N_2O emissions from forest soils. *Source: USEPA, 2009b*

Forest Ecosystems	Emission Factor	
	Lbs N_20 /acre/yr	**MT N_20/ha/yr**
Tropical forest	3.692	0.0041
Savanna	2.521	0.0028
Temperate forests (coniferous)	1.404	0.0016
Temperate forest (deciduous)	0.563	0.0006
Grassland	1.503	0.0017
Shrubs/woodlands	2.456	0.0028

Equations Used

The following relationship was used to convert C-density to the CO_2 sequestration capacity (MT CO_2e) lost due to site-preparation. This methodology is in accordance with IPCC Tier-2 level good practice emissions estimation.

$$EM_{\text{Site-Prep}} = [EM_{\text{Deforest}} + EM_{\text{Soil}}]$$
$$EM_{\text{Deforest}} = \sum(C\sim density \cdot A_{\text{Forest}} \cdot CC \cdot U)$$
$$EM_{\text{Soil}} = \sum(C\sim density \cdot A_{\text{Soil}} \cdot CC \cdot U)$$

Notation

$EM_{Site\text{-}Prep}$: Emissions from site-preparation (MT of CO_2)

$EM_{Deforest}$: Emissions from clearing and grubbing or deforestation (MT of CO_2)

EM_{Soil} : Emissions from movement of soil (MT of CO_2)

C~density : Carbon density (MT of C/ha)

A_{Forest} : Area of forest cleared by construction (acres)

A_{Soil} : Area of soil removed for construction (acres)

CC : Carbon Conversion = Ratio of CO_2 to carbon = 3.67

U : Unit Conversion; 1 ha = 2.47 acres

5.3.2 Equipment Usage

This component calculates emissions produced from the operation of various types of equipment, like bull dozers, loaders, scrapers, dump trucks, etc., during the period of construction.

Input Data

This component requires the user to input information about the characteristics of the equipment used within the construction site. Specifically, the user describes his/her inventory of equipment, choosing from a list of 35 equipment categories. The user then enters the number of pieces and hours of operation for each type of equipment chosen. Other details such as the age, model year and engine horsepower (hp) or instead, if known, the EPA tier level of each type of equipment, would also need to be entered into the tool. If only the tier level of the equipment is available, the user will enter the tier level and choose an appropriate maximum horsepower within the tier level. Based on this information, CFET will automatically associate the appropriate model year for the equipment piece. If the user's equipment inventory contains any pieces that were retrofit with an emission reduction technology, the tool allows the user to pick from a list of EPA approved retrofit technologies. In addition, the type of fuel used by the equipment, such as ULSD, B5, B20 and B100, also need to be entered. A screenshot of a mock user-interface illustrating these categories of input data as required from the user is shown in Figure 5-3.

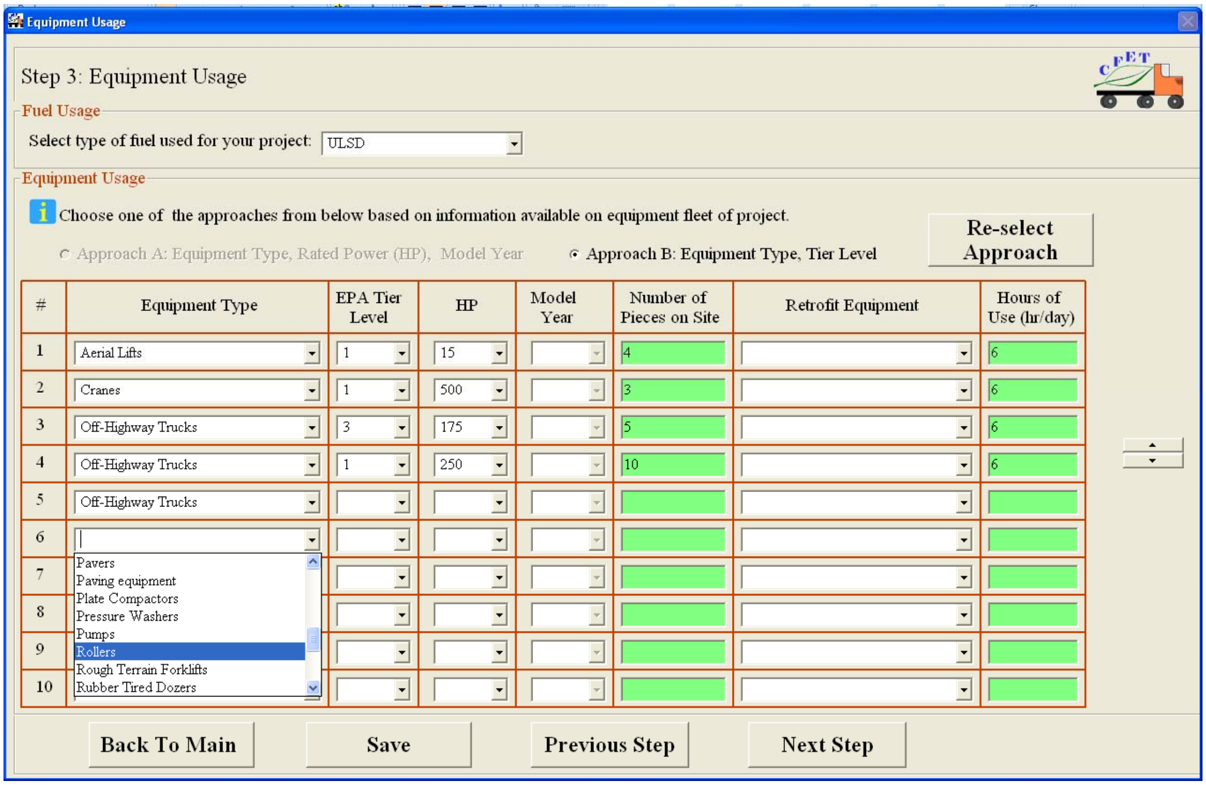

Figure 5-3. Screenshot of the user-interface for equipment usage component.

Database

The component's database was developed based on the best available data that ordinarily exist for the purpose of this component, accumulated from several sources. The component's database is a compilation of EFs for all GHGs and is categorized yearly (1995-2025) by equipment type, and all available rated power for each equipment type (hp). The equipment categories and their rated powers are consistent with those listed by EPA and in other emissions models used nation-wide [USEPA, 2009e & ARB, 2009].

The EFs for the 35 categories of equipment options in the proposed tool are obtained directly from California ARB's OFFROAD2007 Model. The EF data obtained from the OFFROAD2007 model were derived based on the average annual fleet make-up of the equipment category for each year through 2020, vehicle population in each equipment category by horsepower rating and load factor. This data, however, was only available for the years 2007 to 2025. Since the average life expectancy of construction equipment is typically 10 to 20 years, the data needed to be extended to accommodate older equipment that may still be in use. Thus, a new database was developed for this component by extrapolating the

OFFROAD2007 data for all equipment categories to the years 1995 through 2025. The extrapolation was conducted based on the average percent difference obtained by calculating the changes in the PM standards mandated by the EPA Tier System over time (Appendix B). These standards are specific to a range of horsepower and model years of any non-road equipment. Therefore, for any given year, the extrapolated database applies a 21% increase in all GHG emissions (ROG, NOx, SOx, CO_2, CO and CH_4) to that equipment that falls within a certain range of rated power only if that range and model year underwent changes in PM standards in the EPA Tier System. The assumptions used to establish this extrapolation rate are explained in the following section. Table 5-4 provides a sample data of the rated power and model years to which the extrapolation trend was applied in the database for the years 2002 to 2007. A complete summary of the years and rated power the extrapolation trend was applied to is listed in Appendix D. This EF database is in compliance with AP-42 Type-A standards.

In addition to the EF database for equipment, an intermediary database was created so as to allow for flexibility with the information input by the user, while also letting the tool obtain and process the information appropriately. Thus, the input-interface lets the user either enter the tier level of equipment type or the age, rated power and model year to determine the appropriate EF from the database.

This database allows the tool to associate a maximum rated power and a median model year should the user input just the tier level for the equipment type. The maximum rated power was determined directly from the EPA NONROAD model; the median year was calculated based on the model year range established by EPA for each tier level and every range of rated power. Appendix F outlines the details of this intermediary database. An example of the emission factor database for the year 2006 is documented in Appendix G.

Table 5-4. Extrapolation trend as applied to model years 2002-2007 & rated power based on analysis of PM standards.

Applicable Rated Power Range	2007-06	2006-05	2005-04	2004-03	2003-02
>11 to 25 hp	same	same	21	same	same
>25-50 hp	same	same	same	21	same
>100-175 hp	21	same	same	same	21
>175-300 hp	same	21	same	same	21
>300-600 hp	same	21	same	same	same
>600-750 hp	same	21	same	same	same
>750-1200 hp	same	21	same	same	same
>1210-9999 hp	same	21	same	same	same

**same= EF will remain the same as the previous year*

Assumptions

The original EF data was obtained from the California ARB's OFFROAD2007 model [ARB, 2009]. Although ambient changes in temperature and pressure from state to state may result in temporal and spatial differences in emission production, it was assumed that these EFs are representative of the emissions due to only the equipment performance, with negligible effects due to environmental conditions. The EPA Tier System and other related emission standards primarily regulate PM and NOx emissions. PM emission standards in particular have been consistently monitored since 1988 [USEPA, 2007c]. Consequently, consistent data for PM emission factors are available via various models. Also, it is assumed that as EPA mandated these standards over time, equipment manufacturers met these standards accordingly. This implies that equipment manufactured in 2004 would have met all the EPA emissions standards established prior to 2004. Therefore, in determining the change in emissions so as to estimate the implied improvement in equipment emissions from 1998 to 2007, chronological analysis of the PM emission factors (acquired from 2009 Diesel Tier standards) was performed.

From the analysis of the differences in PM standards of the EPA Tier System as shown in Appendix E, it can be seen that there is approximately 21% average increase in standards, implying a 21% decrease in emissions from pre-tier 1 (tier 0) to tier 1, tier 1 to tier 2, and tier 2 to tier 3. Subsequently, emissions for appropriate equipment categories from the year 1995 to 2007 were increased by 21% annually as shown in Table 5-4 and summarized in Appendix D in accordance with EPA Tier System standards. Thus, a comprehensive emission factor database was established from years 1995 to 2025.

It must be noted that this database reflects EFs for diesel fuel only. To accommodate the use of other fuels, a correction factor is applied during calculation. EPA mandated the use of low sulfur diesel (LSD) in 2006, and the use of ultra low sulfur diesel (ULSD) in construction equipment will be mandated as of June 2010 [USEPA, 2007b]. Moreover, some companies may wish to use biodiesel blends, such as B5, B20 and B100, in the future. Therefore, correction factors were determined to accommodate all fuel types that are anticipated for use in construction equipment. Again, these correction factors were developed based on the percent PM emissions reduction that the fuel offers with diesel fuel as a base case.

It was assumed that with the requirement to use of ULSD in all non-road vehicles in 2010, the diesel fuel used to produce biodiesel will be ULSD only, and thus, the PM emissions reductions will be enhanced as such. For example, B5 biodiesel typically offer a 2% reduction in PM emissions from diesel fuel. If ULSD with a 32% (25%+7%) reduction is used in production, a total of 34% reduction will be achieved [USEPA, 2007b]. Appendix H describes in detail how the correction factors were determined. Table 5-5 lists these fuel-based correction factors.

Table 5-5. Fuel-based correction factors used in equipment usage emissions calculation.

Fuel	Reductions in PM from Base Case
Diesel	0 (Base case)
Low Sulfur Diesel (LSD)	25%
Ultra-Low Sulfur Diesel (ULSD)	32%
Biodiesel B5	34%
Biodiesel B20	44%
Biodiesel B100	81%

Equations Used

The operation of construction equipment emits several GHGs (NO_x, CO_2, CH_4, CO) and air pollutants (ROG and SO_x). A basic emissions calculation relationship [EPA, 2009] was adapted to develop the following equation for determining emissions of individual GHGs and air pollutant emissions from operating equipment during an activity [EPA, 2009]. This relationship is in accordance with the IPCC Tier-3 level good practice emissions estimation.

$$EM_{\text{GHG/AP}} = EF_{\text{GHG/AP}} \cdot [(1 - CF_{\text{Fuel}}) + (1 - CF_{\text{Retrofit}})] \cdot U$$
$$where, \quad GHG \in \{NO_x, CO_2, CH_4, CO, ROG, SO_x\}$$

Notation

$EM_{GHG/AP}$: Emissions per equipment (MT of GHG or air pollutant/hour)

$EF_{GHG/AP}$: Emission factor (lbs of GHG or air pollutant/hour)

CF_{Fuel} : Fuel-based correction factor (%/100)

$CF_{Retrofit}$: Retrofit technology-based correction factor (%/100)

U : Unit Conversion; 1lb = 0.000454 MT

The air pollutant emissions, i.e. PM, SOx and ROG, are listed separately; whereas, individual GHG emissions, i.e. NO_x, CO, CO_2 and CH_4, were converted to total CO_2e emissions emitted from each equipment type using the following relationship.

$$EM_{\text{Equipment}} = \Sigma\left[\left(EM_{\text{GHG}} \cdot GWP_{\text{GHG}}\right) \cdot N \cdot A \cdot P\right]$$
$$where, \quad GHG \in \{NO_x, CH_4, CO, CO_2\}$$

<u>Notation</u>

$EM_{\text{Equipment}}$	:	Total on-site equipment emissions (MT of CO_2e)
EM_{GHG}	:	Emissions per equipment type (MT of GHG/hour)
GWP_{GHG}	:	Global warming potential of GHG (NO_x = 310, CH_4 = 21, CO =3, CO_2 =1) [IPCC, 2007]
A	:	Operation time per equipment (hours/day)
N	:	Number of pieces per equipment type
P	:	Period of stay of per equipment or period of construction (days)

5.3.3 Materials Production

This component captures emissions from the production or use of major materials (EM_{Material}) used on-site, namely cement, concrete, asphalt, solvents (i.e. grease and coatings), fertilizers, and steel. The air pollutants and GHGs produced by usage of these materials are calculated primarily from their stoichiometric relationships based on their respective chemical compositions. The component then summarizes the total emission from each material produced to estimate total emissions from all materials production on the construction site as follows.

$$EM_{\text{Material}} = EM_{\text{Cement}} + EM_{\text{Concrete}} + EM_{\text{Asphalt}} + EM_{\text{Solvent}} + EM_{\text{Fert}} + EM_{\text{Steel}}$$

5.3.3.1 Cement and Concrete

The production of cement primarily emits CO_2 gas. CO_2 is formed during the calcination process, when calcium carbonate ($CaCO_3$) is heated in a kiln to produce lime (CaO), which is mixed with silica to form raw forms of cement called clinkers. Clinkers are then mixed with water and other materials to form various types of cement, like Portland or masonry cement [USEPA, 2009a]. The percentage of clinker used in cement varies by the type of cement. Therefore, the amount of CO_2 emitted is directly proportional to the amount of cement produced and the percentage of clinker used to produce it. CO_2 emitted can be quantified using the stoichiometric relationship of the calcination process to yield an EF that reflects the mass of CO_2 produced per unit of lime (clinker). Although the use of cement in concrete, do not directly produce emissions (i.e. emissions from concrete are only during the production phases of cement at off-site facilities), due to the extensive use of concrete in infrastructure construction, this component includes emissions estimation from both cement and concrete.

Input Data

To estimate CO_2 emissions from cement, the user would enter the amount and type of cement consumed on-site after specifying the clinker type used in the cement, i.e. 65% CaCO or 65% CaCO & 2% MgO blend. The amount of cement consumed on site would include the amount produced on-site (Q_{Prod}) and that amount brought into or imported to the site (Q_{Imp}). A screenshot of the user-interface is shown in Figure 5-4.

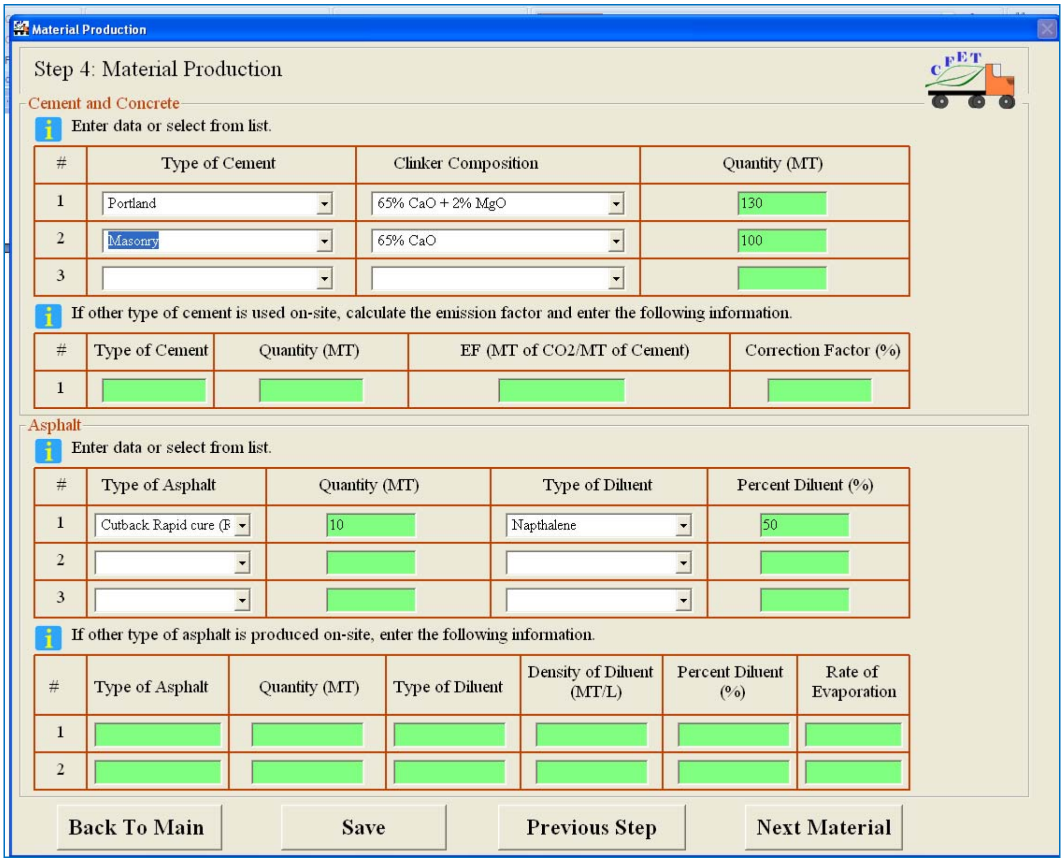

Figure 5-4. Screenshot of the user-interface for cement and asphalt in materials production component.

Database

The EF for the clinkers was calculated based on the stoichiometric equations of the calcification process as shown below, yielding the amount of CO_2 produced per unit of lime or clinker to make the cement. This is an AP-42 Type-B EF. The EF determination for each blend is summarized in Table 5-6 [USEPA, 2009b].

65% CaCO Clinker Blend:

$$CaCO_3 + Heat \rightarrow CaO\ \text{(clinker)} + CO_2$$

65% CaCO & 2% MgO Clinker Blend:

$$CaCO_3 + MgCO_3 + Heat \rightarrow [CaO + MgO]\text{(clinker)} + 2CO_2$$

Table 5-6. Calculation of emission factor for cement based on clinker type.

Clinker Blend	EF Calculation
65% CaCO	$EF_{\text{CaO}} = 0.65CaO \cdot \left[\frac{44.01g/moleCO_2}{56.08g/moleCaO}\right]$ = 0.51 tons CO_2/ton clinker
65% CaCO & 2% MgO	$EF_{\text{CaO+MgO}} = 0.65CaO \cdot \left[\frac{44.01g/moleCO_2}{56.08g/moleCaO}\right] + 0.02MgO \cdot \left[\frac{44.01g/moleCO_2}{40.31g/moleMgO}\right]$ = 0.53 tons CO_2/ton clinker

<u>Notation</u>

EF_{CaO} : Emission factor for 65% CaCO (MT CO_2/MT clinker)

$EF_{CaO+MgO}$: Emission factor for 65% CaCO & 2% MgO (MT CO_2/MT clinker)

M_{CO2} : Atomic mass of CO_2 = 44.01g/mole CO_2

M_{CaO} : Atomic mass of CaO = 56.08g/mole CaO

M_{MgO} : Atomic mass of MgO = 40.31g/mole MgO

The average fraction of clinker of 96% for Portland cement and 64% for masonry is generally accepted world-wide [IPCC-NGGIP, 2000].

Assumptions

Although in addition to cement manufacturing, limestone ($CaCO_3$) may be used in construction as a raw material to prepare road-beds, it is assumed that emissions are only produced when used to produce cement on construction sites, because CO_2 is only emitted when limestone is heated. Therefore, emission from limestone usage is limited to its consumption as an aggregate in cement production. It has been theorized that the use of concrete (made from cement with the addition of water and gravel) may result in some emissions. Due to lack of literature supporting this theory, this component assumes emissions from production of concrete ($EM_{Concrete}$) on-site may account for 1% of emissions due to cement production.

Equations Used

The EFs calculated above, and the amount of cement input by the user, were converted to CO_2 emissions using the following relationship developed from the IPCC Tier-1 level good practice emissions methodology.

$$EM_{\text{Cement}} = \sum\left(Q_{\text{Cement}} \cdot EF_{\text{Clinker}} \cdot WF_{\text{Cement}}\right)$$
$$EM_{\text{Concrete}} = 0.01 \cdot EM_{\text{Cement}}$$

<u>Notation</u>

EM_{Cement}	:	Total emissions from use of cement (MT of CO_2)
Q_{Cement}	:	Quantity of cement used (MT)
$EF_{Clinker}$	:	Emission factor based on clinker type i.e. $EF_{CaO} = 0.51$, $EF_{CaO+MgO} = 0.53$ (MT CO_2/ton clinker)
WF_{Cement}	:	Weight fraction of clinker in type of cement (%/100)
$EM_{Concrete}$	:	Total emissions from use of concrete (MT of CO_2)

5.3.3.2 Asphalt

Asphalt in paving operations is typically used by combining aggregate materials with asphalt binders. The binders consist of asphalt cement formed of distilled crude oils and liquefied asphalt. Of the major types of asphalt, i.e. hotmix, cutback and emulsion, cutback liquefied asphalt are primarily used for the purposes of construction, and tack and seal of roadways. Additionally, the other types of asphalt also produce negligible amounts of emissions. Cutback asphalt contains diluents that are used to thin the asphalt cement. Depending on the viscosity desired, the diluents' content can vary between 25% and 45%. After application on surfaces, these diluents evaporate, resulting in the hardening of the asphalt. Cutback asphalts are, therefore, classified based on the amount of diluent evaporation or curing that occurs. The classifications include rapid cure (RC) with 95% evaporation, medium cure (MC) with 70%, and slow cure with 25% evaporation [IPCC, 2006]. The use of asphalt results in VOC emissions that primarily consist of CH_4 and hazardous air pollutants [USEPA, 2007a].

Input Data

To estimate emissions from use of asphalt, the user enters the type of asphalt, i.e. RC, MC or SC, and the percent diluents by volume, if known. If the diluents percentage is unknown, the user may assume an average of 35%. Additionally, the user would input the density of diluents should other types aside from naphthalene and kerosene be used. A screenshot of the user-interface is shown in Figure 5-4 in the previous section (Section 5.3.3.1).

Database

The emission factors were estimated based on the AP-42 and IPCC methodologies. The amount of VOC emitted is assumed to be directly proportional to the amount of diluents evaporated (1:1 ratio). Thus, an equation was developed based on material balance to estimate the amount of diluents, i.e. VOC emitted, given the type of asphalt and its diluents percentage.

$$M_{\text{Diluent}} = \left\{ \frac{Q_{\text{Asphalt}}}{D_{\text{Diluent}} + D_{\text{AspCement}} \cdot \left(\frac{1 - Percent_{\text{Diluent}}}{Percent_{\text{Diluent}}} \right)} \right\} \cdot D_{\text{Diluent}}$$

The following equations were used to obtain a relationship for the amount of diluents (VOC emitted) in the asphalt used.

$$Q_{Asphalt} = (V_{Diluent} \cdot D_{Diluent}) + (V_{AspCement} \cdot D_{AspCement})$$
$$V_{Diluent} = Percent_{Diluent} \cdot (V_{Diluent} + V_{AspCement})$$
$$M_{Diluent} = V_{Diluent} \cdot D_{Diluent}$$

Notation

$M_{Diluent}$	:	Mass of diluents in asphalt = Mass of VOCs (MT)
$Q_{Asphalt}$	:	Quantity of asphalt used (MT)
$V_{Diluent}$	:	Volume of diluent in asphalt (L)
$D_{Diluent}$	:	Density of diluent (kg/L)
$V_{AspCement}$	:	Volume of asphalt cement in the asphalt (L)
$D_{AspCement}$	:	Density of asphalt cement (kg/L)
$Percent_{Diluent}$	:	Percentage of diluents in asphalt, if unknown assumed to be 35% (%/100)

Assumptions

Although other forms of asphalt may be used, since primarily cutback asphalt is used in construction, and this type produces the highest emissions amongst all types, this component only estimates emissions from the use of cutbacks. Due to the prominent use of naphthalene and kerosene (in addition to asphalt cement) as diluents, only these two diluents are accounted for in the component. Also, since VOC emissions from asphalt primarily constitute of CH_4, the emissions calculated in this section are converted to CO_2e by applying the GWP for CH_4 (21) [USEPA, 2009b].

Equations Used

The equation for $M_{Diluent}$ calculated above is used as the emission factor to convert the amount of asphalt consumed on-site to CO_2 emissions using the following relationship developed from the IPCC Tier-1 level good practice emissions methodology.

$$EM_{Aspahlt} = \sum (M_{Diluent} \cdot R_{Evap} \cdot GWP_{CH_4} \cdot U)$$

Notation

$EM_{Asphalt}$	:	Emissions from use of asphalt (MT of CO_2e)
$M_{Diluent}$	:	Mass of diluents in asphalt = Mass of VOCs (MT)
R_{Evap}	:	Rate of evaporation during curing (%/100)
GWP_{CH4}	:	Global warming potential of CH_4 = 21

Table 5-7. Percent evaporation of diluents by cutback asphalt curing type.
Source: USEPA, 2007a

Cutback Asphalt Type	Percent Evaporation (%)
RC	95
MC	70
SC	25

Table 5-8. Density of diluents used in asphalt production emissions calculations.
Source: USEPA, 2007a

Diluent	Density (kg/L)
Naphthalene	0.7
Kerosene	0.8
Asphalt Cement	1.1
Note: Densities of other diluent types used must be obtained separately.	

5.3.3.3 Coatings & Solvents

Several types of paints and coating are used for protective and decorative purposes of construction structures. These typically include paints, varnishes, stains, etc. Emissions from this category primarily include VOCs.

Input Data

This component requires the user to choose the type of coatings/solvents used on-site and determine the volumes used. He/she then enters the density and solids content of each coating/solvent chosen. If the type of coating/solvent other than those provided by the tool is used on-site, the user may manually enter the type, volume, percent solid (by volume) and density data for the coating/solvent. A screenshot of the user-interface for this component is shown in Figure 5-5.

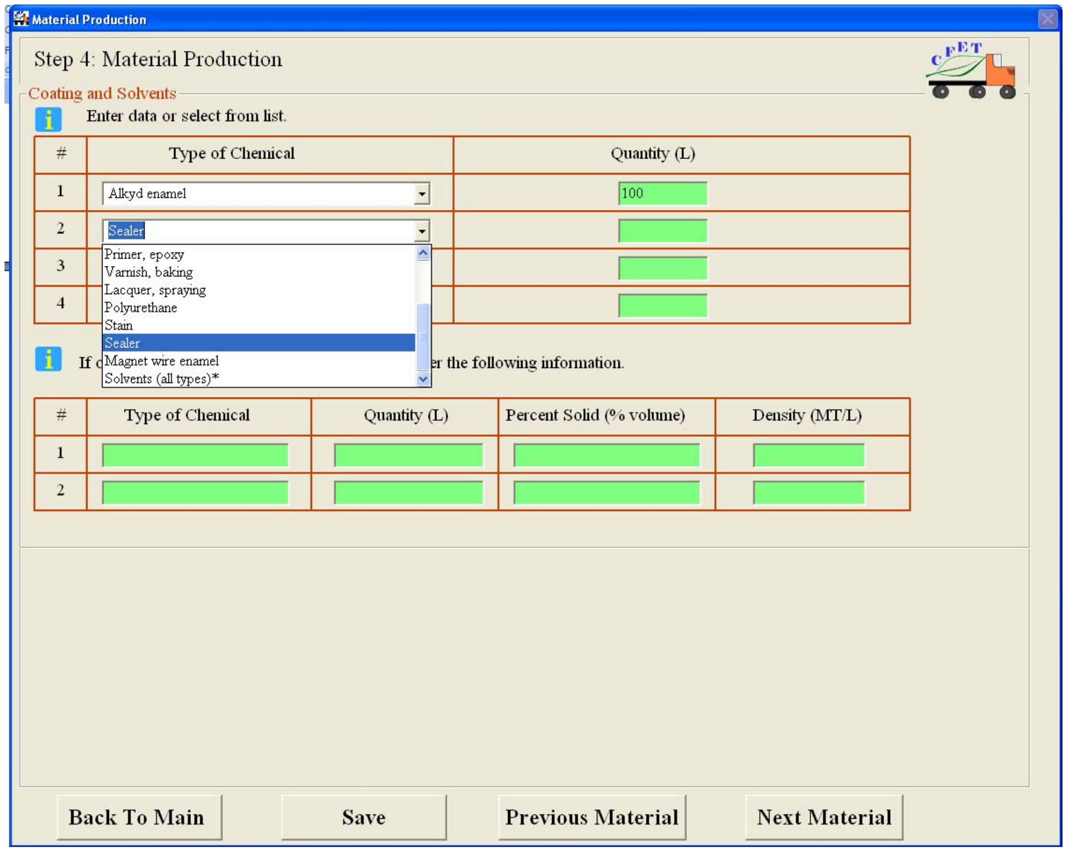

Figure 5-5. Screenshot of the user-interface for coatings and solvents in materials production component.

Database

As the types of chemicals and their characteristic information may vary from project to project, and with time, typical categories of coatings/solvents as listed in the EPA's AP-42 document were used. These categories and their respective information (i.e. percent solid and density data) are listed in Appendix I. The use of these national (U.S.) data in estimating emissions is in accordance with the IPCC Good Practice Guidelines.

Assumptions

Due to the lack of availability of information determining the constituents of the VOCs, emissions from coatings/solvents are not converted to CO_2e. Instead, emissions from this component are listed separately solely to indicate their existence and quantify them.

Equations Used

The VOC emissions from coatings/solvent use are determined by performing a mass balance-based calculation estimating the amount of solid VOCs present in the material used.

$$EM_{Solvent} = \sum(Q_{Solvent} \cdot Percent_{Solid} \cdot D_{Solvent} \cdot U)$$

Notation

$EM_{Solvent}$	:	Emissions from use of coating/solvent (MT of VOC)
$Q_{Solvent}$	:	Quantity of coating/solvent used on-site (L)
$Percent_{Solid}$	:	Percentage of solid in coating/solvent (%/100)
$D_{Solvent}$	:	Density of coating/solvent (kg/L)
U	:	Unit Conversion; 1kg = 0.001 MT

5.3.3.4 Fertilizers

The addition of chemical fertilizers to soil produces atmospheric NOx emissions as soil bacteria degrades the nitrogen content through various microbial processes to produce primarily nitrous oxide (N_2O) emissions.

Input Data

To estimate NO_2 emissions from fertilizer usage, the user would enter the amount and choose from a list the type of fertilizer used on-site. If the type of fertilizer used on-site in not listed in the tool, the user may manually enter the name and nitrogen content (% N/ton fertilizer). A screenshot of the user-interface for this component is shown in Figure 5-6.

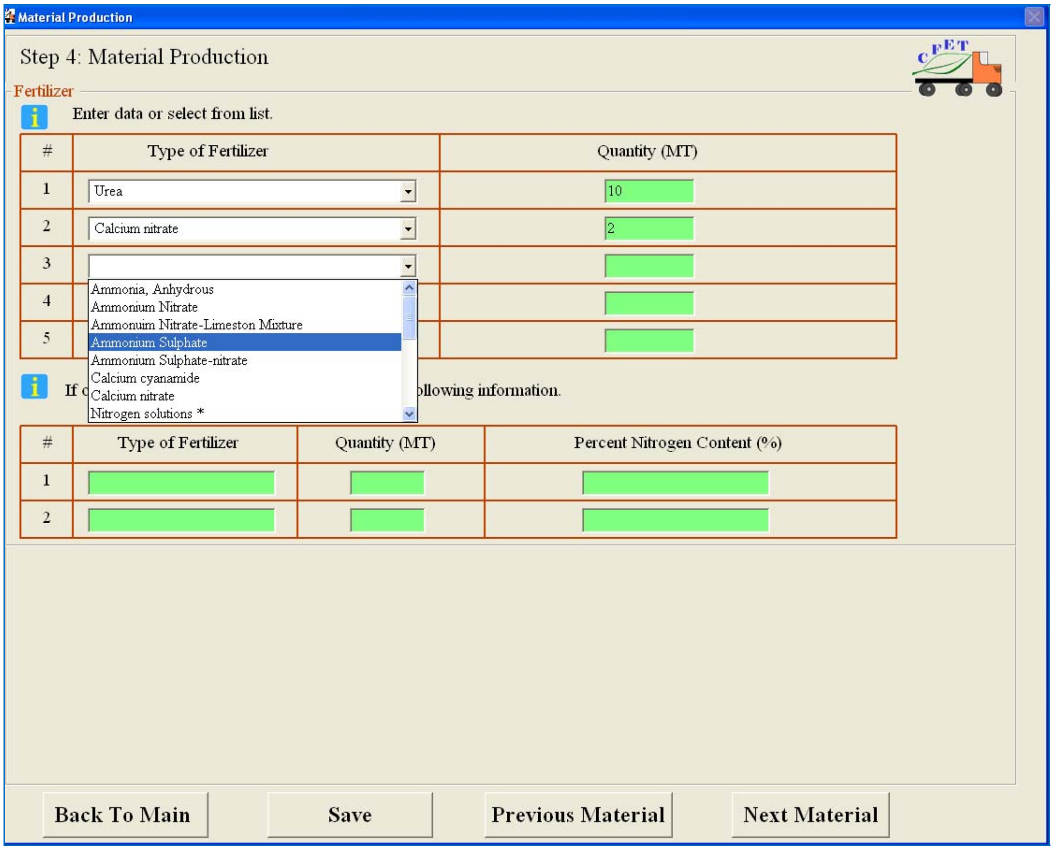

Figure 5-6. Screenshot of the user-interface for fertilizers in materials production component.

Database

The EFs were determined based on the nitrogen (N) content in each fertilizer type. A list of common fertilizers and their respective N-content are listed in Appendix J. These are obtained directly from AP-42 Compilation of Air Pollutant [USEPA, 2009b] and were calculated based on the chemical composition of the fertilizer. The EF for fertilizer is the emission coefficient based on research by the USDA, which estimates approximately 1.84 kg of N_2O is produced per 100 kg of nitrogen applied as fertilizer. These EFs have an AP-42 Type-D rating.

Equations Used

The NOx emissions from the use of commercial fertilizers on-site can be calculated using the following relationship developed from the IPCC Tier-1 good practice emissions methodology. It must be noted that a Tier 1 methodology only exits for NOx emissions for fertilizers under the IPCC Guidelines.

$$EM_{Fert} = \sum[(Q_{Fert} \cdot N \sim Content_{Fert}] \cdot EF_{Fert} \cdot N \sim Conversion$$

<u>Notation</u>

EM_{Fert}	:	Total emissions from use of fertilizers (MT of CO_2)
Q_{Fert}	:	Quantity of each type of fertilizer used on-site (MT)
$N\sim Content_{Fert}$	:	Nitrogen content by weight in fertilizer type (%/100 N/MT of Fertilizer)
EF_{Fert}	:	Emissions coefficient = 0.0184 (MT N_2O as N/MT of N applied)
N~Conversion	:	Ratio of N_2O to N = 1.57

5.3.3.5 Steel

Though on-site use of steel (i.e. finished products) does not produce direct emissions, the emissions resulting from production of steel at off-site facilities during the manufacturing phases are quantified by the Steel component. Specifically, significant quantities of CO_2 are generated during the production of steel. This component enables the user, should he or she so choose, to calculate the added carbon footprint due to the production of steel for use on a construction project.

Input Data

To estimate CO_2 emissions from use of steel, the user would choose from a list, the method used in the production of the steel (e.g. electric arc furnace, basic oxygen furnace or open hearth furnace) and enter the amount of related steel used on-site. If the production method used is not listed in the tool, the user may manually enter the name and calculate an emission factor (MT CO_2/MT steel) using a carbon mass-balance described below. The mass-balance is based on the general processes involved in steel making.

$$EF_{\text{Process}} = \frac{44}{12} \cdot \left\{ \left[\Sigma \left(Q_{\text{Inputs}} \cdot C_{\text{Inputs}} \right) - \Sigma \left(Q_{\text{Residue}} \cdot C_{\text{Residue}} \right) \right] - C_{Steel} \right\}$$

Notation

EF_{Process}	:	Emission factor for a steel manufacturing process (MT of CO_2/MT of Steel Produced)
Q_{Inputs}	:	Quantity of each type of input i.e. iron, steel scraps, flux and carbonaceous material (MT)
Q_{Residue}	:	Quantity of residue i.e. slag or ash (MT)
C_{Residue}	:	Carbon content of residue (MT of C/MT of residue)
C_{Steel}	:	Carbon content of steel produced (MT of C/MT of steel)

A screenshot of the user-interface for this component is shown in Figure 5-7.

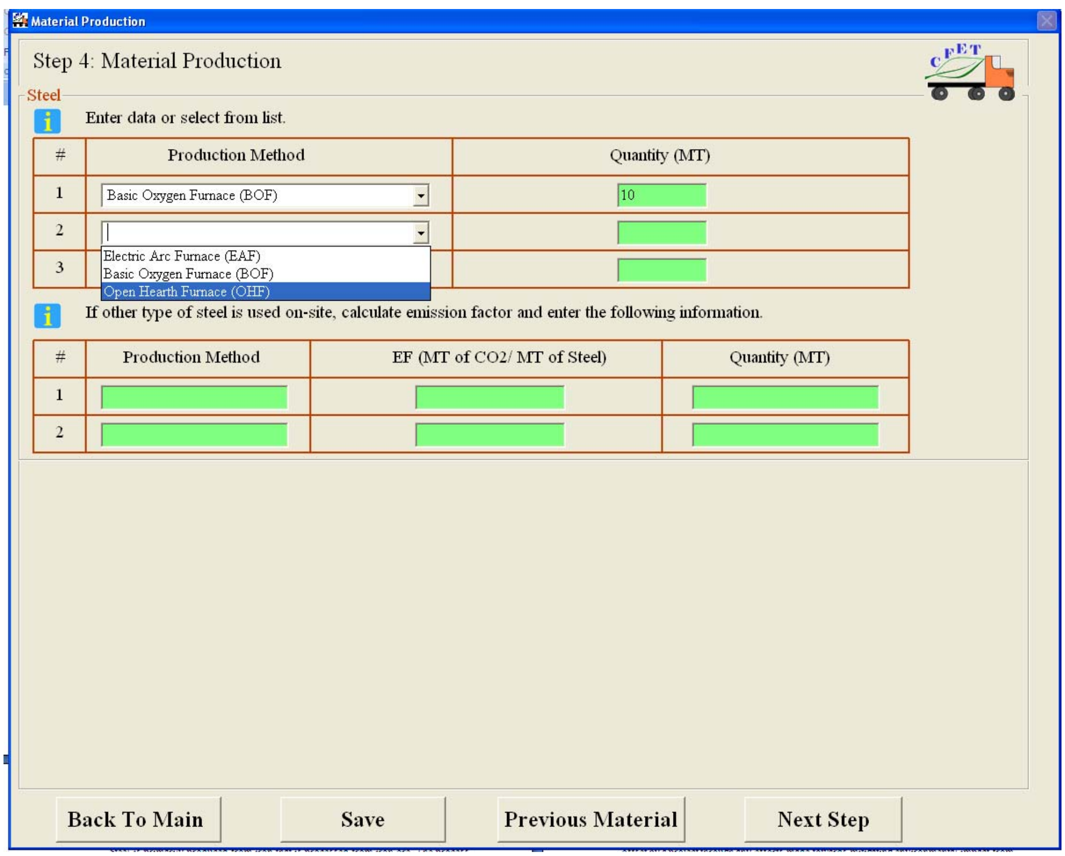

Figure 5-7. Screenshot of the user-interface for steel in materials production component.

Database

This component utilizes emission factors from three major processes in steel production, namely, those that use basic oxygen furnaces (BOFs), open hearth furnaces (OHFs) and electric arc furnaces (EAFs). The production-based Tier 1 emission factors for this component were obtained from the IPCC Guidelines [IPCC, 2006] and are listed in Table 5-9.

Table 5-9. Emission factors for calculation of steel production emissions.
Source: IPCC, 2006

Steel Production Process	Emission Factor (MT of CO_2/MT of Steel)
Basic Oxygen Furnace (BOF)	1.46
Open Hearth Furnace (OHF)	1.72
Electric Arc Furnace (EAF)	0.08

Assumptions

Steel is primarily produced from iron that is processed from iron ore. The process flow for steel production begins with the processing of iron ore at iron-making facilities to form pig iron. Pig iron is then processed into raw steel either within the same facility (integrated facilities) or transported to an alternate steel-making facility. These facilities where pig iron is converted to raw steel are called primary or secondary facilities. Raw steel may be transformed to various steel grades (where steel is strengthened by increasing its carbon content through metallurgical processes) and cast into a variety of shapes and sizes at steel mills.

It is assumed that emissions from production of steel are primarily from steel furnaces at production facilities and those emissions from mills or metallurgical processes are negligible. Also, the component does not include CO_2 emissions from blast furnace iron production, but only furnace production of steel from iron (i.e. BOF, OHF and EAF). Thus, this component captures emissions from only primary (i.e. steel made from iron) and secondary facilities (i.e. steel made from recycled steel scrap), and not from steel mills. Moreover, emissions resulting from the use of energy for the operation of steel furnaces are excluded.

Equations Used

The CO_2 emissions from the use of steel on-site can be calculated using the following relationship developed from the IPCC Tier-1 good practice emissions methodology.

$$EM_{\text{Steel}} = \sum[(Q_{\text{Process}} \cdot EF_{\text{Process}}]$$

Notation

EM_{Steel}	:	Total emissions from steel production (MT of CO_2)
$Q_{Process}$	:	Quantity of steel related to each process (MT of steel)
$EF_{Process}$	:	Emission factor for steel production method (MT of CO_2/MT of steel)

5.3.4 Environmental Impact Mitigation

The Environmental Impact Mitigation component primarily calculates the emissions offset by a project through any efforts made towards mitigating environmental impact from the construction project. The component accounts for any efforts by a construction project towards re-plantation of trees (or reforestation) after the building of structures. This component, thus, calculates the amount of atmospheric CO_2 absorbed by trees re-planted on the construction site.

Input Data

Since the amount of carbon sequestered in trees is specific to the region, type and age of the trees, this component classifies the vegetation to be re-planted on the construction-site post construction. Users must identify the location of their construction site in the U.S. and specify type and age of trees to be planted. Additionally, the user manually enters the spacing used for re-plantation (ha/tree). For example, a 12’x10’ spacing requirement would translate to 120 square foot per tree or 0.0028 acre/tree spacing. If the data for the number of trees planted is unknown, but the area of reforestation for each type of tree is available, the tree spacing requirement may be used to obtain an estimate of the number of trees replanted by means of the relationship as follows.

$$No.\,Trees = \frac{Area_{\text{Reforestation}}}{Tree - Spacing}$$

<u>Notation</u>

No. Trees	:	Number of trees replanted by tree type
$\text{Area}_{\text{Reforestation}}$	:	Known area of reforestation by tree type (acres)
Tree-Spacing	:	Spacing per tree used for reforestation (acres), e.g. 12'x10' per tree or 0.0028 acre/tree

A screenshot of the user-interface illustrating these categories of input data as required from the user is shown in Figure 5-8.

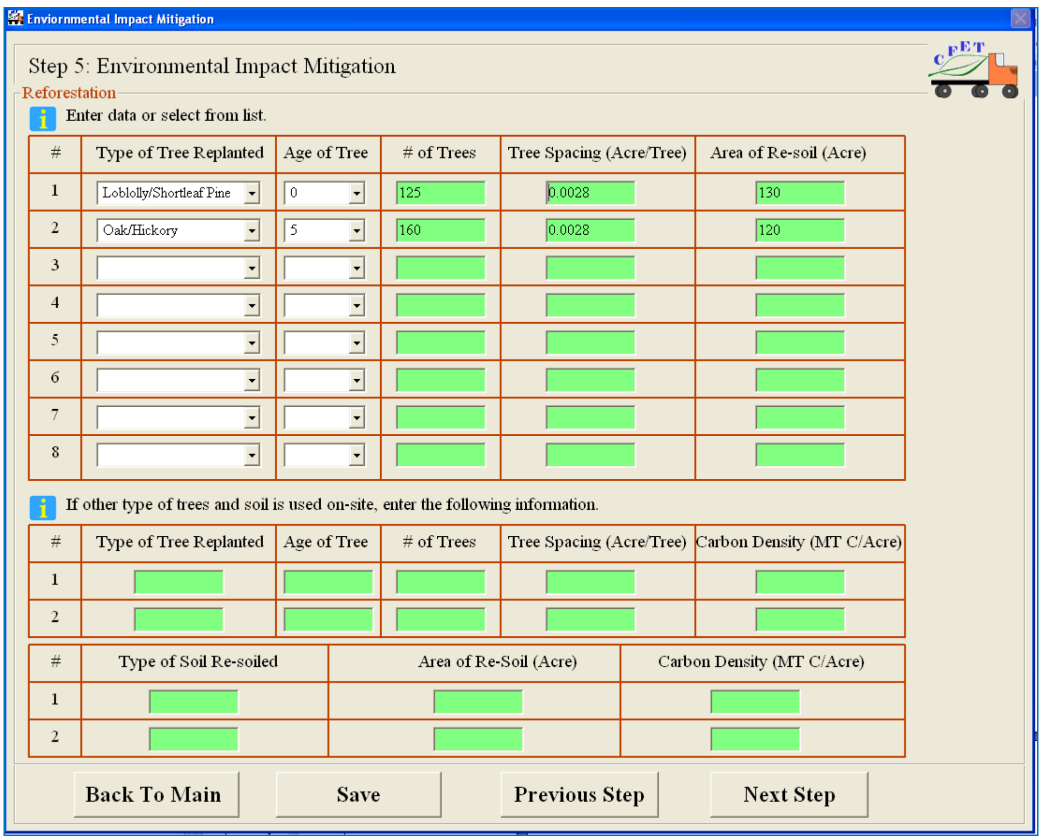

Figure 5-8. Screenshot of the user-interface for environmental impact mitigation component.

Database

The database for the environmental impact mitigation component of CFET was based on data obtained directly from USDA Forest Services documents. The document compiles look-up tables that record mean C-density values of common forest trees by region. These tables further establish age-growth volume relationships for tree categories and previous land use, based on national data for average levels of planting or stand establishments. Moreover, the tables list C-density values by various carbon pools in forest ecosystems, namely: live tree, standing dead tree, understory vegetation, down dead tree, forest floor, and soil organic carbon. The categories in the database and the C-density values reflect USDA's most recent data obtained from various projection and inventory models, and are in accordance with the IPCC guidelines [Smith et al., 2006].

This component's database uses the afforestation tables in [Smith et al., 2006] and lists the C-density (MT/ha) of major forest types in each region of the United States. The classification of regions and tree types in this component are similar to those in the site-preparation component of this tool. The C-density values, again, were summarized into only non-soil (including live tree, standing dead tree, understory, down dead tree, forest floor) and soil organic carbon pools for trees between the ages 0 to 35.

Appendix K contains the environmental mitigation database as used in the tool.

Assumptions

This component uses afforestation data from the USDA [Smith et al., 2006] based on the assumption that the areas to be re-planted on the construction site are primarily barren and are considered previously non-forest land. In addition, the database consists of only C-density values for trees of ages 0 to 35 years, even though the sequestration capabilities of trees extend well beyond 35 years. This assumes that trees beyond the age of 35 years would not be used for reforestation due to the high costs and logistic difficulties that would be associated with the transport and planting of very large trees.

Also, it was assumed that the soil used for landscaping and to support reforestation would be equivalent to the organic soil layer of a tree type to ensure compatibility. Moreover, this is supported by the common practice of using organic soil salvaged from the site-preparation process of construction. Therefore, the sequestration capacity of the soil used in the reforestation efforts would be determined using the C-density values of the soil carbon pool of the trees chosen for re-plantation by the user. However, if the soil used is not equivalent to the organic soil of the tree type, an average soil C-density value may be used instead. This value can be estimated by calculating the averages of the soil C-density values for the various tree types and their respective age groups of trees re-planted on the project. The volume of soil re-soiled is converted to area based on the depth of soil replaced (i.e. Area = volume/depth). For example, if 500 cubic meters of soil were used to re-soil a depth of 0.5 meters, the area re-soiled would be 500 cubic meters/0.5 meters = 1000 square meters.

Equations Used

The following relationships were used to convert C-density to the CO_2 sequestration capacity (MT) gained with reforestation of a construction site.

$$EM_{\text{Environ Mit}} = [EM_{\text{Reforest}} + EM_{\text{Resoil}}]$$
$$EM_{\text{Reforest}} = \sum(C \sim density \cdot N_{\text{Tree}} \cdot S \cdot CC \cdot U)$$
$$EM_{\text{Resoil}} = \sum(C \sim density \cdot A_{\text{Resoil}} \cdot CC \cdot U)$$

Notation

$EM_{EnvironMit}$	:	Sequestration capacity gained through environmental mitigation efforts (MT of CO_2)
$EM_{Reforest}$	:	Sequestration capacity gained through reforestation (MT of CO_2)
EM_{Resoil}	:	Sequestration capacity gained through soil used for reforestation (MT of CO_2)
C~density	:	Carbon density (MT of C/ha)
$N_{Reforest}$	:	Number of trees re-planted by tree type
S	:	Spacing per tree used for reforestation, e.g. 12'x10' per tree or 0.0028 acres/tree (acres/tree)
A_{Resoil}		Area of land that was re-soiled (acre)
CC	:	Carbon Conversion = Ratio of CO_2 to carbon = 3.67
U	:	Unit conversion; 1 ha = 2.47 acres

5.3.5 Offsets

The introduction of the American Clean Energy and Security Act of 2009 (ACES) for approval by the U.S. Senate proposes a cap-and-trade system in the U.S. and highlights the importance of estimating offsets for or from a project [U.S. House of Representatives, 2009]. With the future potential establishment of a carbon market, it would be beneficial for construction agencies to determine if their project would require the purchase of carbon credits to meet a carbon cap or if the project has the ability to generate offsets that may be sold as carbon credits in the market. To support this, CFET incorporates an additional component to the tool that will enable the estimation of offsets, if any, from reforestation efforts by a construction project.

Input Data

To estimate carbon offsets, the user must first re-define the conditions of deforestation and reforestation within a project. For both processes, the user would choose the class and number of trees removed and replanted (hardwood or conifers). Under deforestation, the user must enter the duration of construction. The number of trees removed through deforestation may be determined by the user from the area of deforestation and an average forest density in the U.S. of 12 trees per hectare (trees with 15-16.9 diameters) [Smith et al., 2009]. If available, a more accurate estimate for the forest density may be used in the determination of the number of trees deforested. For the reforestation segment of this component, the average age of trees re-planted, the time of reforestation within the construction period, and the duration for the offset period the user wishes to calculate must be inputted. If the user is unaware of the species of trees removed or re-planted, Table L-1 of Appendix L may be used to estimate tree species from tree type. A screenshot of the user-interface illustrating the input data required from the user is shown in Figure 5-9.

Database

To estimate carbon offsets, the annual sequestration rates for two general species of urban trees typically used for reforestation, hardwood and conifers, were obtained from U.S.

DOE documents [U.S. DOE, 1998]. The document lists sequestration rates and survival rates for slow, medium- and fast-growing trees under these species for ages 0 to 60 years. For the purpose of this tool, however, average values of sequestration rates for these species of trees were determined for ages 0 to 50 years to establish the component's database [Table L-2 of Appendix L].

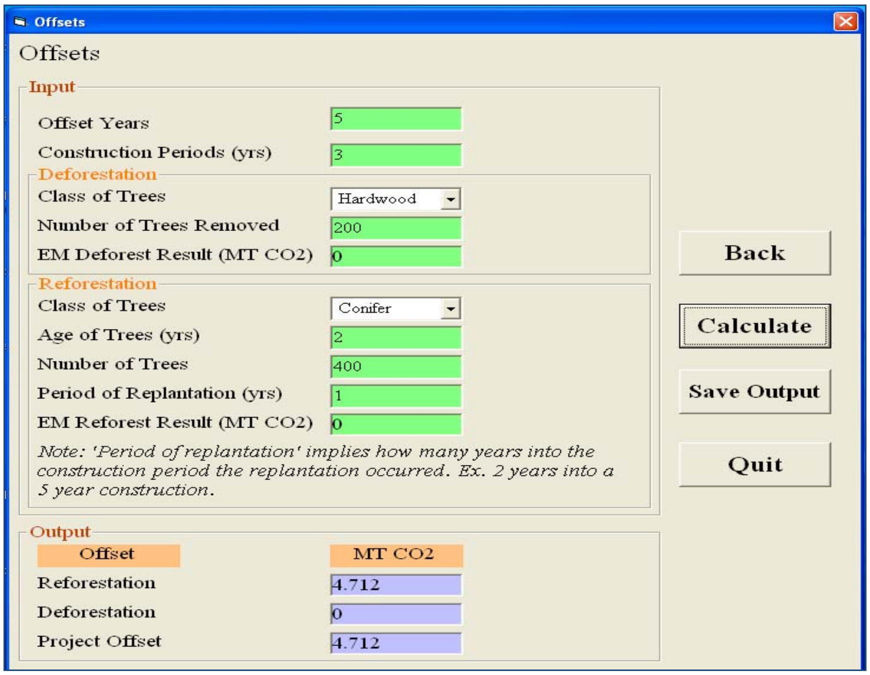

Figure 5-9. Screenshot of the user-interface for offsets component.

Assumptions

The offsets component estimates offsets only due to the emissions produced and sequestered from biogenic sources on the construction project, i.e. the carbon accounting is for only deforestation and reforestation processes on a project, and does not account for emissions from equipment usage or materials production. Based on the popular use of hardwood and conifers in reforestation efforts, the database only accounts for these two general species of trees. This is further reflected in the reforestation component of the tool (Section 5.3.4), where the list of trees offered to the user can be classified as belonging to either hardwood or conifer tree species. Also, to determine the appropriate sequestration rate of the forests removed, the average age of trees deforested (baseline age of trees) was assumed to be 20 years of age.

Under the Kyoto Protocol, the crediting period to obtain a certified emission reduction (CER) for projects under the Protocol's clean development mechanisms (CDMs) is limited to a maximum of 20 to 30 years from the start of a reforestation effort [UNFCCC, 2003]. Based on the accounting rules as developed by the Kyoto Protocol to estimate offsets achieved from reforestation efforts, the component only offers the user to estimate carbon offsets for up to 20 years. While several types of projects (such as reforestation projects, establishment or use of green energy sources, etc.) qualify as a CDM project, proposals for such projects are typically large-scale expensive projects undertaken by big companies and national governments, and are subject to lengthy and extensive review by the UNFCCC panels. The methodology and results used in CFET and its offsets component may be used to support submission of CDM proposals involving reforestation should the user so choose. However, since construction firms/DOTs usually have relatively small budgets (as compared to multi-national organizations), methods to mitigate environmental impact from construction projects are often limited to retrofitting and/or reforestation. Although such agencies may not be able to execute large CDM projects, their reforestation efforts (or other similar efforts) may enable them to participate in smaller local carbon markets. This component, therefore, was developed to help such agencies identify and quantify the positive impacts of a project's reforestation efforts. Each carbon market is unique in its requirements for offset and carbon credit determination. Users should, therefore, carefully review such requirements before utilizing CFET in offset determination.

Equations Used

The following relationship was used to estimate potential offsets, if any, from a construction project. A positive value for O_{Constr} implies that the project generates offsets (i.e. reforestation produces carbon credits that may be sold in a carbon market); whereas, a negative value implies that a project requires further offsets (i.e. the project would require the purchase of carbon credits from a carbon market to offset the deforestation process).

$$O_{\text{Constr}} = [EM_{\text{Reforest}} + (R_{ij} \cdot CC \cdot N_{\text{Reforest}})] - [EM_{\text{Deforest}} + (R_{ij} \cdot CC \cdot N_{\text{Deforest}})]$$
$$For\ \text{Reforest}: j = P + T + a - t_R$$
$$For\ \text{Deforest}: j = P + T + 20$$

Notation

O_{Constr}	:	Offsets due to reforestation efforts on a construction project (MT of CO_2)
$EM_{Reforest}$	:	Sequestration capacity gained through reforestation; output from environmental impact mitigation component (MT of CO_2)
R_{ij}	:	Annual sequestration rate of tree species i and age j (MT of C/tree)
CC	:	Ratio of CO_2 to carbon = 3.67
P	:	Duration of construction (years)
T	:	Period of offset determination (years)
t_R		Time period during construction at which reforestation was conducted (years)
a	:	Age of the trees replanted (years)
$N_{Reforest}$	:	Number of trees re-planted by tree type (same as in environmental impact mitigation component)
$EM_{Deforest}$	:	Emissions from clearing and grubbing/deforestation; from site-preparation component (MT of CO_2)
$N_{Deforest}$	:	Estimated number of trees removed by tree type

5.4 Output

The net emissions of a construction project are estimated from the total emissions computed in each component of the tool. The CFET output displays the sequestration capacity lost during site-preparation ($\sum EM_{Site\text{-}Prep}$), the emissions produced by the use of all construction equipment on site ($\sum EM_{Total\ Equip}$), GHGs emitted during the production of construction materials ($\sum EM_{Total\ Mat}$), and the emissions offset through any reforestation efforts ($\sum EM_{Environ\text{-}Mit}$). A user-interface screenshot displaying an example of the output is shown below in Figure 5-10.

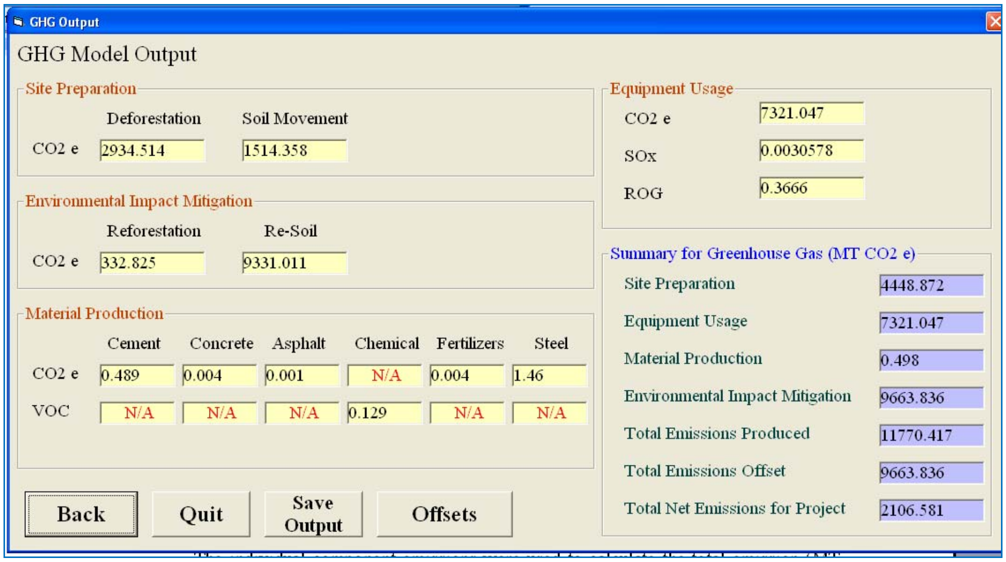

Figure 5-10. Screenshot of user-interface of output from model.

Equations Used

The individual component emissions were used to calculate the total emission (MT CO2e) for a project using the following relationship.

$$EM_{\text{Project}} = \Sigma EM_{\text{Site-Prep}} + \Sigma EM_{\text{Equipment}} + \Sigma EM_{\text{Material}} - \Sigma EM_{\text{Environ Mit}}$$

<u>Notation</u>

EM_{Project}	:	Net emissions of a construction project (MT of CO_2)
$\Sigma EM_{\text{Site-Prep}}$	:	Total emissions from site-preparation (MT of CO_2)
$\Sigma EM_{\text{Equipment}}$	:	Total emissions from equipment usage (MT of CO_2)
$\Sigma EM_{\text{Material}}$	:	Total emissions from on-site materials production (MT of CO_2)
$\Sigma EM_{\text{Environ Mit}}$	:	Total emissions sequestered by reforestation (MT of CO_2)

Emissions of other air pollutants (e.g. SOx, ROG, and VOC) from each component are listed separately.

Chapter 6. A Decision Support Methodology

6.1 Description of Decision Support Tool

Within construction projects in the transportation sector, the operation of equipment on-site accounts for the majority of project emissions. Equipment categorization, age, and horsepower, as well as the type of fuel used, can greatly affect rates of emissions. For example, backhoes, bulldozers, excavators, motor graders, off-road trucks, track loaders, and wheel loaders produce significantly more emissions than other construction equipment pieces per hour of use [Lewis, 2009]. However, such projects often offer flexibility in the choice of equipment assigned for each task. Thus, it may be possible to reduce project emissions through careful assignment of equipment from a pool of available equipment for specific jobs. This can be accomplished with little or no increase in project costs.

An optimization-based methodology is proposed herein to aid construction firms in making profitable decisions in terms of equipment choice and usage while minimizing project emissions or satisfying emissions cap requirements. Specifically, the problem of optimally selecting equipment for project tasks to simultaneously minimize emissions and project costs given project duration, workload, compatibility, working conditions, equipment availability and regulatory constraints was formulated as a multi-period, bi-objective, mixed integer program (MIP) and is referred to as the Optimal Equipment Selection Problem (*OESP*). Two techniques were considered for its solution: a weighting technique, which seeks to create the Pareto-frontier, and a constraint approach whereby costs are minimized while maintaining an emissions cap. The tool was created to reflect all transportation construction processes, from site cleaning and grubbing to final landscaping. The proposed approach as developed is generic and can be applied over varying geographic locations, site elevations, soil properties and other factors that affect equipment operation and productivity.

6.2 Mathematical Formulation and Solution

6.2.1 Problem Formulation of OESP

A multi-period, bi-objective, linear, integer program is presented for *OESP*. The formulation has the objective of choosing equipment from a pool of available equipment for each stage of a construction project so as to meet task, regulatory and temporal requirements while minimizing the total cost of equipment from ownership and operation, rental, lease or purchase and emissions abatement over the project's duration. The construction period is considered at a set S of discrete times $t=\{t_0+n\Delta\}$, where $n=0,1,2,\ldots,I$. Δ may be any increment of time, e.g. one minute, hour, day, week, or even longer. It should be noted that the number of selected pieces of equipment should be based on the specified amount of work that needs to be completed in each period *t*.

Many states have begun to require contractors working on large state roadway construction projects to ensure their equipment fleet follow the EPA's Non-road Diesel Engine Tier System. The designation of a tier to a particular piece of equipment is a function of fuel-usage type, engine efficiency (horse power and year of production), and whether or not the equipment has been retrofitted to reduce emissions. Also, many federal projects recommend guidelines for construction fleets, based on the EPA Tier System classification, to encourage emissions reduction from equipment usage. For example, Maryland's requirements associated with the ICC case study described in the next section (herein referred to as the Tier System Guidelines) specify that no more than a small percentage of all equipment present on the construction site fall under one of several tiers associated with high rates of emissions. The mix given as a percentage of equipment located on site at any point in time permitted within each pre-designated tier is described in Table 6-1, where the highest tier, Tier 3, includes the least emissive equipment. These Tier System requirements are included within the proposed model.

Table 6-1. Maryland's Tier System Guidelines for equipment on construction sites. *Source: ICC, 2010.*

EPA Tier	Limitations on number of pieces of equipment on site by tier
Tier 0	Must not exceed 10%
Tier 1	Must not exceed 70% (when combined with Tier 0)
Tier 2	Must not exceed 90% (when combined with Tiers 0 and 1)
Tier 3	Must be no less than 10%

6.2.1.1 Notation Used in Problem Definition

Notation for variables employed in the mathematical formulation of the *OESP* are defined as follows.

A	=	Set of activities, i, to be completed
X	=	$\{0,1,2,3\}$, the set of tier levels
Y	=	Set of equipment types (e.g. excavators, tractors, loaders)
Y_i	=	Subset of equipment in Y that can be used for activity $i \in A$, $Y_i \subseteq Y$.
Y_i^C	=	Subset of equipment in Y compatible with equipment in Y_i, $i \in A$, $Y_i^C \subseteq Y$.
N_t	=	Number of pieces of equipment permitted on site in each period $t \in S$.
c_{xy}	=	Cost of operating (renting, leasing or owning) each type of equipment $y \in Y$ in tier $x \in X$.
V_{it}	=	Amount of work (in terms distance, surface area, volume, or weight, depending on the activity) associated with task $i \in A$, that must be completed in period t
w_t	=	Number of working days in period $t \in S$
v_y	=	Daily capacity of work that can be completed by equipment type $y \in Y$, computed as a function of cycle time (time period required by piece of equipment to complete task and return to its original position).
D_{it}	=	Calculated or assigned duration of task $i \in A$, in period $t \in S$
g_{xy}	=	GHG emissions rate for equipment type $y \in Y$, in tier $x \in X$, expressed in CO_2e
P_{xyt}	=	Quantity of available equipment of type $y \in Y$, belonging to tier $x \in X$, in period $t \in S$
f	=	Leniency factor for each N_t assumed constant over all $t \in S$
q	=	Adjustment factor for equipment compatibility, limits differences in capacities of equipment that must operate together for any task
β_t	=	Discounting factor for inflation by period $t \in S$

The decision variable α_{xyt} used in the objective function is defined below.

α_{xyt} = Quantity of equipment of type y, y∈Y, belonging to tier x, x∈X, to be used during period t∈S

6.2.1.2 Mathematical Definition of the OESP

The *OESP* contains two objectives. The first, objective (1a), seeks the selection of equipment so as to minimize the total cost associated with completing the construction tasks over the construction period. The second, objective (1b), aims to minimize emissions in terms of CO_2e released during the construction's duration. The functional constraints (2 to 12) of the model fall into two general categories: those that address construction activity requirements and those that address emissions regulations.

$$Minimize \quad Z(\alpha_{xyt}) = [Z_1(\alpha_{xyt}), Z_2(\alpha_{xyt})] \tag{1}$$

where:

$$Z_1 = Min\sum_{t\in S}\left[\sum_{x\in X}\sum_{y\in Y} c_{xy}\cdot\alpha_{xyt}\right]\cdot\beta_t \tag{1a}$$

$$Z_2 = Min\sum_{t\in S}\left[\sum_{x\in X}\sum_{y\in Y} w_t\cdot g_{xy}\cdot\alpha_{xyt}\right]\cdot\beta_t \tag{1b}$$

subject to:

$$\alpha_{xyt} \le P_{xyt} \qquad \forall t\in S, x\in X, y\in Y \tag{2}$$

$$w_t\cdot\sum_{x\in X}\sum_{y\in Y_i} v_y\cdot\alpha_{xyt} \ge V_{it} \qquad \forall t\in S, \quad i\in A \tag{3}$$

$$\frac{V_{it}}{\sum_{x\in X}\sum_{y=Yi} v_y\cdot\alpha_{xyt}} \le D_{it} \qquad \forall t\in S, \quad i\in A \tag{4}$$

$$q\cdot\sum_{x\in X}\sum_{y\in Y_i} v_y\cdot\alpha_{xyt} \ge \sum_{x\in X}\sum_{y\in Y_i^c} v_y\cdot\alpha_{xyt} \qquad \forall t\in S, i\in A \tag{5}$$

$$\sum_{x \in X} \sum_{y \in Y_i} v_y \cdot \alpha_{xyt} \leq q \cdot \sum_{x \in X} \sum_{y \in Y_i^c} v_y \cdot \alpha_{xyt} \qquad \forall t \in S,\ i \in A \tag{6}$$

$$\sum_{x \in X} \sum_{y \in Y} \alpha_{xyt} \leq f \cdot N_t \qquad \forall t \in S \tag{7}$$

$$\sum_{y \in Y} \alpha_{0yt} \leq 0.1 \cdot \sum_{x \in X} \sum_{y \in Y} \alpha_{\text{xyt}} \qquad \forall t \in S \tag{8}$$

$$\sum_{y \in Y} \alpha_{0yt} + \sum_{y \in Y} \alpha_{1yt} \leq 0.7 \cdot \sum_{x \in X} \sum_{y \in Y} \alpha_{\text{xyt}} \qquad \forall t \in S \tag{9}$$

$$\sum_{y \in Y} \alpha_{0yt} + \sum_{y \in Y} \alpha_{1yt} + \sum_{y \in Y} \alpha_{2yt} \leq 0.9 \cdot \sum_{x \in X} \sum_{y \in Y} \alpha_{\text{xyt}} \qquad \forall t \in S \tag{10}$$

$$\sum_{y \in Y} \alpha_{3yt} \geq 0.1 \cdot \sum_{x \in X} \sum_{y \in Y} \alpha_{\text{xyt}} \qquad \forall t \in S \tag{11}$$

$$\alpha_{xyt} \in \mathbb{Z}^{+} \qquad \forall t \in S,\ x \in X,\ y \in Y \tag{12}$$

Equipment availability for project use through a construction firm's fleet or local rental or leasing office stocks is enforced through constraints (2). Workload requirements are enforced through constraints (3) and (4). Constraints (3) ensure that equipment is selected for a given period to guarantee that all work required for the given activities can be completed. To illustrate, consider a specific task involving cut and fill that requires soil compaction. Thus, the equipment to be assigned to complete this work must be chosen so that the total capacity of the equipment in terms of the ability to cover the required surface area exceeds the amount of work associated with the compaction activity for the period. Constraints (4) ensure that selected equipment can efficiently handle the activities to be accomplished in a specified duration. Note that each piece of equipment has its own work rate that is a function of its horsepower and other technical characteristics, as well as conditions associated with the site, including soil type, elevation, and weather. Constraints (5) and (6) ensure compatibility between chosen equipment pieces in terms of productivity and ability that are paired for the completion of specific tasks. These constraints limit the difference in the capacities of equipment to be operated together. They apply, for example, where a loader is paired with a truck: a loader to move dirt or other materials into a vessel and a truck to act as the vessel to move the material within or off the site. The effect of cycle time difference between such paired equipment must be considered and is handled in the constraints accordingly. The total number of pieces of equipment in the construction site during a given period must be restricted to permit sufficient working space within a construction site. This restriction is satisfied through the inclusion of constraints (7). A leniency factor f allows for a small increase in N_t for any $t \in S$ and is set to a value greater than one as desired. Constraints (8) through (11) apply the Tier System Guidelines. Integrality constraints are given in (12).

6.2.2 Solving OESP

Ideally, a single solution would simultaneously satisfy the cost and emissions objectives of *OESP*. However, as these objectives are conflicting in nature, it is not likely that such an ideal solution will exist. Thus, a set of non-inferior solutions can be generated, where no solution exists that is better than a non-inferior solution in terms of both objectives simultaneously. This set of non-inferior solutions is often referred to as the set of Pareto-optimal solutions and can be plotted on a graph with x-y coordinates corresponding to each objective to illustrate the Pareto-frontier. A method employing weights on the objective function components is employed in generating the Pareto-frontier as described next. This is followed by description of a constrained method through which an emissions cap can be modeled.

6.2.2.1 Weighting Method for Developing Pareto-Frontier

The weighting method was employed whereby the objectives are combined (and weighted) so as to reduce the problem to a single objective MIP that can be solved using off-the-shelf optimization software. Specifically, objectives (1a) and (1b) were replaced by new objective (1').

$$Min \sum_{t \in S} \left[\sum_{x \in X} \sum_{y \in Y} (\Omega \cdot c_{xy} + (1-\Omega) \cdot cc_t \cdot w_t \cdot g_{xy}) \cdot \alpha_{xyt} \right] \cdot \beta_t \qquad (1')$$

Since objectives (1a) and (1b) were not in common units, a conversion factor, cc_t is was applied to change emissions to a monetary value. cc_t is an assumed value for the price set for one MT of carbon in time period t in a carbon market. Objective (1') assumed a linear preference function. Each component was weighted by Ω (or 1-Ω), where $0 \leq \Omega \leq 1$. When Ω was set to 1, only the cost objective was considered. Likewise, when it was set to zero, only the emissions objective was active. By varying the value of Ω over its range and solving the resulting MIPs, the Pareto-frontier can be identified. Alternatively, a decision-maker can set Ω as a function of preference for one component over the other and solve the MIP only once to generate a preferred solution. Generation of the entire frontier aids decision-makers in evaluating trade-offs between the objectives. This can also be particularly helpful when a decision-maker is uncertain as to how to set the weights, either due to lack of certainty in preference for one objective over the other or how to set the weights so as to reflect his/her preference.

In generating the Pareto-frontier by means of a weighting method, the modeler/user must choose an appropriate increment for adjusting Ω from one run to the next. In applying this technique herein, solutions are plotted as they are derived and the increment is adjusted so as to fill in voids such that the Pareto-frontier is fully visualized. Thus, some portions of the curve may be developed through coarser analyses, while other portions may be developed from very fine increments.

6.2.2.2 Constrained Method Given an Emissions Cap

A second method was considered for approaching *OESP* in which only the cost objective (1a) was included and the emissions objective (1b) was reformulated as a constraint. The objective here was merely to minimize cost from the selection of equipment, while an emissions cap is imposed (constraints (13)).

$$w_t \cdot \sum_{x \in X} \sum_{y \in Y} g_{xy} \cdot \alpha_{xyt} \leq G_t, \qquad \forall t \in S \qquad (13)$$

where,

G_t = cap on GHG emissions expressed as CO_2 equivalent for period t, $t \in S$.

Such a cap would be set to be consistent with existing emissions regulations (e.g. a carbon cap) or policies. Thus, (1) was replaced by its component (1a) and constraints (13) were added to create the constrained-version of formulation (*OESP*):

$$Min\sum_{t \in S}\left[\sum_{x \in X}\sum_{y \in Y} c_{xy} \cdot \alpha_{xyt}\right] \cdot \beta_t \text{ subject to constraints (2)-(13).}$$

This constrained-version of formulation (*OESP*) (i.e. constrained-*OESP*) may be solved directly. Alternatively, one might consider generating solutions over a wide array of values of G_t. A comparison of solutions in which constraints (13) are binding for one or more time periods can provide additional insight.

Chapter 7. ICC Case Study

7.1 Description of ICC Project

The proposed carbon footprint estimation tool was demonstrated on a case study involving construction of a major new Maryland State Highway Administration (SHA) roadway facility called the Intercounty Connector (ICC). This 18.8 mile toll road will link highways I-270 and I-370 in Montgomery County, Maryland to I-95 and US Route-1 in Prince George’s County, Maryland. The length of this $2.4 billion roadway is broken into five segments of sequenced contracts (A, B, C, D and E) for which contracts to various design-builders were awarded (Figure 6-1): Contract A from I-270/370 to MD 97, Contract B from MD 97 to US 29, Contract C from US 29 to I-95 and collector-distributor lanes along I-95 south of the ICC, Contract D from the collector-distributor lanes along I-95 north of the ICC, and Contact E from I-95 to US Route-1.

The ICC project has addressed the environmental impact of construction by incorporating into construction contracts a $370 million environmental mitigation and stewardship package. This package aims to not only minimize environmental impact from the ICC project itself, but to also correct environmental problems unrelated to the ICC caused by decades of past development in Montgomery and Prince George's Counties. The package will protect the environment via many methods, including state-of the-art stormwater and roadway controls, use of sound barriers, stream and park restorations, air quality studies and reforestation [ICC, 2010].

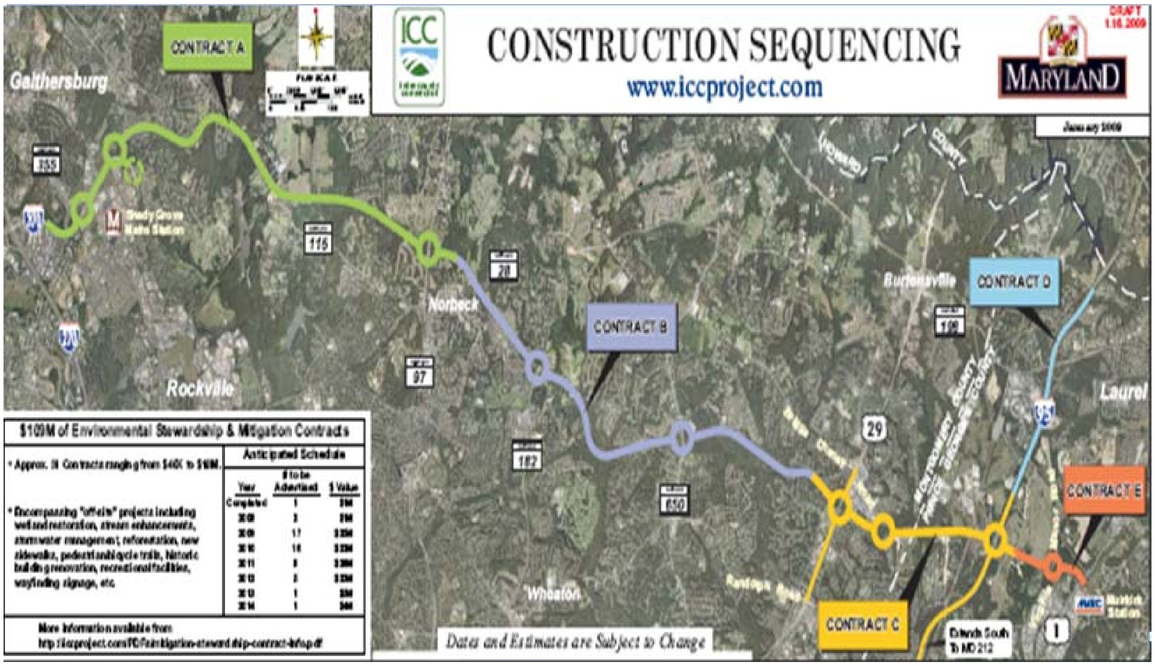

Figure 7-1. Map featuring the various segment of the ICC roadway project. *Source: ICC, 2010*

Contract A of this sequence is the furthest along in its construction and, therefore, was able to provide the greatest amount of input data for the model. Hence, it was chosen to illustrate the proposed utilities of the tools and potential benefits that can be derived from their application. Contract A is a 7.2 mile, 6-lane portion of the ICC, extending from I-370 to Georgia Avenue. Construction started in mid 2007. The roadway is due to open in early 2011 [ICC, 2010].

7.2 List of Data Obtained from the ICC Project

Data obtained from Contract A of the ICC project was used as inputs. These data were used directly or estimates from the data were made before feeding input into the models. The data were provided in two construction periods: Quarter 1 extending from November 2007 to June 2009 and Quarter 2 extending from July 2009 to January 2010. The data provided for use in these models are listed in Table 7-1.

Table 7-1. Data provided for use in case study by ICC Contract A.

Name of Data File	Content of Data File
CPM Gantt Chart	Timeline of construction including estimated task durations and percent task completion.
ICC Equipment Emissions Tracking Report	List of heavy equipment present on site by tier level and length on site.
Major Quantities	Volume and major quantities of materials placed on-site (Substructure, bridge girder and superstructure concrete; graded aggregate base course; miscellaneous aggregate hot mix asphalt pavement; steel girders and reinforcing steel; pipes) including total on-site fuel consumption.
Forest Map	Depicting and quantifying areas of deforestation and reforestation of entire project.
Chemicals List	List of chemicals delivered on site.
2002 Land Use File	Base mapping for the pre-ICC conditions.
Contract Document for ICC Reforestation at Seneca Creek State Creek Park / ICC Forest Mitigation Agreement	Lists contract provisions, terms and conditions for drainage, landscaping and utilities used and maintained post-construction in relation with the ICC environmental impact mitigation efforts.
Access and Mobility Plan	Blue-prints of project site depicting temporary roadways for access into and out of the site.
Equipment assignment to tasks	Equipment used for major tasks completion specified by general categories, such as articulated trucks, crawler loaders, wheel loaders, excavators, cranes, compactors, etc.
Major tasks list	Clearing and grubbing; earthwork cut and fill; installation of piles and retaining walls; placement of substructure concrete, steel/concrete bridge girders, superstructure concrete, and reinforcing steel, culverts, culvert wing-walls/headwalls, water and sewer pipes, drainage pipes, structures, and noise walls equipment used for major tasks completion were specified by general categories, such as articulated trucks, crawler loaders, wheel loaders, excavators, cranes, compactors, etc.

7.3 Estimates Made from ICC Project Data for CFET

The data received from Contract A of the ICC project were processed before it was fed into CFET for emissions estimation. The inventory of equipment as provided were listed by equipment type, make, dates of arrival and exit from site, fuel type, and tier level classification. The 184 pieces of equipment on the list were categorized into various equipment classes to fit the 35 equipment categories in the model. For example, the 730 CAT articulated truck was classified to be an off-highway truck. Equipment's rated power was determined from the engine specifications of individual equipment. Moreover, based on the tier level of each piece of equipment, model years were estimated for the equipment inventory (refer to Section 5.3.2 and Appendix F). The length of stay of equipment on-site was calculated from the entrance and exit dates provided in the inventory. Based on communication with the lead contractor, the activity duration of all equipment was estimated at 8 hours per day, 7 days per week. However, the exit dates listed in the inventory represented the reporting dates, and not the actual dates the equipment left the site. To accommodate for times equipment spent being stored on-site, and therefore, allow for a more accurate representation of the equipment activity on the project, the activity duration of all equipment was assumed to be at 6 hours per day, 7 days per week. Table M-1 of Appendix M lists the processed data used in the model to estimate emissions from equipment on the ICC's Contract A site.

Since data related to types of forests were not available, it was assumed that all of the forest types found in the state of Maryland were involved; whereas, the data from the Forest Map was used to estimate the area of deforestation. The volume of soil moved was obtained from the Major Quantities list. However, an estimate for the surface area of the soil moved was made based on the assumption that 1 meter (m) depth of organic soil was excavated from the site (i.e. Area = volume/depth). Collectively, this data was used as input into the site-preparation component of the carbon footprint estimation tool (Appendix N).

Inputs for the materials production component were also determined from the Major Quantities list in conjunction with information obtained from communication with the lead contractors. To estimate emissions from the use of concrete structures on-site, it was assumed that the cement used to make the concrete was produced on-site. 1% of emissions from cement production was used to determine emissions from concrete use on the ICC Contract A project site. Specifically, the quantities of place substructures concrete, place superstructures concrete, culvert wingwalls/headwalls, and bridge approach slabs were used to establish the amount of cement used on-site. This amount was determined based on the estimates of 377 lbs cement per cubic yard substructure, and 459 lbs cement per cubic yard superstructure, as provided by the lead contractors. The cement estimate of 459 lbs cement per cubic yard of structure was extended to culverts and bridge slabs, as well. The quantities of asphalt, fertilizer, and other chemicals were not provided. Hence, an estimate of the contribution of these materials to total emissions was made in reporting the results of the analysis. Based on opinions from contractors, it was assumed that emissions from these materials account for 2% of cement emissions (Appendix O).

The Forest Mitigation Agreement provided number and types of trees that will be re-planted post construction. The Agreement provided this data for a few sites on Contract A; not all reforestation efforts on Contract A was covered. In order to establish a more detailed representation of the ICC Contract A reforestation efforts, the total area of reforestation and tree spacing requirements for reforestation, as provided in the Forest Map and Mitigation Agreement, were used to estimate an approximate total number of trees re-planted. The number of trees was then divided appropriately amongst tree types in the mix of reforestation vegetation stated in the Mitigation Agreement.

Some trees, especially floral and fruit trees listed in the Agreement, were entered in the model component by matching them with tree types of similar characteristics (e.g. type of foliage and size). Also, the ICC reforestation effort uses 6”-12” saplings, which corresponds to 0 years in the component and, hence, the C-density values for tree types of age 0 years were used. The type of soil used to support reforestation was assumed to be a mixture of organic soils from all tree types found in Maryland and, therefore, an average of soil C-density was determined and used in calculating emissions sequestration by soil. A 1 m depth of re-soil was assumed to estimate the area of re-soil. Collectively, this data was used in the environmental mitigation component of the model to calculate emissions sequestered by reforestation. The input data and emissions calculations for this component are documented in Appendix P.

7.4 Estimates Made from ICC Project Data for Decision Support Tool

The project time period was broken into one-month intervals for a $|S|=27$. In addition to the information supplied by Contract A in Table 7-1, numerous calculations and assumptions were required to support the use of the decision support tools. Specifically, equipment cycle times and, thus, the amount of work each piece of available equipment could complete in a given day were estimated from equipment specifications assuming 75% "duty days" and eight-hour workdays. The amount of work to be completed in each work category was calculated from provided total work estimates prior knowledge of construction processes, categories of equipment assigned to task, and equipment productivity. The productivity of each piece of equipment when employed on a particular task depends in part on its cycle time, which is a function of its speed and the distance over which it must work. Equipment cycle times are subject to many factors, such as soil properties, water content, geographic location, and rolling resistance. Since this information was not provided by the contractors, estimates were made.

Estimation of the work required to complete cut and fill tasks illustrates the procedures used. Articulated trucks, excavators, smooth drum rollers, track loaders, compactors, dozers, and scrapers were assigned to this task in Contract A. It was presumed that the articulated trucks are used to move the entire volume of soil from cut areas to fill areas. Excavators and loaders are employed in loosening and loading soil, respectively. Assuming that the quantity of soil to be cut is equivalent to the quantity to be filled, the amount of work supported by compactors and rollers in this stage of the project is assumed to be half of the surface area of the project. Given the local terrain and its impact on maneuverability, scrapers were assumed to conduct their work over 40% of the project area. Dozers serve in leveling the project area and loosening the soil for loaders. It was assumed that half of the cut volume of soil is handled by dozers. Thus, the amount of soil to be moved, the types of equipment involved in completing the move, and the area over which the activity takes place are predicted. With this knowledge and information pertaining to the characteristics of available equipment, cycle times and ultimately productivity can be estimated.

Similar estimates were made to capture other activities on the construction site. For example, the number of trees that needed removal during the clearing and grubbing phase was discerned from information available through the USDA [Zhu, 1994], where the average forest density mapping is provided by region. An average tree diameter was assumed based on the forest type and age. Tonnage of trees to be removed was thus assessed from forest density and expected tree weights. Work (in terms of volume) required to cut and move these trees was approximated based on presumed types of equipment that would be involved in these processes.

In an application of the proposed methodology to such a construction project, more accurate information pertaining to the required amount of work for each task is typically obtained through field measurements and such measurements are routinely taken. The types of equipment that can be used for a given task were specified based on field experience. Work completed by each piece of equipment will produce emissions.

CFET can provide equipment emissions rates for the required equipment emissions calculations for the decision support tool. Rates employed within CFET, however, are averaged over a range of values of equipment horsepower. As more precise estimates are required so as to distinguish between individual pieces of equipment whose rated power (hp) values may vary only slightly, an alternate method was used. Specifically, to estimate daily emissions of CO, CO_2, CH_4, NOx, and SOx by equipment piece, the USEPA's formula shown below for emissions calculation was used.

$$EM_{\text{GHG}} = EF_{\text{GHG}} \cdot P \cdot AF \cdot LF \cdot A$$
$$where, \quad GHG \in \{NO_x, CO_2, CH_4, CO, SO_x\}$$

<u>Notation</u>

EM_{GHG}	:	Emissions per equipment (MT of GHG /day)
EF_{GHG}	:	Emission factor (g/hp-hr) [USEPA, 2001; DieselNet, 2010; Lewis, 2009]
P	:	Power (hp)
AF	:	Adjustment factor = 0.80
LF	:	Measure of equipment efficiency (%/100)
A	:	Equipment activity (hr/d) ; assumed to be 6 hours/day

An adjustment factor of 0.85 is employed here to account for inaccuracies in load factor and fuel type. This value was chosen so as to reflect recent reductions in the sulfur content of diesel fuel and inaccuracies in estimates of load factors. The load factors were obtained from [USEPA, 2005b]; however, more accurate values can be obtained from the manufacturer. Likewise, Contract A uses low sulfur diesel only; however, the above formula presumes the use of more emissive regular diesel. Emission data collected from equipment use in prior projects or from information supplied in equipment performance handbooks can be employed in daily emissions estimation for equipment usage and emission factor setting.

For CO, CH_4, NOx, and SOx, the emission factors were obtained directly from the USEPA. An emission factor is not provided in relation to CO_2; however, a formula based on brake-specific fuel consumption (BSFC), as described below was used for its computation [USEPA, 2005b]. One will note that hydrocarbon (HC) emissions are removed to avoid their being double counted, as they include CH_4.

$$EF_{CO2} = \frac{44}{12}\left[\left(BSFC \cdot U - HC\right) \cdot C_F\right]$$

Notation

EF_{CO2}	:	Emission Factor for CO_2 (lb of CO_2/hp-hr)
BSFC	:	Fuel consumption (lb/hp-hr)
U	:	Unit conversion; 1 lb = 453.6 g
HC	:	In-use adjusted hydrocarbon emissions (g/hp-hr)
C_F	:	Carbon mass fraction of gasoline and diesel fuel = 0.87

Other categories for which calculations were made or approximation schemes were devised are listed in Table 7-2.

Table 7-2. Additional input information not provided by ICC Contract A used in decision support tool.

Data Type	Details
Amount of work to be completed by each type of equipment	Based on assignment of equipment types to task types.
Assignment of specific equipment to tasks	Based on assignment of equipment types to task types and specific capabilities of equipment.
Compatibility of equipment	Daily capacity differences between coupled equipment that need to be operated together for task completion cannot exceed 10%.
Cost for equipment by tier	For a given piece of equipment, the cost of equipment falling within Tiers 0, 1 and 3 are assumed to be 15% less expensive, 10% less expensive and 20% more expensive than the same equipment falling within Tier 2 (in which the majority of the contract equipment falls).
Emission Caps	G_t for each $t \in S$ is set such that $\sum_{t \in S} G_t = 160{,}000$. G_t is set for each period to vary over the construction period according to a beta distribution, $\sim\beta(A, B, p, q)$ $(p>0, q>0, A<B)$, with $p=2$, $q=1.2$, $A=0$, and $B=1.2$.
Total number of equipment pieces allowed on site simultaneously	Set based on actual number of pieces on site in each period.
Equipment productivity	Set based on known capacities and estimated cycle times, where cycle time estimates are based on the roadway profile where appropriate and equipment characteristics; an average productivity was computed over all time periods based on required travel distances per period.

As it is possible for the contractor to use equipment from his/her own fleet or to purchase, rent or lease equipment externally, it was assumed that all equipment listed on the supplied list of on-site equipment was available for every tier level. Ownership and operating expenses for equipment were set based on information available from the U.S. Army Corps of Engineers for Region II [Hill, 2009].

The price for CO_2e (i.e. carbon credit) used herein is based loosely on the carbon price on the Chicago Climate Exchange, one of the best organized carbon markets in the U.S. The price ranges between pennies and a few dollars per MT of carbon credit. Carbon price on this market reflects the amount a company or individual might be willing to pay on a voluntary basis, since carbon allowances are not currently imposed within the U.S. Assuming that once carbon allowances are enforced the carbon price will rise steeply, and given that the price is close to $30/MT in Europe where carbon allowances exist in certain sectors, in this case study, three values are used for the price of carbon on a carbon market: $5/MT, $30/MT and $50/MT. $50/MT is considered because economists estimate that this price is required to pay for 65% emission reductions to be reached by 2030 in developing countries [World Bank, 2010].

7.5 Results & Discussion from CFET

After the inputs were entered into CFET, the tool provided outputs for each component and calculates the net emissions from the ICC project. Since the primary purpose of this tool was the estimation of GHGs from construction, the table only lists results in CO_2e. The equipment usage component and coatings/solvent sub-component quantifies other air pollutants, as well. A summary of these results are shown in Table 7-3 below.

Assuming that all equipment on-site was in use for 6 hours per day, 7 days per week, Contract A of the ICC project emitted a net total of 179,022.30 MT CO_2e from the period beginning November 2007 to January 2010 (i.e. 2.5 years). Subsequently, Contract A of the ICC generated approximately 24,864 MT CO_2e per mile of roadway that was constructed. The calculations performed by each component on the ICC data are documented in Appendices M-P.

It must be noted that the model calculates net emissions for the entire project duration and not net annual emissions. Thus, the total impact of the construction project in terms of emissions was estimated. If a rudimentary comparison of the ICC annual average of emissions of 71,609 MT CO_2e per year (i.e. total emissions divided by 2.5 years) is made to annual emissions of 131 MMT of CO_2e (2006) by the entire U.S. construction industry [USEPA, 2008], Contract A of the ICC project alone contributed approximately 0.1% annually to national emissions from the construction industry.

Figure 7-2 below shows that the majority of emissions from the ICC construction project under Contract A can be attributed to the use of equipment (55%). This is followed closely by site-preparation at 45%, and almost negligible materials production emissions at

0.06%. The environmental mitigation efforts undertaken within Contract A offer minor carbon sequestration capabilities, accounting for 9% of the total emissions (Table 7-3) generated by the other construction activities (i.e. site-preparation, equipment usage and materials production).

Within biogenic emissions sequestration, it is generally observed that organic soil absorbs more carbon than trees, particularly in the case of young trees (6-12" seedlings) as used in the reforestation efforts of the ICC. Soil systems are typically more stable and, therefore, sequester more carbon over time as compared to young trees. If older trees are used for reforestation, the combined absorption of re-planted trees and organic soil would be substantial, as reflected in the reforestation C-density tables in Appendix K.

Table 7-3. Summary of results of ICC case study from CFET.

Construction Process	Total Emissions (MT CO_2 or CO_2e/ project)
Site-Preparation	89,328.03
- *Deforestation*	43,394.58
- *Soil Movement*	45,933.45
Equipment Usage	107,483.35
Materials Production	118.77
- *Concrete**	39.59
- *Solvents, Asphalt & Fertilizers***	79.18
Environmental Mitigation	17,907.86
- *Reforestation*	681.72
- *Resoil*	17,226.14
TOTAL EMISSIONS PRODUCED	196,930.15
TOTAL EMISSIONS OFFSET	17,907.86 (9%)
NET EMISSIONS	179,022.86

**Assumes 1% of cement emissions due to lack of data,*
***Assumes 2% of cement emissions due to lack of data*

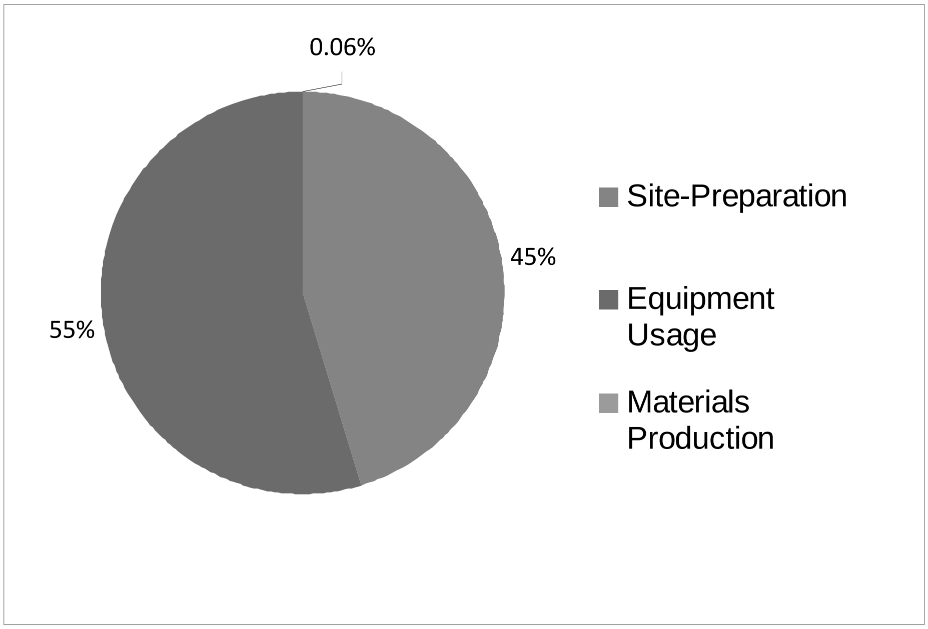

Figure 7-2. Chart illustrating the contribution of activities on the ICC Contract A to emissions produced.

Moreover, based on the mix of trees for reforestation, it would be beneficial to increase the number of trees that fall into the Oak/Pine category, since this category accounts for only 6% of the vegetation population, but results in almost 11% of the total sequestration capacity achieved through reforestation on the project (Figure 7-3).

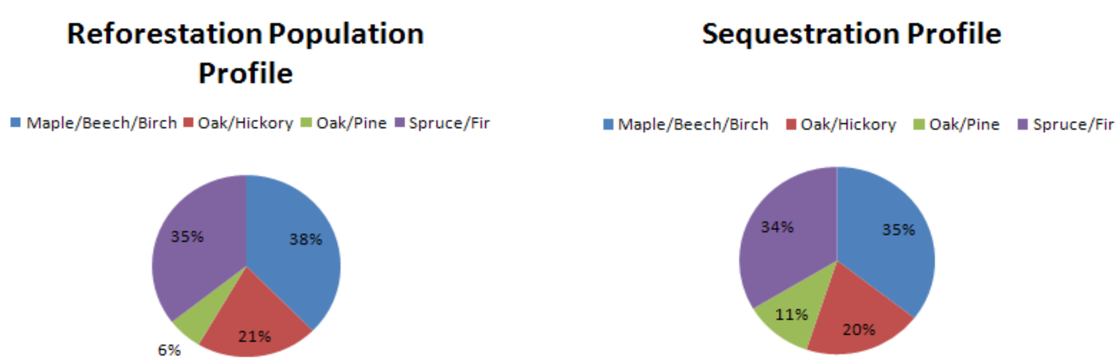

Figure 7-3. Comparison of population profile to sequestration profile of reforestation vegetation.

Results from the equipment usage component are listed in Table M-2 of Appendix M. The model estimated a total of 107,843 MT of CO_2e (GHGs), 0.25 MT of SOx and 33 MT of ROG (air pollutants) from the 184 pieces of equipment used on the project from the start to January 2010. Of the fleet of equipment on-site for the duration of the project, off-highway trucks, excavators and bull dozers contributed the most, accounting for 19%, 17% and 15% of the total emissions from equipment usage, respectively (Figure 7-4).

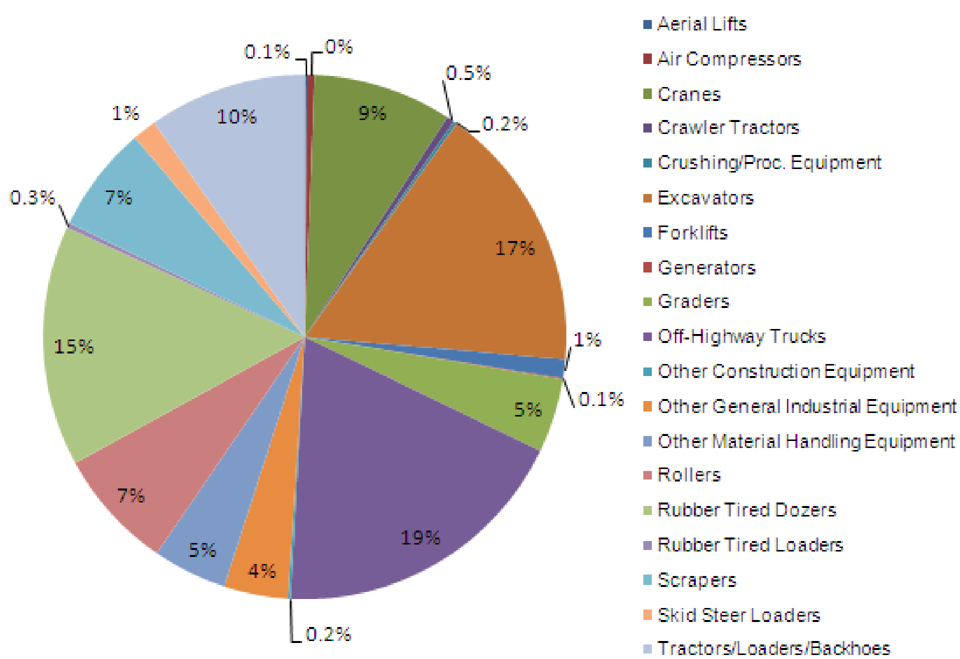

Figure 7-4. Emissions profile of the ICC Contract A equipment usage by equipment type.

Specifically, these top emitters included tier 3 excavators, tier 2 dozers, and 3 off-highway trucks, each producing greater than 8,000 MT CO_2e. Of these, tier 3 excavators ranked the highest, emitting 10,600 MT CO_2e. Amongst the group of equipment that produced the least emissions were tier 2 aerial lifts, tier 2 generators, and tier 1, 2 and 3 skid steered loaders. Within this group, each piece of equipment contributed less than 700 MT CO_2e (Figure 7-5).

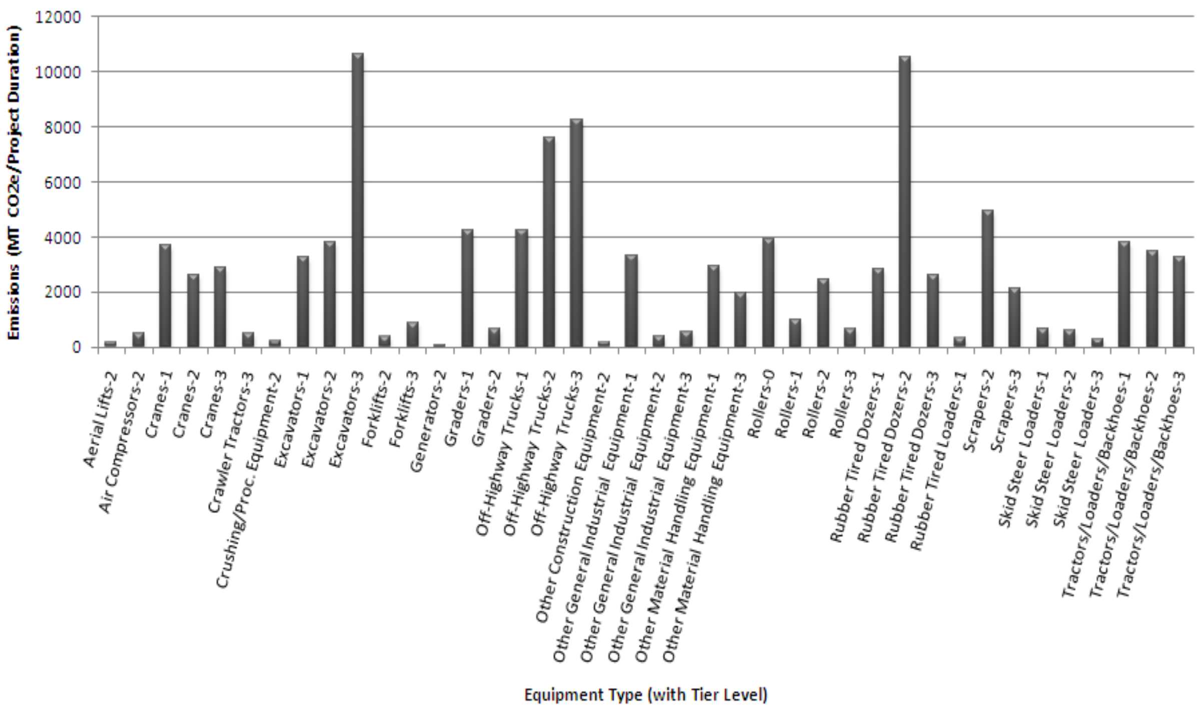

Figure 7-5. Total emissions produced on the ICC Contract A by equipment type.

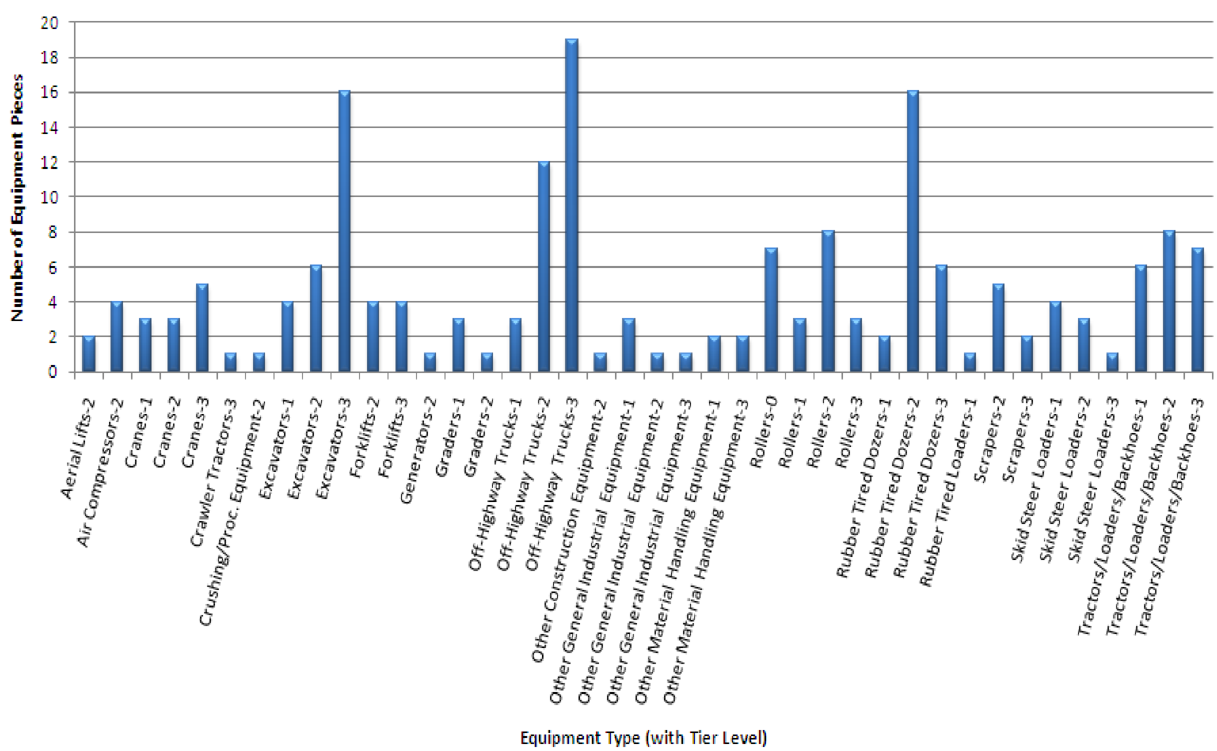

Figure 7-6. Number of equipment piece by type on the ICC Contract A.

It can be noticed in Figure 7-5 that some of the higher tiered equipment contribute to high emissions. According to the EPA Tier system, the higher tiered equipment typically emit less than their lower tired counterparts. The high emissions from higher tiered equipment is explained by the large number of equipment pieces belonging to tiers 2 and 3 (Figure7-6) that were present on-site of ICC Contract A. This is illustrated by comparing figures 7-5 and 7-6 where the equipment categories with significantly large number of equipment pieces contribute to the high emissions despite belonging to a higher tier level.

The equipment fleet on Contract A of the ICC was also categorized by tier level to determine the contribution of each level to total emissions from equipment usage. Table 7-4 classifies equipment emissions by tier level. It must be noted that these values are average estimates, i.e. total emissions per tier divided by number of pieces of equipment per tier. While the table depicts that the tier 0 category accounts for the least emissions, it only represents one category of equipment (i.e. rollers), whereas, the other tier levels (tiers 1 to 3) include a wide variety of equipment types. However, it must also be noted that equipment in tier 1 produces emissions relatively close to that from tier 3 although tier 3 contains approximately twice the number of equipment pieces as tier 1.

Table 7-4. Contribution of equipment emissions by tier level over project period on the ICC Contract A site.

Tier Level	Number of pieces	% Total Equipment Population	Emissions per Tier (MT of CO_2e/Equipment)
0	7	4	3916.8
1	34	18	30379.4
2	76	41	38561.0
3	67	36	34626.1
TOTAL	**184**	**100**	

Although several assumptions and estimates were made from the data obtained from the ICC to fit the model requirements, these were relatively easy to make and required minimal time. It must be noted that estimation of emissions was limited to those produced by activities performed on-site only. For example, emissions produced by movement of waste and materials to and from locations outside the construction site were not estimated.

However, the use of vehicles for purposes of materials transport within the ICC Contract A site was accounted for while calculating emissions from trucks used on-site.

The implication of the deforestation process and reforestation efforts (1:1) by Contract A was estimated by using the offset component of the carbon footprint estimation model for a variety of offset durations. Specifically, the component was used to determine the extent of positive impact the ICC Contract A reforestation efforts had on abating the negative impact of deforestation. 5, 10, 20 and 30 years were used as the crediting time period to calculate potential offset. As seen in Table 7-5, for a 20 year crediting period, the deforestation on the project had a significant negative effect and the reforestation efforts would not be able to fully offset this impact. With an increase in duration of offset, offsets due to reforestation improves. For a 20 year offset period, the ICC Contract A would achieve a zero carbon footprint created by deforestation (i.e. net offset = 0) by re-planting 1,037,548 tree saplings i.e. 24:1 reforestation to deforestation ratio.

An analysis of the annual sequestration rates of trees by their age as in Table 7-6 reveals that although the younger trees have a significantly higher sequestration rates (i.e. sequester faster) than the older trees, the older trees still sequester more carbon annually than the younger trees. For example, when changing from an offset duration of 5 to 10 years, the younger trees used in reforestation sequester 86% more; whereas, the older trees sequestration rate only increases by 21%. However, for a 5 and 10 year offset period, the older trees sequester almost six and four times more than the younger trees, respectively.

Table 7-5. Summary of offset determination for ICC Contract A.

Offset Period	Process (MT CO_2)			Purchase Credit? (Yes/No)
	Deforestation	Reforestation	Net Offset	
5	43469.50	1491.72	- 42712.94	Yes
10	43485.41	2184.82	- 41300.59	Yes
20	43519.49	3813.18	- 39706.31	Yes

Table 7-6. Analysis of annual sequestration rates of trees.

Offset Period	Age of Tree (years)*		Annual Sequestration Rate ($MT\ CO_2$/tree)		Increase in Sequestration Rate (%)	
	Deforestation	Reforestation	Deforestation	Reforestation	Deforestation	Reforestation
5	28	5	0.0165	0.0029	21	86
10	33	10	0.0200	0.0054	38	108
20	43	20	0.0276	0.0112	n/a	n/a

** Age of the tree as estimated by the model = j in equations in Section 5.3.5*

Furthermore, the minor offset provided by reforestation may also be explained by the effect of units of measurements of the rates of growth of trees. For example, the average growth rate of a hardwood species in year 1 is 2.77 lbs/year/tree (0.00125 MT C/year/tree) and increases significantly in year 20 when the growth rate is 25 lbs/year/tree (0.00939 MT C/year/tree). However, this un-hinders the outcome that the ICC's Contract A would need to purchase carbon credits to offset the deforestation on the project, regardless of the duration of the offset period

7.6 Results & Discussion from the Application of the Decision Support Techniques

7.6.1 Results

The *OESP* problem once formulated was solved with EXPRESS-MP running on a personal computer with a 2.27 GHz Intel Duo Core CPU P8400, with 3.00 GB of RAM on a 32 bit Windows 7 operating system. Ω was set between 0 and 1 in 5% increments, generating 25 problem instances. The component objective function values were plotted against each other to produce the Pareto-frontier. Typical runs of EXPRESS required approximately 35 minutes in real-time. Problem instances contained approximately 12,000 variables. An optimality gap of 0.35% was permitted, consistent with recommendations to solve to within

5% of optimality. The resulting Pareto-frontier is visualized in Figures 7-7 through 7-11 for each setting of the cost of one MT of carbon credit.

It can be seen from the figures that significant reductions in emissions are expected through intelligent selection of construction equipment for use in completing project tasks. Figure 7-7 shows that at a cost of \$5 per MT of CO_2e, a dramatic improvement in emissions can result from a modest increase in equipment usage costs. For instance, when Ω is decreased from 0.1 to 0.08, the equipment cost increases by just over \$312,000 (approximately 4.7%). For this increase in equipment cost, a reduction by 28% in emissions (and its associated cost) can be obtained. Similar efficiencies are noted when the price per MT of CO_2e is set to \$30 (Figure 7-8) and \$50 (Figure 7-9).

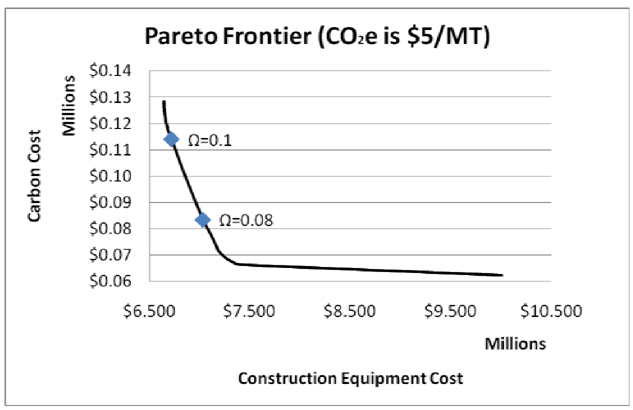

Figure 7-7. Pareto-Frontier for CO_2e at \$5/MT

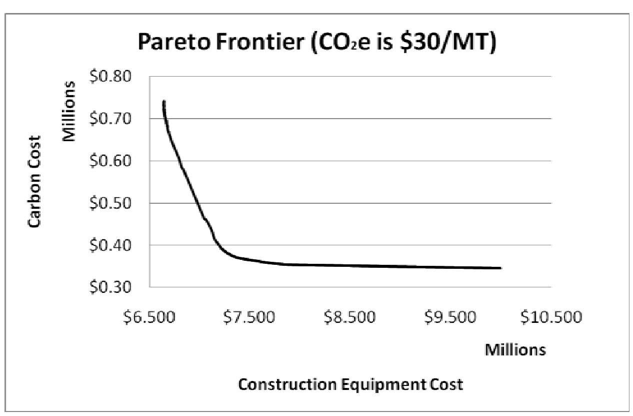

Figure 7-8. Pareto-Frontier for CO_2e at \$30/MT

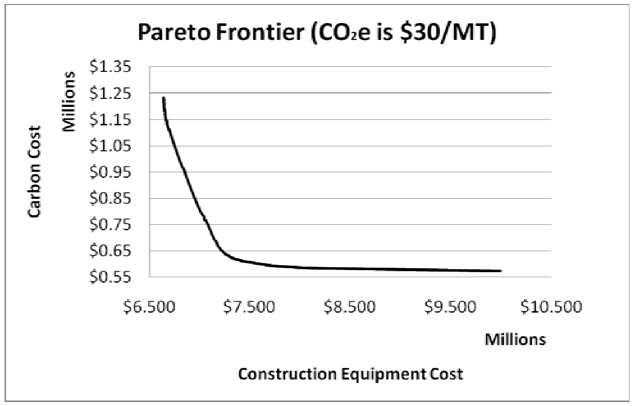

Figure 7-9. Pareto-Frontier for CO_2e at $50/MT

An estimate of emissions at 160,000 MTs of CO_2e produced from equipment use in Contract A over the study period was made based on the number of days each piece of equipment in the on-site equipment list spent on site, number of assumed working hours per day and emissions rate per equipment type. This estimate was used to create the initial settings for G_t for each $t \in S$ in (13) of the (*constrained-OESP*) formulation. Solution of this formulation was obtained and the objective function value (i.e. equipment cost) was plotted against a reduced $\sum_{t \in S} G_t$. That is, to show how more restrictive cap values affect the optimal solution, the value of the sum of G_t over all $t \in S$ was reduced from its initial value, assumed at 160,000 MTs over the entire time horizon. The resulting cost from equipment is plotted against the reduced values of $\sum_{t \in S} G_t$. This is depicted in Figure 5, where the horizontal axis indicates the relative value (in terms of percentage decrease) of $\sum_{t \in S} G_t$ with respect to its initial value. X% on the horizontal axis refers to an X% reduction in $\sum_{t \in S} G_t$ from the initial $\sum_{t \in S} G_t$ of 160,000 MTs. A percentage emissions reduction of 80%, for example, corresponds with a value for $\sum_{t \in S} G_t$ of 32,000 MTs (a reduction of 128,000 MTs). As indicated in the figure, $\sum_{t \in S} G_t$ can be reduced substantially before a notable increase in equipment cost arises. This confirms that constraints (13) are not binding at the initial $\sum_{t \in S} G_t$ value. In fact, if constraint (13) is binding for any particular time period *t*, when the associated G_t is reduced, the problem will be infeasible. At approximately 78% of the initial $\sum_{t \in S} G_t$ value, equipment cost begins to rise sharply to comply with this constraint. When set even lower, it becomes difficult to comply with the constraint at any cost, as indicated by the nearly vertical line beginning at approximately 89% on the horizontal axis.

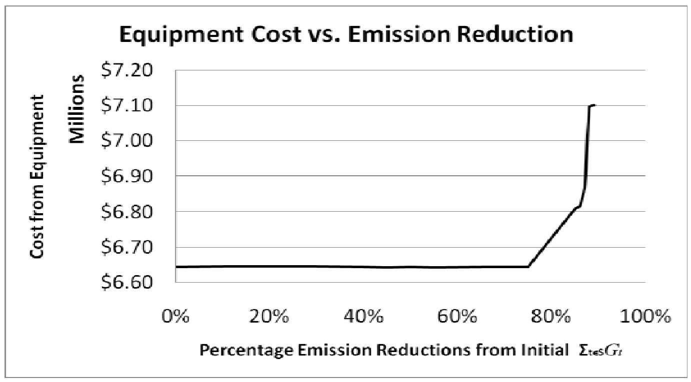

Figure 7-10. Impact of reduced emissions cap on equipment cost.

Figure 7-10 also shows how an industry might set a reasonable cap for a given project. In the case of ICC, the cap might be set in the range of 80-85% of the initial $\sum_{t \in S} G_t$ value. Moreover, if the estimated initial $\sum_{t \in S} G_t$ value accurately reflects emissions as a result of equipment use in the project (recall that it was assumed that equipment on site was in use 6 hours per day, 7 days per week), one will note that for a very small equipment cost increase, a very significant improvement in emissions reductions can be achieved.

To illustrate the potential impact in terms of emissions prevented and choice of equipment that results from the use of the proposed methodology, equipment plans generated through solution of *OESP* with Ω = 1, 0.9, 0.1, and 0 are compared for cc_t of \$5 at a single select time interval, t = 21. These results are compared in Tables 7-7 through 7-11.

Results given in Table 7-7 indicate that when cost is the only consideration (i.e. Ω=1), few pieces of equipment from the top tier are selected, i.e. the minimum required to meet Tier System constraints (8-11). When emissions are the only consideration (i.e. Ω=0), and cost is of no consequence, all equipment are chosen to be in the top tier (Tier 3). While little difference in number of equipment pieces in each tier level is noted for Ω at 0.1 as at 1, there are changes in equipment within a category as shown in Table 7-8. For example, within the Off-Highway Trucks category, there is a change from 14 "ArtA335D" selected when Ω=1 to 13 "Art730s" and three "ArtA35Ds" when Ω=0.1. These pieces of equipment fall under the same tier level. Additionally, there are changes in tier level, as is the case in the Dozers category. 11 Tier 1 equipment pieces are selected when Ω=1, while 11 similar pieces of equipment that fall under Tiers 2 and 3 are selected when Ω=0.1. Appendix Q provides information associated with t=21 that supports these conclusions.

Table 7-7. Number of equipment pieces assigned by tier for t=21.

Tier	Ω=1	Ω=0.9	Ω=0.1	Ω=0
0	7	7	7	0
1	43	43	44	0
2	14	14	15	0
3	8	8	8	78
Total	**72**	**72**	**74**	**78**

Table 7-8. Number of equipment pieces assigned by equipment type and category for t= 21 .

Equipment Category	Equipment ID	Ω=1	Ω=0.9	Ω=0.1	Ω=0
Off-Highway Trucks	ArtA35D	14	14	3	0
	ArtT730	0	0	13	17
Graders	Com815F	1	1	1	1
Cranes	Cr165TN	3	3	3	3
Dozers	DozD65	0	0	0	11
	Doz650J	1	1	0	0
	DozD5GLGP	2	2	3	0
	DozD6N	7	7	7	0
	Ex315CL	1	1	1	1
Excavators	Ex330CL	0	0	0	5
	Ex345CL	4	4	4	0
	Ex325DL	0	0	0	1
Forklifts	Fork10054	6	6	6	6
Tractors/Loaders/Backhoes	L410J	2	2	2	2
	L644G	4	4	4	4
Rollers	Rol50	2	2	2	0
	Rol66	0	0	0	11
	RolSD100D	11	11	11	0

	RolSD110D	0	0	0	1
Scrapers	Scrap621G	9	9	9	9
Skid Steer Loaders	Skid460D	1	1	1	1
Other Construction Equipment	ConcF4800	1	1	1	1
Other Material Handling Equipment	FB643J	1	1	1	1
	HB260HP	1	1	1	1
Other General Industrial Equipment	TGrind6600	1	1	1	1
Total		**72**	**72**	**74**	**77**

From Table 7-9 it can be seen that at a carbon price of $5/MT, over $3 million (a 50% increase) is incurred in excess costs in selecting the optimal equipment with consideration only for emissions (i.e. Ω = 0). A more modest increase (of a bit over $64,000) is incurred when equipment cost is given small weight, i.e. when Ω = 0.1. It can also be noted that when funds are expended on more efficient (high tier) equipment, the cost from emissions in the objective function decreases, as indicated in Table 7-9. Specifically, as Ω decreases, more weight is placed on emissions costs and less on equipment costs, making solutions with higher cost, more efficient equipment more desirable. This trend is particularly notable in the comparison of costs for Ω=0 vs. Ω=1 in the last row of the table.

Table 7-9. Costs comparison by Ω for a carbon price of $5/MT.

Weight Ω	Equipment Cost	Emissions Cost	Total
Ω=1	$ 6,641,602	$ 123,384	$ 6,764,986
Ω=0.9	$ 6,642,333	$ 123,196	$ 6,765,529
Ω=0.1	$ 6,720,404	$ 108,946	$ 6,829,351
Ω=0	$ 10,008,880	$ 57,449	$ 10,066,329
Ω=0.9 vs. Ω=1	$ 731	$ (187)	$ 543
Ω=0.1 vs. Ω=1	$ 78,802	$ (14,437)	$ 64,365
Ω=0 vs. Ω=1	$ 3,367,277	$ (65,935)	$ 3,301,343

Figure 7-11 depicts the relationship between the Ω setting and objective function value. The solution is not sensitive to Ω in the range of values from 0.1 to 1. As Ω is reduced below 0.1 (the cost of emissions is given more weight), there is a steep change in curvature of the line, indicating a significant change in equipment selection.

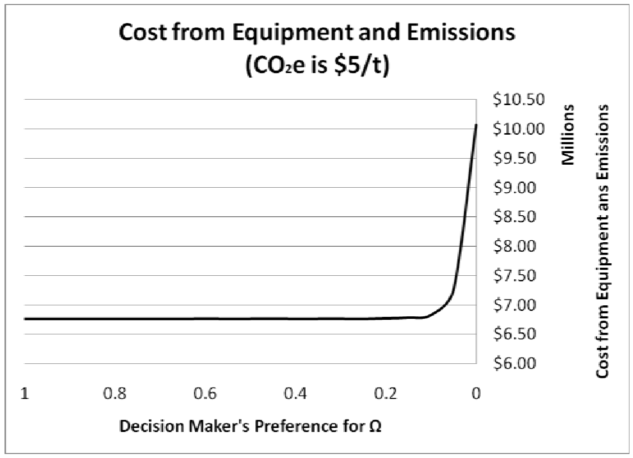

Figure 7-11. Costs from equipment and emissions.

Tables 7-10 and 7-11 indicate the percentage increase in cost and reduction in estimated actual emissions, respectively, that result from considering the cost of emissions in the objective function for Ω at 0 and 0.1 (i.e. when equipment cost is ignored or is given little preference, respectively). These tables indicate that for a 0.95% increase in total cost from equipment, a savings of 12% in emissions can be achieved. Likewise, for a 51% increase in equipment cost, a reduction in emissions by 53% can be achieved. If new, less emissive equipment were available to the project, improved emissions reductions might be possible, albeit possibly at a higher cost.

Table 7-10. Equipment and total cost increases compared with cost for Ω = 1.

Weight Ω	Equipment Cost	Total Cost
Ω=0.1	1.19%	0.95%
Ω=0	50.70%	48.80%

Table 7-11. Emission reductions compared with cost for Ω = 1.

Weight Ω	Emissions Reduction
Ω=0.1	12%
Ω=0	53%

7.6.2 Discussion

Solution to OESP of the decision support tool provides an optimal choice of equipment to be used in each period of a construction project. It further aids a contractor in deciding whether to buy, lease or rent equipment for the project. Also, by including equipment that can be rented or leased in the equipment pool, the tool aids in decisions related to augmentation of an equipment fleet through renting or leasing. Costs considered in the objective function of formulation (*OESP*) can account for changes in cost as a function of purchase price, depreciation, terms of lease, rental prices, and tax regulations.

Delays in task completion may result as a consequence of unforeseeable circumstances, such as inclement weather. Such delays adversely affect project length. Through solution of the mathematical formulation using updated task durations, the proposed methodology provides optimal equipment selection for future time periods so as to reduce the impact of delays. The viability (and cost) of shortening the project's duration so as to obtain a bonus for early completion can also be evaluated.

While all bids must show that designated requirements regarding the environment in the call for proposals are met, rarely is environmental impact considered in choosing the winning bid. The decision tool permits a contractor to propose an environmentally cognizant bid by helping develop an equipment-usage plan that adheres to current and future environmental regulations that might affect construction, including the EPA's Non-road Diesel Engine Tier System, and possible establishment of a carbon tax or cap and trade programs. The tool will, likewise, enable state agencies to consider emissions in addition to project costs and duration in assessing bids.

The proposed methodology can aid construction firms in maintaining profitability in a carbon regulated future by facilitating decisions aimed at meeting new regulations or reducing environmental impacts by making changes to its equipment fleet. This can also aid in better positioning a construction firm to receive government-provided incentives for environmental stewardship. Consideration of solutions to *OESP* for a select project generated by setting Ω to its extreme values (i.e. 0 and 1) will provide policy makers with reasonable estimates of achievable emissions reductions, and an understanding of costs associated with emissions abatement. Likewise, in an emissions regulated future, solution of the *constrained-*

OESP can facilitate a construction firm in determining the amount of money in terms of an acceptable carbon price for expanding its carbon allowance through either the purchase of surplus carbon credits or by paying penalties for noncompliance. It may also be possible to profit from selling surplus allowances. Additional costs associated with producing such a surplus through equipment selection can also be assessed. Furthermore, this feature facilitates policy makers or contracting agencies in setting a reasonable cap for a given project.

Chapter 8. Conclusions

As support for emissions reduction continues to grow, an increasing number of policies and regulations are being developed to encourage all industries to reduce their carbon footprint. With the construction industry ranking third in emissions production in the country, these policies are bound to have a significant effect on the industry and will define how construction contracts are developed and chosen. Since the construction industry supports the development of the nation's long-standing infrastructure and other civil structures, the industry holds a novel position in facilitating the reduction of emissions. Moreover, as public and political sentiment for greener ways strengthens, the construction industry will need to develop greener construction practices. A green construction industry will aid national efforts to diminish the industry's environmental impact.

The carbon footprint estimation tool, CFET, described herein was developed specifically to aid in the quantification of emissions from all major processes observed on a construction project, such as site-preparation, equipment usage, on-site materials production and environmental impact mitigation efforts, while accounting for the principles of federally mandated programs, such as NCDC. The tool was developed using the state-of-the-practice methodologies available nationally and is in accordance with global regulations under the IPCC Guidelines for National Greenhouse Gas Inventories. Several GHG models, research papers and national methodologies were studied to determine appropriate methods of estimation. Basic conceptual equations for emissions estimation were obtained and customized to calculate emissions specifically from construction projects. Additionally, extensive research was conducted to accumulate recent data from various sources such that the most accurate determination of these emissions can be made. Collectively, the proposed tool encompasses the most recent data available and utilizes adapted equations for calculations and to determine emission factors with high AP-42 ratings, in accordance with IPCC guidelines. Therefore, CFET functions as a single, stand-alone tool specific to the estimation of all activities undertaken during a construction project. Also, since the tool integrates current standards and can accommodate new regulations that might affect construction, it is designed to be beneficial for many years to come.

The scope of CFET is limited to estimating emissions due to processes only within a construction site. Therefore, emissions produced due to transport of materials outside the construction site are not accounted for in the model. Additional materials used on-site that are known to contribute high off-site emissions during their production, such as cement and steel production, were also accounted for in the model. Thus, the use of end-product construction materials, such as insulation materials, etc., were not included in the model as they do not emit GHGs during their use on-site despite that GHGs are still emitted during their production in the factory. The accuracy of the emissions estimates are dependent on the accuracy of the input data and how the user accounts for the effect of variables on results.

The results from CFET would be primarily used to help agencies identify the major sources of emissions, thereby providing recommendations on which of the construction processes to focus mitigation efforts. Study of the relationship between choice of equipment, materials and other plans, and emissions estimates produced will provide insight as to specific actions that might be taken to enhance emissions reductions. Furthermore, through its ability to quantify emissions absorbed by reforestation, CFET highlights the magnitude and importance of environmental impact mitigation efforts on a project. With the potential establishment of the American Clean Energy and Security Act of 2009, which proposes a cap-and-trade system in the U.S., this tool will help contractors determine their baseline emissions (business as usual), and also the final project emissions after making appropriate modifications to the construction process that may produce offsets or enable purchase or sale of carbon allowances. Thus, the tool will enable the easy transition of contractors to a future involving a cap-and-trade system should such a future be realized.

CFET is particularly advantageous in its extent of simplicity to end users. The tool has been configured to use minimal input data (via a set of drop-down menus), employing appropriate estimations and assumptions in calculating emissions. It is also flexible in performing emissions calculations should the user have access to more detailed information, as the model requires the user to classify the information to fit the categories in the tool. Furthermore, the databases and input data used in the model development are relevant nation-wide, ensuring the applicability of the model to projects over a large geographic extent. The simplicity and effectiveness of this tool was demonstrated on the ICC case study, a major transportation infrastructure construction project undertaken by the Maryland State Highway

Administration, where readily available data from the contractors was used to estimate the project's net emissions. The quantification of the ICC Contract A emissions highlighted the major sources of emissions on the project and subsequently emphasized the need to use construction management practices that support emissions reduction.

The output of the decision support tool provides an optimal equipment fleet mix that enables contractors to simultaneously analyze economic, technical and environmental requirements of a project. Specifically, the tool helps contractors in quantifying the potential value in terms of costs to meet environmental standards or identify requirements for investment in new equipment to reduce project emissions. Since the tool incorporates task durations in its formulation, the tool helps evaluate the impact (on costs and equipment choices) of changes in the length of a project. Moreover, it aids contractors in trading off project cost, duration and resulting emissions in the development and proposal of construction bids, allowing green construction decisions. Solutions to varying emissions caps, as modeled by the tool, provides policy makers with a better understanding of the economic impacts of emissions abatement strategies and supplies reasonable estimates for carbon prices in a carbon regulated future.

In conclusion, this research and project have provided widely applicable tools that will enable both private companies and government agencies in the construction industry to estimate emissions and optimize processes used on construction projects, especially those in the transportation sector. This will therefore help the sector in transitioning towards a greener future.

APPENDIX

Appendix A: GWP Values for all species of air pollutants as mandated by the IPCC.

Species	Chemical Formula	Lifetime (years)	Global Warming Potential (Time Horizon)		
			20 years	100 years	500 years
CO2	CO_2	variable	1	1	1
Methane	CH_4	12+/-3	56	21	6.5
Nitrous oxide	N_2O	120	280	310	170
HFC-23	CHF_3	264	9100	11700	9800
HFC-32	CH_2F_2	5.6	2100	650	200
HFC-41	CH_3F	3.7	490	150	45
HFC-43-10mee	$C_5H_2F_{10}$	17.1	3000	1300	400
HFC-125	C_2HF_5	32.6	4600	2800	920
HFC-134	$C_2H_2F_4$	10.6	2900	1000	310
HFC-134a	CH_2FCF_3	14.6	3400	1300	420
HFC-152a	$C_2H_4F_2$	1.5	460	140	42
HFC-143	$C_2H_3F_3$	3.8	1000	300	94
HFC-143a	$C_2H_3F_3$	48.3	5000	3800	1400
HFC-227ea	C_3HF_7	36.5	4300	2900	950
HFC-236fa	$C_3H_2F_6$	209	5100	6300	4700
HFC-245ca	$C_3H_3F_5$	6.6	1800	560	170
Sulfur hexfluoride	SF_6	3200	16300	23900	34900
Perfluromenthane	CF_4	50000	4400	6500	10000
Perfluroethane	C_2F_6	10000	6200	9200	14000
Perfluropropane	C_3F_8	2600	4800	7000	10100
Perflurobutane	C_3F_{10}	2600	4800	7000	10100
Perflurocyclobutane	c-C_4F_8	3200	6000	8700	12700
Perfluropentane	C_5F_{12}	4100	5100	7500	11000
Perflurohexane	C_6F_{14}	3200	5000	7400	10700

Source: IPCC, 2007

Appendix B: Nonroad exhaust emissions standards: EPA Tier System.

Rated Power (kW)	Tier	Model year	NMHC	NMHC+NOx	NOx	PM	CO	Smoke Percentage
			(g/kW-hr)					
kW < 8	1	2000-2004	-	10.5	-	1	8	20/15/50
	2	2005-2007	-	7.5	-	0.8	8	
	4	2008+	-	7.5	-	0.4	8	
8 ≤ kW < 19	1	2000-2004	-	9.5	-	0.8	6.6	
	2	2005-2007	-	7.5	-	0.8	6.6	
	4	2008+	-	7.5	-	0.4	6.6	
19 ≤ kW < 37	1	1999-2003	-	9.5	-	0.8	5.5	
	2	2004-2007	-	7.5	-	0.6	5.5	
	4	2008-2012	-	7.5	-	0.3	5.5	
37 ≤ kW < 56	1	1998-2003	-	-	9.2	-	-	
	2	2004-2007	-	7.5	-	0.4	5	
	3	2008-2011	-	4.7	-	0.4	5	
	4	2008-2012	-	4.7	-	0.3	5	
56 ≤ kW < 75	1	1998-2003	-	-	9.2	-	-	
	2	2004-2007	-	7.5	-	0.4	5	
	3	2008-2011	-	4.7	-	0.4	5	
	4	2012-2013	-	4.7	-	0.02	5	
75 ≤ kW < 130	1	1997-2002	-	-	9.2	-	-	
	2	2003-2006	-	6.6	-	0.3	5	
	3	2007-2011	-	4	-	0.3	5	
	4	2012-2013	-	4	-	0.02	5	
130 ≤ kW < 225	1	1996-2002	1.3	-	9.2	0.54	11.4	

	2	2003-2005	-	6.6	-	0.2	3.5	
	3	2006-2010	-	4	-	0.2	3.5	
	4	2011-2013	-	4	-	0.02	3.5	
	1	1996-2000	1.3	-	9.2	0.54	11.4	
	2	2001-2005	-	6.4	-	0.2	3.5	
	3	2006-2010	-	4	-	0.2	3.5	
225 ≤ kW < 450	4	2011-2013	-	4	-	0.02	3.5	
	1	1996-2001	1.3	-	9.2	0.54	11.4	
	2	2002-2005	-	6.4	-	0.2	3.5	
	3	2006-2010	-	4	-	0.2	3.5	
450 ≤ kW < 560	4	2011-2013	-	4	-	0.02	3.5	
	1	2000-2005	1.3	-	9.2	0.54	11.4	
	2	2006-2010	-	6.4	-	0.2	3.5	
560 ≤ kW < 900	4	2011-2014	0.4	-	3.5	0.1	3.5	
	1	2000-2005	1.3	-	9.2	0.54	11.4	
	2	2006-2010	-	6.4	-	0.2	3.5	
kW > 900	4	2011-2014	0.4	-	3.5	0.1	3.5	

Source: USEPA, 2009e

Appendix C: Database used in site-preparation component of CFET.

REGION	FOREST TYPE	CARBON DENSITY (MT/ha)	
		NON-SOIL	SOIL
Northeast (CT,DE,MA,MD,ME,NH,NJ,NY,OH,PA,RI,VT,WV)	White/Red/Jack Pine	135.8	78.1
	Spruce/Fir	104.2	98
	Oak/Pine	127.1	66.9
	Oak/Hickory	115	53.1
	Elm/Ash/Cottonwood	96.2	111.7
	Maple/Beech/Birch	129.4	69.6
	Aspen/Birch	72.6	87.4
	Minor Types & Nonstocked	80.1	82.7
	All	118.2	69.7
Northern Lake States (MI,MN,WI)	White/Red/Jack Pine	86.6	120.8
	Spruce/Fir	89.9	261.8
	Oak/Hickory	103.8	97.1
	Elm/Ash/Cottonwood	94.6	179.9
	Maple/Beech/Birch	121.5	134.3
	Aspen/Birch	65.6	146.1
	Minor Types & Nonstocked	62.4	125.8
	All	92.2	152.9

Northern Prairie States ((IA,IL,IN,KS,MO,ND,NE,SD)	Ponderosa Pine	70.7	48.5
	Oak/Pine	94.1	39.9
	Oak/Hickory	100.1	48.9
	Elm/Ash/Cottonwood	121.2	83.2
	Maple/Beech/Birch	111.4	70.7
	Minor Types & Nonstocked	61.7	57.5
	All	99.8	55.7
South Central (AL,AR,KY,LA,MS,OK,TN,TX)	Longleaf/Slash Pine	64	55.5
	Loblolly/Shortleaf Pine	69.7	41.9
	Oak/Pine	72.6	41.7
	Oak/Hickory	88.6	38.6
	Oak/Gum/Cypress	108.1	52.8
	Elm/Ash/Cottonwood	78.7	49.9
	Minor Types & Nonstocked	60.9	49.6
	All	81.5	42.7
Southeast (FL,GA,NC,SC,VA)	Longleaf/Slash Pine	54.8	110
	Loblolly/Shortleaf Pine	73.7	72.9
	Oak/Pine	76.7	61.4
	Oak/Hickory	100.4	45.3
	Oak/Gum/Cypress	104.2	158
	Elm/Ash/Cottonwood	83.7	95.7
	Minor Types & Nonstocked	65.1	101.4

	All	84.6	78.1
Coastal Alaska	Fir/Spruce/Mt.Hemlock	177.5	62.1
	Lodgepole Pine	83.9	52
	Hemlock/Sitka Spruce	251	116.3
	Aspen/Birch	61.2	42.5
	Minor Types & Nonstocked	171.2	77.3
	All	196.6	89.7
Pacific Northwest, Westside (Western OR & WA)	Douglas-fir	238.7	94.8
	Fir/Spruce/Mt.Hemlock	261.6	62.1
	Hemlock/Sitka Spruce	295.7	116.3
	Alder/Maple	129.9	115.2
	Minor Types & Nonstocked	104.2	85.7
	All	222.5	95.5
Pacific Northwest, Eastside (Eastern OR & WA)	Pinyon/Juniper	38.2	46.9
	Douglas-fir	146.7	94.8
	Ponderosa Pine	91.3	50.7
	Fir/Spruce/Mt.Hemlock	176	62.1
	Lodgepole Pine	82.1	52
	Western Larch	133	45.1
	Minor Types & Nonstocked	82.5	81.9
	All	110	64.4
Pacific Southwest (CA)	Pinyon/Juniper	49.2	26.3

	Douglas-fir	265.1	40.1
	Ponderosa Pine	120.6	41.3
	Fir/Spruce/Mt.Hemlock	267.9	51.9
	Lodgepole Pine	183.6	35.2
	Redwood	347.6	53.8
	California Mixed Conifer	224.5	49.8
	Western Oak	114.5	27.6
	Tanoak/Laurel	207.4	27.6
	Minor Types & Nonstocked	94.7	40.1
	All	160.7	37.6
Rocky Mountain, North (ID,MT)	Douglas-fir	139.5	38.8
	Ponderosa Pine	79.9	34.3
	Fir/Spruce/Mt.Hemlock	140.5	44.1
	Lodgepole Pine	96.1	37.2
	Western Larch	124.8	34.2
	Minor Types & Nonstocked	73.1	43.2
	All	113.7	40.1
Rocky Mountain, South (AZ,CO,NM,NV,UT,WY)	Pinyon/Juniper	49.7	19.7
	Douglas-fir	144.7	30.9
	Ponderosa Pine	89.7	24.1
	Fir/Spruce/Mt.Hemlock	158.7	31.5
	Lodgepole Pine	101.6	27

	Aspen/Birch	110.2	58.8
	Western Oak	53.5	38
	Minor Types & Nonstocked	50.6	25.6
	All	75.8	26.7

Source: USEPA, 2009a

Appendix D: Summary of extrapolation trend as applied to model year & rated power in equipment usage emission factor database.

Applicable Rated Power	2007-2006	2006-2005	2005-2004	2004-2003	2003-2002	2002-2001	2001-2000	2000-1999	1999-1998	1998-1997	1997-1996	1996-1995
>11 to 25 hp	same	same	21	same	same	same	same	21	same	same	same	same
>25-50 hp	same	same	same	21	same	same	same	same	21	same	same	same
>100-175 hp	21	same	same	same	21	same	same	same	same	same	21	same
>175-300 hp	same	21	same	same	21	same	same	same	same	same	same	21
>300-600 hp	same	21	same	same	same	same	21	same	same	same	same	21
>600-750 hp	same	21	same	same	same	21	same	same	same	same	same	21
>750-1200 hp	same	21	same	same	same	same	same	21	same	same	same	same
>1210-9999 hp	same	21	same	same	same	same	same	21	same	same	same	same

**same= EF will remain the same as the previous year*

Appendix E: Analysis of EPA Tier System's PM standards used to determine extrapolation trend for equipment usage emission factor database.

0-11 hp

for reference			Pollutant (g/bhp-hr)	% difference
Tier	**Start Year**	**End year**	**PM**	**PM**
	1988	1999	1	25
1	2000	2004	0.75	20
2	2005	2007	0.6	
3	-	-		

11-25 hp

for reference			Pollutant (g/bhp-hr)	% difference
Tier	**Start Year**	**End year**	**PM**	**PM**
	1988	1999	0.8	25
1	2000	2004	0.6	0
2	2005	2007	0.6	
3				

25-50 hp

for reference			Pollutant (g/bhp-hr)	% difference
Tier	**Start Year**	**End year**	**PM**	**PM**
	1988	1998	0.8	25
1	1999	2003	0.6	25
2	2004	2007	0.45	
3	-	-		

50-75 hp

for reference			Pollutant (g/bhp-hr)	% difference
Tier	**Start Year**	**End year**	**PM**	**PM**
	1988	1997	0.72	16.67
1	1998	2003	0.6	50
2	2004	2007	0.3	0
3	2008	2011	0.3	

75-100 hp

for reference			Pollutant (g/bhp-hr)	% difference /
Tier	**Start Year**	**End year**	**PM**	**PM**
	1988	1997	0.72	16.67
1	1998	2003	0.6	50
2	2004	2007	0.3	0
3	2008	2011	0.3	

100-175 hp

for reference			Pollutant (g/bhp-hr)	% difference /yr
Tier	**Start Year**	**End year**	**PM**	**PM**
	1988	1996	0.4	-50
1	1997	2002	0.6	63.33
2	2003	2006	0.22	0
3	2007	2011	0.22	

175-300 hp

for reference			Pollutant (g/bhp-hr)	% difference /yr
Tier	**Start Year**	**End year**	**PM**	**PM**
	1988	1995	0.4	0
1	1996	2002	0.4	62.5
2	2003	2005	0.15	0
3	2006	2010	0.15	

300-600 hp

for reference			Pollutant (g/bhp-hr)	% difference /yr
Tier	**Start Year**	**End year**	**PM**	**PM**
	1988	1995	0.4	0
1	1996	2000	0.4	62.5
2	2001	2005	0.15	0
3	2006	2010	0.15	

600-750 hp				
for reference			**Pollutant (g/bhp-hr)**	**% difference /yr**
Tier	**Start Year**	**End year**	**PM**	**PM**
	1988	1995	0.4	0
1	1996	2001	0.4	62.5
2	2002	2005	0.15	0
3	2006	2010	0.15	

750-1200 hp				
for reference			**Pollutant (g/bhp-hr)**	**% difference /yr**
Tier	**Start Year**	**End year**	**PM**	**PM**
	1988	1999	0.4	0
1	2000	2005	0.4	62.5
2	2006	2010	0.15	
3	-	-	-	

1200-9999 hp				
for reference			**Pollutant (g/bhp-hr)**	**% difference /yr**
Tier	**Start Year**	**End year**	**PM**	**PM**
	1988	1999	0.4	0
1	2000	2005	0.4	62.5
2	2006	2010	0.15	
3	-	-	-	

Average % increase = 20.68452

Source: USEPA, 2009c

Appendix F: Intermediary database used to estimate median model year by tier level based on the EPA Tier System.

EPA Tier	EPA Rated Power Range		EPA Model Year Range		Database Med. Yr
	Min Hp	Max Hp	Start Year	End Year	
1	0	11	2000	2004	2002
1	11	25	2000	2004	2002
1	25	50	1999	2003	2001
1	50	75	1998	2003	2000
1	75	100	1998	2003	2000
1	100	175	1997	2002	1999
1	175	300	1996	2002	1999
1	300	600	1996	2000	1998
1	600	750	1996	2001	1998
1	750	1200	2000	2005	2002
1	1200	9999	2000	2005	2002
2	0	11	2005	2007	2006
2	11	25	2005	2007	2006
2	25	50	2004	2007	2005
2	50	75	2004	2007	2005
2	75	100	2004	2007	2005
2	100	175	2003	2006	2004
2	175	300	2003	2005	2004
2	300	600	2001	2005	2003
2	600	750	2002	2005	2003
2	750	1200	2006	2010	2008
2	1200	9999	2006	2010	2008
3	0	11	-	-	2008*
3	11	25	-	-	2008*
3	25	50	-	-	2008*
3	50	75	2008	2011	2009
3	75	100	2008	2011	2009
3	100	175	2007	2011	2009
3	175	300	2006	2010	2008
3	300	600	2006	2010	2008
3	600	750	2006	2010	2008
3	750	1200	-	-	2008*
3	1200	9999	-	-	2008*
4	0	11	2008	CY	2008
4	11	25	2008	CY	2008

4	25	50	2008	2012	2010
4	50	75	2008	2012	2010
4	75	100	2012	2013	2012
4	100	175	2012	2013	2012
4	175	300	2011	2013	2012
4	300	600	2011	2013	2012
4	600	750	2011	2013	2012
4	750	1200	2011	2014	2012
4	1200	9999	2011	2014	2012

Note: Median year was determined by calculating the arithmetic mean of model years.
*2008**: Assumed due to lack of data to be model year 2008 based on previous tier levels*

Source: USEPA, 2009c

Appendix G: Example of emission factor database for equipment usage component (2006) of carbon footprint estimation model.

Year	Equipment	MaxHP	ROG	CO	NOX	SOX	CO2	CH4
2006	Aerial Lifts	15	0.0120	0.0539	0.0784	0.0001	8.6527	0.0011
2006	Aerial Lifts	25	0.0268	0.0678	0.1103	0.0001	10.9601	0.0024
2006	Aerial Lifts	50	0.0867	0.2042	0.2062	0.0003	19.6128	0.0078
2006	Aerial Lifts	120	0.0990	0.3101	0.6183	0.0005	46.0669	0.0089
2006	Aerial Lifts	500	0.1827	0.7381	2.2160	0.0021	212.8560	0.0165
2006	Aerial Lifts	750	0.3397	1.3341	4.1001	0.0039	384.7561	0.0306
2006	Air Compressors	15	0.0163	0.0539	0.0928	0.0001	7.2231	0.0015
2006	Air Compressors	25	0.0376	0.0934	0.1473	0.0002	14.4462	0.0034
2006	Air Compressors	50	0.1306	0.2933	0.2468	0.0003	22.2713	0.0118
2006	Air Compressors	120	0.1402	0.4132	0.8182	0.0007	56.8098	0.0126
2006	Air Compressors	175	0.1736	0.6232	1.3888	0.0012	107.0646	0.0157
2006	Air Compressors	250	0.1459	0.4071	1.6003	0.0015	131.2199	0.0132
2006	Air Compressors	500	0.2288	0.8865	2.5465	0.0023	231.7415	0.0206
2006	Air Compressors	750	0.3607	1.3701	4.0281	0.0036	358.1459	0.0325
2006	Air Compressors	1000	0.6027	2.3256	6.5406	0.0049	486.3562	0.0544
2006	Bore/Drill Rigs	15	0.0124	0.0632	0.0788	0.0002	10.3456	0.0011
2006	Bore/Drill Rigs	25	0.0222	0.0689	0.1397	0.0002	15.9887	0.0020
2006	Bore/Drill Rigs	50	0.0980	0.2886	0.2959	0.0004	31.0368	0.0088
2006	Bore/Drill Rigs	120	0.1461	0.6063	1.0179	0.0011	93.3174	0.0132
2006	Bore/Drill Rigs	175	0.1673	0.9122	1.5628	0.0019	170.7025	0.0151

2006	Bore/Drill Rigs	250	0.1125	0.3532	1.6315	0.0021	188.1019	0.0102
2006	Bore/Drill Rigs	500	0.1628	0.5678	2.2334	0.0031	311.3085	0.0147
2006	Bore/Drill Rigs	750	0.3368	1.1219	4.6545	0.0062	615.0932	0.0304
2006	Bore/Drill Rigs	1000	0.7011	1.9338	9.8820	0.0093	928.2825	0.0633
2006	Cement and Mortar Mixers	15	0.0092	0.0399	0.0596	0.0001	6.3202	0.0008
2006	Cement and Mortar Mixers	25	0.0428	0.1084	0.1763	0.0002	17.5562	0.0039
2006	Concrete/Industrial Saws	25	0.0215	0.0689	0.1402	0.0002	16.4777	0.0019
2006	Concrete/Industrial Saws	50	0.1513	0.3517	0.3238	0.0004	30.2092	0.0136
2006	Concrete/Industrial Saws	120	0.2001	0.6234	1.2327	0.0011	89.7212	0.0181
2006	Concrete/Industrial Saws	175	0.2827	1.0816	2.3817	0.0022	193.8421	0.0255
2006	Cranes	50	0.1555	0.3455	0.2666	0.0003	23.1867	0.0140
2006	Cranes	120	0.1619	0.4664	0.9277	0.0007	60.6790	0.0146
2006	Cranes	175	0.1715	0.6019	1.3320	0.0011	97.2170	0.0155
2006	Cranes	250	0.1478	0.4119	1.4665	0.0013	112.1589	0.0133
2006	Cranes	500	0.2121	0.8483	2.1049	0.0018	180.1013	0.0191
2006	Cranes	750	0.3600	1.4213	3.6197	0.0030	303.0446	0.0325
2006	Cranes	9999	1.2786	5.2275	13.5665	0.0098	970.6057	0.1154
2006	Crawler Tractors	50	0.1727	0.3812	0.2897	0.0003	24.8796	0.0156
2006	Crawler Tractors	120	0.2232	0.6313	1.2752	0.0009	79.6308	0.0201
2006	Crawler Tractors	175	0.2730	0.9455	2.1014	0.0016	146.6372	0.0246
2006	Crawler Tractors	250	0.2386	0.6707	2.2824	0.0019	166.1316	0.0215
2006	Crawler Tractors	500	0.3324	1.5264	3.1976	0.0025	259.2295	0.0300
2006	Crawler Tractors	750	0.5988	2.7193	5.8408	0.0047	464.6869	0.0540
2006	Crawler Tractors	1000	0.9273	4.2839	9.5523	0.0066	658.1057	0.0837
2006	Crushing/Proc. Equipment	50	0.2623	0.5917	0.4879	0.0006	44.0158	0.0237
2006	Crushing/Proc. Equipment	120	0.2481	0.7371	1.4427	0.0012	100.6006	0.0224

2006	Crushing/Proc. Equipment	175	0.3277	1.1882	2.6047	0.0023	202.3848	0.0296
2006	Crushing/Proc. Equipment	250	0.2682	0.7429	2.9565	0.0028	244.5324	0.0242
2006	Crushing/Proc. Equipment	500	0.3634	1.3803	4.0348	0.0037	373.6455	0.0328
2006	Crushing/Proc. Equipment	750	0.5796	2.0915	6.5366	0.0059	588.8341	0.0523
2006	Crushing/Proc. Equipment	9999	1.6038	5.9800	17.5501	0.0131	1307.7594	0.1447
2006	Dumpers/Tenders	25	0.0137	0.0383	0.0709	0.0001	7.6244	0.0012
2006	Excavators	25	0.0206	0.0677	0.1353	0.0002	16.4401	0.0019
2006	Excavators	50	0.1510	0.3526	0.2778	0.0003	25.0176	0.0136
2006	Excavators	120	0.2161	0.6660	1.2470	0.0010	89.0839	0.0195
2006	Excavators	175	0.2169	0.8177	1.6815	0.0015	135.7881	0.0196
2006	Excavators	250	0.1726	0.4642	1.8559	0.0018	158.6827	0.0156
2006	Excavators	500	0.2295	0.7653	2.3809	0.0023	233.7354	0.0207
2006	Excavators	750	0.3841	1.2645	4.0758	0.0039	387.4146	0.0347
2006	Forklifts	50	0.0932	0.2119	0.1643	0.0002	14.6719	0.0084
2006	Forklifts	120	0.0951	0.2828	0.5274	0.0004	37.7821	0.0086
2006	Forklifts	175	0.1130	0.4045	0.8499	0.0008	67.8258	0.0102
2006	Forklifts	250	0.0762	0.1920	0.8930	0.0009	77.1218	0.0069
2006	Forklifts	500	0.0988	0.2777	1.1190	0.0011	110.9801	0.0089
2006	Generator Sets	15	0.0198	0.0761	0.1277	0.0002	10.2077	0.0018
2006	Generator Sets	25	0.0349	0.1140	0.1798	0.0002	17.6314	0.0032
2006	Generator Sets	50	0.1294	0.3076	0.3197	0.0004	30.6230	0.0117
2006	Generator Sets	120	0.1982	0.6274	1.2509	0.0011	94.3188	0.0179
2006	Generator Sets	175	0.2353	0.9158	2.0495	0.0019	171.7950	0.0212
2006	Generator Sets	250	0.1982	0.5974	2.3843	0.0024	212.5050	0.0179
2006	Generator Sets	500	0.2824	1.1211	3.4731	0.0033	336.8529	0.0255
2006	Generator Sets	750	0.4695	1.8098	5.7390	0.0055	543.7900	0.0424

2006	Generator Sets	9999	1.1949	4.4076	13.2584	0.0105	1048.6050	0.1078
2006	Graders	50	0.1733	0.3929	0.3101	0.0004	27.5381	0.0156
2006	Graders	120	0.2302	0.6845	1.3340	0.0011	90.7075	0.0208
2006	Graders	175	0.2508	0.9124	1.9672	0.0017	149.9450	0.0226
2006	Graders	250	0.2088	0.5808	2.1482	0.0019	172.1132	0.0188
2006	Graders	500	0.2487	0.9672	2.5414	0.0023	229.4842	0.0224
2006	Graders	750	0.5320	2.0374	5.5148	0.0049	485.7415	0.0480
2006	Off-Highway Tractors	120	0.3424	0.9345	1.9532	0.0013	113.4223	0.0309
2006	Off-Highway Tractors	175	0.3195	1.0696	2.4452	0.0018	157.8050	0.0288
2006	Off-Highway Tractors	250	0.2149	0.6125	1.9515	0.0015	130.4173	0.0194
2006	Off-Highway Tractors	750	0.8341	4.3552	7.8223	0.0057	568.1303	0.0753
2006	Off-Highway Tractors	1000	1.2771	6.7362	12.5734	0.0082	814.2930	0.1152
2006	Off-Highway Trucks	175	0.2533	0.9314	1.9216	0.0017	151.3562	0.0229
2006	Off-Highway Trucks	250	0.1933	0.5096	1.9993	0.0019	166.5454	0.0174
2006	Off-Highway Trucks	500	0.2870	0.9451	2.8530	0.0027	272.3339	0.0259
2006	Off-Highway Trucks	750	0.4689	1.5279	4.7727	0.0044	441.7384	0.0423
2006	Off-Highway Trucks	1000	0.7528	2.6058	8.3284	0.0063	624.7241	0.0679
2006	Other Construction Equipment	15	0.0121	0.0617	0.0770	0.0002	10.1073	0.0011
2006	Other Construction Equipment	25	0.0183	0.0570	0.1155	0.0002	13.2173	0.0017
2006	Other Construction Equipment	50	0.1356	0.3262	0.2942	0.0004	27.9896	0.0122
2006	Other Construction Equipment	120	0.2070	0.6785	1.2801	0.0011	97.8391	0.0187
2006	Other Construction Equipment	175	0.1772	0.7206	1.4894	0.0015	128.8842	0.0160
2006	Other Construction Equipment	500	0.2095	0.7692	2.4473	0.0025	254.2385	0.0189
2006	Other General Industrial Equipment	15	0.0067	0.0391	0.0470	0.0001	6.3955	0.0006
2006	Other General Industrial Equipment	25	0.0192	0.0632	0.1266	0.0002	15.3491	0.0017
2006	Other General Industrial Equipment	50	0.1476	0.3260	0.2499	0.0003	21.7446	0.0133

2006	Other General Industrial Equipment	120	0.2022	0.5754	1.1296	0.0009	75.0636	0.0182
2006	Other General Industrial Equipment	175	0.2064	0.7115	1.5747	0.0013	116.0777	0.0186
2006	Other General Industrial Equipment	250	0.1630	0.4366	1.7266	0.0015	135.5838	0.0147
2006	Other General Industrial Equipment	500	0.2851	1.0467	3.0123	0.0026	265.4117	0.0257
2006	Other General Industrial Equipment	750	0.4755	1.7251	5.0871	0.0044	437.4497	0.0429
2006	Other General Industrial Equipment	1000	0.7280	2.7744	7.7949	0.0056	559.6030	0.0657
2006	Other Material Handling Equipment	50	0.2034	0.4495	0.3473	0.0004	30.3346	0.0184
2006	Other Material Handling Equipment	120	0.1960	0.5598	1.1003	0.0009	73.4097	0.0177
2006	Other Material Handling Equipment	175	0.2604	0.9007	1.9959	0.0017	147.7145	0.0235
2006	Other Material Handling Equipment	250	0.1729	0.4654	1.8395	0.0016	145.0140	0.0156
2006	Other Material Handling Equipment	500	0.2038	0.7541	2.1690	0.0019	191.6257	0.0184
2006	Other Material Handling Equipment	9999	0.9597	3.6689	10.2941	0.0073	741.3470	0.0866
2006	Pavers	25	0.0368	0.0997	0.1770	0.0002	18.6597	0.0033
2006	Pavers	50	0.1881	0.4131	0.3234	0.0004	27.9896	0.0170
2006	Pavers	120	0.2324	0.6570	1.3518	0.0010	83.7277	0.0210
2006	Pavers	175	0.2859	0.9939	2.2456	0.0017	155.2254	0.0258
2006	Pavers	250	0.2844	0.8186	2.7050	0.0022	194.3719	0.0257
2006	Pavers	500	0.3028	1.4943	2.9397	0.0023	233.2463	0.0273
2006	Paving Equipment	25	0.0175	0.0544	0.1103	0.0002	12.6279	0.0016
2006	Paving Equipment	50	0.1593	0.3498	0.2759	0.0003	23.9266	0.0144
2006	Paving Equipment	120	0.1817	0.5139	1.0591	0.0008	65.9442	0.0164
2006	Paving Equipment	175	0.2229	0.7759	1.7596	0.0014	122.2381	0.0201
2006	Paving Equipment	250	0.1774	0.5124	1.6935	0.0014	122.2913	0.0160
2006	Plate Compactors	15	0.0054	0.0263	0.0351	0.0001	4.3138	0.0005
2006	Pressure Washers	15	0.0095	0.0365	0.0612	0.0001	4.8906	0.0009
2006	Pressure Washers	25	0.0142	0.0462	0.0729	0.0001	7.1479	0.0013

2006	Pressure Washers	50	0.0491	0.1223	0.1449	0.0002	14.2957	0.0044
2006	Pressure Washers	120	0.0560	0.1850	0.3697	0.0003	29.1332	0.0051
2006	Pumps	15	0.0168	0.0554	0.0954	0.0001	7.4238	0.0015
2006	Pumps	25	0.0507	0.1260	0.1987	0.0002	19.4874	0.0046
2006	Pumps	50	0.1541	0.3621	0.3619	0.0004	34.3349	0.0139
2006	Pumps	120	0.2039	0.6371	1.2690	0.0011	94.3188	0.0184
2006	Pumps	175	0.2392	0.9177	2.0523	0.0019	169.5493	0.0216
2006	Pumps	250	0.1941	0.5771	2.2926	0.0023	201.3693	0.0175
2006	Pumps	500	0.2982	1.2024	3.5991	0.0034	345.2047	0.0269
2006	Pumps	750	0.5068	1.9878	6.0902	0.0057	570.7010	0.0457
2006	Pumps	9999	1.5682	5.9197	17.3104	0.0136	1354.8351	0.1415
2006	Rollers	15	0.0076	0.0386	0.0482	0.0001	6.3202	0.0007
2006	Rollers	25	0.0185	0.0575	0.1165	0.0002	13.3427	0.0017
2006	Rollers	50	0.1520	0.3436	0.2884	0.0003	25.9831	0.0137
2006	Rollers	120	0.1755	0.5235	1.0466	0.0008	71.3764	0.0158
2006	Rollers	175	0.2116	0.7742	1.7175	0.0015	130.8567	0.0191
2006	Rollers	250	0.1867	0.5391	1.9194	0.0017	153.0898	0.0168
2006	Rollers	500	0.2375	1.0016	2.4749	0.0022	219.1010	0.0214
2006	Rough Terrain Forklifts	50	0.2019	0.4635	0.3746	0.0004	33.8583	0.0182
2006	Rough Terrain Forklifts	120	0.1825	0.5564	1.0671	0.0009	75.5643	0.0165
2006	Rough Terrain Forklifts	175	0.2397	0.8941	1.8996	0.0017	151.1286	0.0216
2006	Rough Terrain Forklifts	250	0.1880	0.5203	2.0303	0.0019	170.7965	0.0170
2006	Rough Terrain Forklifts	500	0.2518	0.8995	2.6920	0.0025	256.5710	0.0227
2006	Rubber Tired Dozers	175	0.3281	1.0846	2.4745	0.0018	156.6669	0.0296
2006	Rubber Tired Dozers	250	0.3139	0.8843	2.8004	0.0021	183.4870	0.0283
2006	Rubber Tired Dozers	500	0.4045	2.1197	3.6630	0.0026	264.8726	0.0365

2006	Rubber Tired Dozers	750	0.6094	3.1710	5.5926	0.0040	398.7885	0.0550
2006	Rubber Tired Dozers	1000	0.9543	5.0610	9.2959	0.0060	591.8939	0.0861
2006	Rubber Tired Loaders	25	0.0221	0.0708	0.1440	0.0002	16.9292	0.0020
2006	Rubber Tired Loaders	50	0.1938	0.4399	0.3495	0.0004	31.1497	0.0175
2006	Rubber Tired Loaders	120	0.1791	0.5347	1.0407	0.0008	71.2853	0.0162
2006	Rubber Tired Loaders	175	0.2129	0.7774	1.6758	0.0014	128.6414	0.0192
2006	Rubber Tired Loaders	250	0.1781	0.4959	1.8452	0.0017	148.9767	0.0161
2006	Rubber Tired Loaders	500	0.2528	0.9705	2.6039	0.0023	237.0084	0.0228
2006	Rubber Tired Loaders	750	0.5240	1.9793	5.4711	0.0049	485.5287	0.0473
2006	Rubber Tired Loaders	1000	0.7317	2.8295	8.0073	0.0060	593.8755	0.0660
2006	Scrapers	120	0.3198	0.9018	1.8311	0.0013	113.6196	0.0289
2006	Scrapers	175	0.3349	1.1574	2.5856	0.0020	179.1693	0.0302
2006	Scrapers	250	0.3046	0.8606	2.9011	0.0024	209.4702	0.0275
2006	Scrapers	500	0.4168	1.9484	4.0046	0.0032	321.4284	0.0376
2006	Scrapers	750	0.7239	3.3467	7.0442	0.0056	555.2767	0.0653
2006	Signal Boards	15	0.0072	0.0377	0.0453	0.0001	6.1697	0.0007
2006	Signal Boards	50	0.1740	0.4062	0.3843	0.0005	36.1908	0.0157
2006	Signal Boards	120	0.2145	0.6682	1.3162	0.0011	97.0500	0.0193
2006	Signal Boards	175	0.2694	1.0333	2.2732	0.0021	186.9988	0.0243
2006	Signal Boards	250	0.2504	0.7317	2.9189	0.0029	255.2918	0.0226
2006	Skid Steer Loaders	25	0.0315	0.0814	0.1358	0.0002	13.7941	0.0028
2006	Skid Steer Loaders	50	0.1126	0.2842	0.2606	0.0003	25.5192	0.0102
2006	Skid Steer Loaders	120	0.1016	0.3537	0.6359	0.0006	51.7418	0.0092
2006	Surfacing Equipment	50	0.0708	0.1644	0.1519	0.0002	14.1076	0.0064
2006	Surfacing Equipment	120	0.1760	0.4496	0.9017	0.0007	63.7665	0.0131
2006	Surfacing Equipment	175	0.1550	0.5924	1.3107	0.0012	103.7871	0.0140

2006	Surfacing Equipment	250	0.1521	0.4563	1.6282	0.0015	134.8690	0.0137
2006	Surfacing Equipment	500	0.2227	0.9888	2.4265	0.0022	221.2077	0.0201
2006	Surfacing Equipment	750	0.3558	1.5437	3.8879	0.0035	347.0479	0.0321
2006	Sweepers/Scrubbers	15	0.0125	0.0729	0.0878	0.0002	11.9382	0.0011
2006	Sweepers/Scrubbers	25	0.0251	0.0821	0.1673	0.0002	19.6128	0.0023
2006	Sweepers/Scrubbers	50	0.1973	0.4427	0.3522	0.0004	31.5510	0.0178
2006	Sweepers/Scrubbers	120	0.2281	0.6703	1.2826	0.0011	90.7985	0.0206
2006	Sweepers/Scrubbers	175	0.2779	0.9871	2.1386	0.0019	168.1836	0.0251
2006	Sweepers/Scrubbers	250	0.1660	0.4343	1.9127	0.0018	162.0184	0.0150
2006	Tractors/Loaders/Backhoes	25	0.0254	0.0741	0.1443	0.0002	15.8633	0.0023
2006	Tractors/Loaders/Backhoes	50	0.1684	0.3985	0.3286	0.0004	30.3471	0.0152
2006	Tractors/Loaders/Backhoes	120	0.1427	0.4535	0.8445	0.0007	62.5909	0.0129
2006	Tractors/Loaders/Backhoes	175	0.1831	0.7161	1.4623	0.0014	122.6782	0.0165
2006	Tractors/Loaders/Backhoes	250	0.1714	0.4715	1.9310	0.0019	171.7370	0.0155
2006	Tractors/Loaders/Backhoes	500	0.3074	1.0278	3.3772	0.0039	344.8535	0.0277
2006	Tractors/Loaders/Backhoes	750	0.4689	1.5370	5.2373	0.0058	517.2803	0.0423
2006	Trenchers	15	0.0099	0.0517	0.0622	0.0001	8.4646	0.0009
2006	Trenchers	25	0.0429	0.1377	0.2800	0.0004	32.9178	0.0039
2006	Trenchers	50	0.2110	0.4651	0.3764	0.0004	32.9178	0.0190
2006	Trenchers	120	0.2138	0.6087	1.2617	0.0009	78.5231	0.0193
2006	Trenchers	175	0.3149	1.1046	2.5079	0.0020	174.1165	0.0284
2006	Trenchers	250	0.3246	0.9471	3.0938	0.0025	222.9008	0.0293
2006	Trenchers	500	0.4018	2.0679	3.9323	0.0031	311.3086	0.0363
2006	Trenchers	750	0.7640	3.8743	7.5254	0.0059	586.8779	0.0689
2006	Welders	15	0.0140	0.0463	0.0798	0.0001	6.2074	0.0013
2006	Welders	25	0.0294	0.0730	0.1151	0.0001	11.2861	0.0026

2006	Welders	50	0.1392	0.3169	0.2825	0.0003	25.9581	0.0126
2006	Welders	120	0.1126	0.3386	0.6722	0.0006	47.7967	0.0102
2006	Welders	175	0.1835	0.6740	1.5043	0.0013	118.8089	0.0166
2006	Welders	250	0.1264	0.3603	1.4180	0.0013	119.0684	0.0114
2006	Welders	500	0.1582	0.6316	1.8085	0.0016	167.5987	0.0143

Source: ARB, 2008

Appendix H: Calculation of fuel-based correction factors used in equipment usage emissions component.

Fuel	Reductions in PM from Base Case	Total Reduction in PM	Source
Diesel	0 (Base case)	0 (Base case)	n/a
Low Sulfur Diesel (LSD)	25%	25%	Low Sulfur Diesel Fact Sheet, California ARB
Ultra-Low Sulfur Diesel (ULSD)	7%	(25+7)% = 32%	Cleaner Diesel, EPA Sector Strategies Program
Biodiesel B5	2%	(32+2)% = 34%	EPA Verified Retrofit Technologies - Biodiesel
Biodiesel B20	10%	(34+10)% =44%	
Biodiesel B100	37%	(44+37)%=81%	

Source: ARB, 2003 & USEPA, 2007b & USEPA, 2010a

Appendix I: Typical coatings/solvents & their percent solids and density data.

Type of Coating	Solids (% Volume)	Density (kg/L)
Enamel, air dry	39.6	0.91
Enamel, baking	42.8	1.09
Acrylic enamel	30.3	1.07
Alkyd enamel	47.2	0.96
Primer surfacer	49	1.13
Primer, epoxy	57.2	1.26
Varnish, baking	35.3	0.79
Lacquer, spraying	26.1	0.95
Vinyl, roller coat	12	0.92
Polyurethane	31.7	1.1
Stain	21.6	0.88
Sealer	11.7	0.84
Magnet wire enamel	25	0.94
Solvents (all types)*	33	0.88
* *Average values*		

Source: USEPA, 2009b

Appendix J: N-content of some common fertilizers used in materials production component.

Fertilizer Type	Average % Nitrogen by weight
Nitrogen	
Ammonia, Anhydrous	82
Ammonia, Aqua *	20.5
Ammonium Nitrate	33.5
Ammonium Nitrate-Limestone Mixture	20.5
Ammonium Sulfate	21
Ammonium Sulfate-nitrate	26
Calcium cyanamide	21
Calcium nitrate	15
Nitrogen solutions *	35
Sodium nitrate	16
Urea	46
Urea-form	38
Phosphate	
Bone-meal *	3.25
Multiple Nutrient	
Ammoniated superphosphate	4.5
Ammonium phosphate-nitrate	27
Ammonium phosphate-sulfate *	14.5
Diammonium phosphate *	18.5
Monoammonium phosphate	11
Nitric phosphates *	18
Nitrate of soda-potash	15
Potassium nitrate	12
*Note: * are average values determined from a range of N-content values*	

Source: USEPA, 2009b

Appendix K: Database used in environmental impact mitigation component of CFET.

REGION	FOREST TYPE	AGE (Yrs)	CARBON DENSITY (MT C/ha)	
			NON-SOIL	SOIL
Northeast (CT,DE,MA,MD,ME,NH,NJ,NY,OH,PA,RI,VT,WV)	White/Red/Jack Pine	0	2.1	58.6
		5	13.8	58.8
		15	41.9	60.3
		25	62.3	62.9
		35	77.9	66.2
	Spruce/Fir	0	2.1	73.5
		5	15.1	73.7
		15	38.5	75.6
		25	59.3	78.9
		35	79.7	83
	Oak/Pine	0	4.2	50.2
		5	15.2	50.3
		15	44.9	51.6
		25	73.3	53.9
		35	98.3	56.6
	Oak/Hickory	0	2.1	39.8
		5	11	39.9
		15	54	40.9
		25	86.6	42.7
		35	114	44.9
	Maple/Beech/Birch	0	2.1	52.2
		5	15	52.3
		15	50	53.7

		25	79.8	56
		35	105.4	58.9
	Aspen/Birch	0	2	65.6
		5	11.5	65.8
		15	30.9	67.4
		25	49.6	70.4
		35	67.1	74
Nothern Lake States (MI,MN,WI)	White/Red/Jack Pine	0	2	90.6
		5	5.7	90.9
		15	18.5	93.2
		25	52.9	97.3
		35	85.3	102.3
	Spruce/Fir	0	2.1	196.4
		5	11.1	197
		15	26.5	202
		25	49.7	210.8
		35	74.2	221.7
	Oak/Hickory	0	2.1	72.8
		5	11	73.1
		15	24.5	74.9
		25	45	78.2
		35	64.8	82.2
	Elm/Ash/Cottonwood	0	2	134.9
		5	10.7	135.4
		15	24.7	138.8
		25	41.1	144.9
		35	56.2	152.4
	Maple/Beech/Birch	0	2.1	100.7
		5	12.2	101

		15	28.3	103.6
		25	53	108.1
		35	76.5	113.7
	Aspen/Birch	0	2	109.6
		5	12.1	109.9
		15	22.5	112.7
		25	39.6	117.6
		35	57.4	123.7
Northern Prairie States (IA,IL,IN,KS,MO,ND,NE,SD)	Oak/Pine	0	4.2	27.1
		5	13.9	27.2
		15	30.6	27.9
		25	53.6	29.1
		35	77.2	30.6
	Oak/Hickory	0	2.1	34.5
		5	11	34.6
		15	22.9	35.4
		25	37.9	37
		35	53	38.9
	Elm/Ash/Cottonwood	0	2.1	63.6
		5	10.8	63.8
		15	23.7	65.4
		25	36.4	68.3
		35	54.3	71.8
	Maple/Beech/Birch	0	2.1	48.6
		5	12.4	48.8
		15	25	50
		25	39	52.2
		35	55.7	54.9
South Central (AL,AR,KY,LA,MS,OK,TN,TX)	Loblolly/Shortleaf Pine	0	4.2	31.4

		5	20.1	31.5
		15	47	32.3
		25	70.5	33.7
		35	87.8	35.5
	Oak/Pine	0	4.2	31.3
		5	17.5	31.4
		15	46	32.2
		25	68.5	33.6
		35	88.2	35.3
	Oak/Hickory	0	4.2	29
		5	17.1	29.1
		15	40.8	29.8
		25	61.5	31.1
		35	81.2	32.7
	Oak/Gum/Cypress	0	1.8	39.6
		5	9.5	39.7
		15	37.8	40.7
		25	61.3	42.5
		35	81.8	44.7
	Elm/Ash/Cottonwood	0	4.2	37.4
		5	16	37.5
		15	38.2	38.5
		25	59.4	40.2
		35	80.2	42.2
Southeast (FL,GA,NC,SC,VA)	Longleaf/Slash Pine	0	4.2	82.5
		5	13.6	82.8
		15	34.9	84.9
		25	56.6	88.6
		35	75.1	93.2

	Loblolly/Shortleaf Pine	0	4.2	54.7
		5	19.8	54.9
		15	46.1	56.3
		25	69.4	58.7
		35	87.9	61.8
	Oak/Pine	0	4.2	46.1
		5	15.6	46.2
		15	42.8	47.4
		25	63.7	49.5
		35	83.9	52
	Oak/Hickory	0	4.2	33.9
		5	14.7	34.1
		15	41	34.9
		25	63.1	36.4
		35	82.5	38.3
	Oak/Gum/Cypress	0	1.8	118.5
		5	10.9	118.9
		15	37.2	121.9
		25	58.9	127.2
		35	77	133.8
Pacific Northwest, Westside (Western OR & WA)	Douglas-fir	0	4.6	71.1
		5	18.1	71.3
		15	50.3	73.1
		25	147.3	76.3
		35	240.6	80.2
	Fir/Spruce/Mt.Hemlock	0	4.8	46.6
		5	14	46.8
		15	31.4	47.9
		25	73.2	50

		35	126.9	52.6
	Hemlock/Sitka Spruce	0	4.7	87.3
		5	15.3	87.6
		15	41	89.8
		25	112.1	93.7
		35	190.5	98.5
	Alder/Maple	0	4.7	86.4
		5	16.1	86.7
		15	45.2	88.9
		25	127.8	92.8
		35	193.9	97.6
Pacific Northwest, Eastside (Eastern OR & WA)	Douglas-fir	0	4.6	71.1
		5	12.7	71.3
		15	27.5	73.1
		25	68.3	76.3
		35	116.7	80.2
	Ponderosa Pine	0	4.8	38
		5	10.8	38.1
		15	19.7	39.1
		25	33.7	40.8
		35	47	42.9
	Fir/Spruce/Mt.Hemlock	0	4.8	46.6
		5	13	46.8
		15	23.7	47.9
		25	40.5	50
		35	66.6	52.6
	Lodgepole Pine	0	4.8	39
		5	9.5	39.1
		15	19.6	40.1

		25	41.4	41.9
		35	62.8	44.1
Pacific Southwest (CA)	Fir/Spruce/Mt.Hemlock	0	4.8	38.9
		5	13.8	39.1
		15	26.7	40
		25	43	41.8
		35	61.5	43.9
	California Mixed Conifer	0	4.8	37.4
		5	14.8	37.5
		15	27.4	38.4
		25	43	40.1
		35	54.5	42.2
	Western Oak	0	4.7	20.7
		5	11.3	20.8
		15	20.8	21.3
		25	28.8	22.2
		35	57.3	23.4
Rocky Mountain, North (ID,MT)	Douglas-fir	0	4.7	29.1
		5	13	29.2
		15	24.8	30
		25	47	31.3
		35	77	32.9
	Ponderosa Pine	0	4.8	25.7
		5	10.9	25.8
		15	18.2	26.5
		25	31.8	27.6
		35	51.6	29
	Fir/Spruce/Mt.Hemlock	0	4.7	33.1
		5	13.6	33.2

		15	24.7	34
		25	42.4	35.5
		35	71.2	37.4
	Lodgepole Pine	0	4.8	27.9
		5	9.2	28
		15	15.9	28.7
		25	29.8	29.9
		35	49.6	31.5
Rocky Mountain, South (AZ,CO,NM,NV,UT,WY)	Douglas-fir	0	4.8	23.2
		5	13.1	23.3
		15	26.3	23.8
		25	46.2	24.9
		35	68.6	26.2
	Ponderosa Pine	0	4.8	18.1
		5	9.4	18.1
		15	15.6	18.6
		25	25.7	19.4
		35	37.5	20.4
	Fir/Spruce/Mt.Hemlock	0	4.8	23.6
		5	12.1	23.7
		15	22.5	24.3
		25	37	25.3
		35	54.5	26.7
	Lodgepole Pine	0	4.8	20.2
		5	9.7	20.3
		15	16.4	20.8
		25	25.5	21.7
		35	36.2	22.8
	Aspen/Birch	0	4.7	44.1

		5	12.1	44.2
		15	22	45.4
		25	35.3	47.4
		35	52.5	49.8

Source: Smith.J et al., 2006

Appendix L: Classification of tree species and database used in offset component of CFET.

Table L-1. Classification of common trees used in reforestation.

Species	Type	Growth Rate	Species	Type	Growth Rate
Ailanthus, Ailanthus altissima	H	F	Maple, bigleaf, Acer macrophyllum	H	S
Alder, European, Alnus glutinosa	H	F	Maple, Norway, Acer platanoides	H	M
Ash, green, Fraxinus pennsylvanica	H	F	Maple, red, Acer rubrum	H	M
Ash, mountain, American,Sorbus americana	H	M	Maple, silver, Acer saccharinum	H	M
Ash, white, Fraxinus americana	H	F	Maple, sugar, Acer saccharum	H	S
Aspen, bigtooth, Populus grandidentata	H	M	Mulberry, red, Morus rubra	H	F
Aspen, quaking, Populus tremuloides	H	F	Oak, black, Quercus velutina	H	M
Baldcypress, Taxodium distichum	C	F	Oak, blue, Quercus douglasii	H	M
Basswood, American, Tilia americana,	H	F	Oak, bur, Quercus macrocarpa	H	S
Beech, American, Fagus grandifolia	H	S	Oak, California black, Quercus kelloggii	H	S
Birch, paper (white), Betula papyrifera	H	M	Oak, California White, Quercus lobata	H	M
Birch, river, Betula nigra	H	M	Oak, canyon live, Quercus chrysolepsis	H	S
Birch, yellow, Betula alleghaniensis	H	S	Oak, chestnut, Quercus prinus	H	S
Boxelder, Acer negundo	H	F	Oak, Chinkapin, Quercus muehlenbergii	H	M
Buckeye, Ohio, Aesculus glabra	H	S	Oak, Laurel, Quercus laurifolia	H	F
Catalpa, northern, Catalpa speciosa	H	F	Oak, live, Quercus virginiana	H	F
Cedar-red, eastern, Juniperus virginiana	C	M	Oak, northern red, Quercus rubra	H	F
Cedar-white, northern, Thuja occidentalis	C	M	Oak, overcup , Quercus lyrata	H	S
Cherry, black, Prunus serotina	H	F	Oak, pin, Quercus palustris	H	F
Cherry, pin, Prunus pennsylvanica	H	M	Oak, scarlet, Quercus coccinea	H	F
Cottonwood, eastern, Populus deltoides	H	M	Oak, swamp white, Quercus bicolor	H	M
Crabapple, Malus spp.	H	M	Oak, water, Quercus nigra	H	M
Cucumbertree, Magnolia acuminata	H	F	Oak, white, Quercus alba	H	S
Dogwood, flowering, Cornus florida	H	S	Oak, willow, Quercus phellos	H	M
Elm, American, Ulmus americana	H	F	Pecan, Carya illinoensis	H	S
Elm, Chinese, Ulmus parvifolia	H	M	Pine, European black, Pinus nigra	C	S
Elm, rock, Ulmus thomasii	H	S	Pine, jack, Pinus banksiana	C	F
Elm, September, Ulmus serotina	H	F	Pine, loblolly, Pinus taeda	C	F
Elm, Siberian, Ulmus pumila	H	F	Pine, longleaf, Pinus palustris	C	F
Elm, slippery, Ulmus rubra	H	M	Pine, ponderosa, Pinus ponderosa	C	F
Fir, balsam, Abies balsamea	C	S	Pine, red, Pinus resinosa	C	F
Fir, Douglas, Pseudotsuga menziesii	C	F	Pine, Scotch, Pinus sylvestris	C	S
Ginkgo, Ginkgo biloba	H	S	Pine, shortleaf, Pinus echinata	C	F
Hackberry, Celtis occidentalis	H	F	Pine, slash, Pinus elliottii	C	F
Hawthorne, Crataegus spp.	H	M	Pine, Virginia, Pinus virginiana	C	M
Hemlock, eastern, Tsuga canadensis	C	M	Pine, white eastern, Pinus strobus	C	F
Hickory, bitternut, Carya cordiformis	H	S	Poplar, yellow, Liriodendron tulipifera	H	F
Hickory, mockernut, Carya tomentosa	H	M	Redbud, eastern, Cercis canadensis	H	M
Hickory, shagbark, Carya ovata	H	S	Sassafras, Sassafras albidum	H	M
Hickory, shellbark, Carya laciniosa	H	S	Spruce, black, Picea mariana	C	S
Hickory, pignut, Carya glabra	H	M	Spruce, blue, Picea pungens	C	M
Holly, American, Ilex opaca	H	S	Spruce, Norway, Picea abies	C	M
Honeylocust, Gleditsia triacanthos	H	F	Spruce, red, Picea rubens	C	S
Hophornbeam, eastern, Ostrya virginiana	H	S	Spruce, white, Picea glauca	C	M
Horsechestnut, common, Aesculus hippocastanum	H	F	Sugarberry, Celtis laevigata	H	F
Kentucky coffeetree, Gymnocladus dioicus	C	F	Sweetgum, Liquidambar styraciflua	H	F
Linden, little-leaf, Tilia cordata	H	F	Sycamore, Platanus occidentalis	H	F
Locust, black, Robinia pseudoacacia	H	F	Tamarack, Larix laricina	C	F
London plane tree Platanus_X_acerifolia	H	F	Walnut, black, Juglans nigra	H	F
Magnolia, southern, Magnolia grandifolia	H	M	Willow, black, Salix nigra	H	F

Type: H = Hardwood, C = Conifer Growth Rate: S = Slow, M = Moderate, F = Fast

Source: USDOE, 1998

Table L-2. Database used in the offset component.

Tree Age (yrs)	Average Sequestration Rate (MT C/yr/tree)	
	Hardwood	Conifers
0	0.00089	0.00047
1	0.00125	0.00069
2	0.00164	0.00093
3	0.00204	0.00120
4	0.00248	0.00149
5	0.00291	0.00180
6	0.00339	0.00213
7	0.00387	0.00248
8	0.00438	0.00282
9	0.00489	0.00321
10	0.00540	0.00362
11	0.00594	0.00401
12	0.00650	0.00444
13	0.00705	0.00486
14	0.00762	0.00530
15	0.00821	0.00578
16	0.00879	0.00624
17	0.00939	0.00672
18	0.00999	0.00723
19	0.01061	0.00773
20	0.01125	0.00824
21	0.01187	0.00878
22	0.01253	0.00932
23	0.01316	0.00987
24	0.01382	0.01041
25	0.01449	0.01098
26	0.01517	0.01157
27	0.01584	0.01215
28	0.01653	0.01275
29	0.01722	0.01335
30	0.01785	0.01397
31	0.01863	0.01460
32	0.01935	0.01523
33	0.02004	0.01586
34	0.02078	0.01650
35	0.02151	0.01718
36	0.02225	0.01785

37	0.02300	0.01851
38	0.02373	0.01920
39	0.02450	0.01989
40	0.02525	0.02058
41	0.02603	0.02129
42	0.02679	0.02199
43	0.02756	0.02273
44	0.02834	0.02345
45	0.02912	0.02418
46	0.02993	0.02493
47	0.03071	0.02568
48	0.03152	0.02643
49	0.03231	0.02721
50	0.03314	0.02798

Source: USDOE, 1998

Appendix M: ICC input data & emissions calculation for equipment usage component of CFET.

Table M-1. ICC equipment inventory as processed to fit analogous equipment categories CFET.

Equip Type	Model #	Tier	Analogous GHG Equip	Start date	End date	# Days	# hrs
Manlift	S80	2	Aerial Lifts	7/31/09	1/19/10	172	1032
manlift	601S	2	Aerial Lifts	8/18/09	1/19/10	154	924
Compressor	185 CFM	2	Air Compressors	11/21/07	1/19/10	790	4740
Compressor	185 CFM	2	Air Compressors	11/21/07	1/19/10	790	4740
Compressor	185 CFM	2	Air Compressors	12/5/08	1/19/10	410	2460
Compressor	185 CFM	2	Air Compressors	12/5/08	1/19/10	410	2460
Crawler Crane	275 TN	1	Cranes	5/28/08	1/19/10	601	3606
Crane	RT700E	1	Cranes	4/9/08	1/19/10	650	3900
Crane	RT760E	1	Cranes	4/10/08	1/19/10	649	3894
Crane	RT700E	2	Cranes	5/2/08	1/19/10	627	3762
Crane	RT760E	2	Cranes	6/5/08	1/19/10	593	3558
Crawler Crane	110 TN	2	Cranes	4/29/08	1/19/10	630	3780
Crane	RT700E	3	Cranes	10/19/07	1/19/10	823	4938
Crane	RT700E	3	Cranes	2/1/08	1/19/10	718	4308
Crane	RT760	3	Cranes	2/12/09	1/19/10	341	2046
Crane	165 TN	3	Cranes	8/7/08	1/19/10	530	3180
Crane	RT760	3	Cranes	6/30/09	1/19/10	203	1218
Tractor	8230	3	Crawler Tractors	3/30/09	1/19/10	295	1770
Power Track	800	2	Crushing/Proc. Equipment	7/2/09	1/19/10	201	1206
Excavator	330 DL	1	Excavators	6/5/08	1/19/10	593	3558
Excavator	330-EXC	1	Excavators	7/25/08	4/21/09	270	1620
Excavator	EX330LC-5	1	Excavators	1/27/09	4/21/09	84	504
Excavator	EX330LC-C	1	Excavators	10/23/07	4/21/09	546	3276
Excavator	320CL	2	Excavators	1/27/09	1/19/10	357	2142

Excavator	325CL	2	Excavators	3/13/08	1/19/10	677	4062
Excavator	330CL	2	Excavators	3/14/08	1/19/10	676	4056
Excavator	330CL	2	Excavators	1/27/09	1/19/10	357	2142
Excavator	PC300LC-7L	2	Excavators	8/10/09	1/19/10	162	972
Excavator	PC400	2	Excavators	5/12/09	1/19/10	252	1512
Excavator	315 CL	3	Excavators	7/1/08	1/19/10	567	3402
Excavator	325 DL	3	Excavators	9/19/07	1/19/10	853	5118
Excavator	325 DL	3	Excavators	7/9/08	1/19/10	559	3354
Excavator	325 DL	3	Excavators	11/21/08	1/19/10	424	2544
Excavator	330 D	3	Excavators	9/5/08	1/19/10	501	3006
Excavator	330 DL	3	Excavators	10/19/07	1/19/10	823	4938
Excavator	330 DL	3	Excavators	11/12/07	1/19/10	799	4794
Excavator	330 DL	3	Excavators	6/20/08	1/19/10	578	3468
Excavator	330 DL	3	Excavators	7/10/08	1/19/10	558	3348
Excavator	330 DL	3	Excavators	10/23/08	1/19/10	453	2718
Excavator	330 DL	3	Excavators	11/19/08	1/19/10	426	2556
Excavator	345 CL	3	Excavators	2/9/09	1/19/10	344	2064
Excavator	330DL	3	Excavators	7/22/08	1/19/10	546	3276
Excavator	345	3	Excavators	3/23/09	1/19/10	302	1812
Excavator	330	3	Excavators	6/17/09	1/19/10	216	1296
EXCAVATOR	330DL	3	Excavators	3/30/09	1/19/10	295	1770
Manlift	60 S	2	Forklifts	3/12/09	1/19/10	313	1878
Forklift	506	2	Forklifts	6/29/09	1/19/10	204	1224
Forklift	10054	2	Forklifts	7/10/09	1/19/10	193	1158
Forklift	1054	2	Forklifts	7/6/09	1/19/10	197	1182
Forklift	TH1255	3	Forklifts	9/20/07	1/19/10	852	5112
Telehandler	TH1255	3	Forklifts	10/23/07	1/19/10	819	4914
Forklift	6000 LB	3	Forklifts	9/23/08	1/19/10	483	2898
Forklift	10054	3	Forklifts	2/6/08	1/19/10	713	4278
Generator	50KW	2	Generators	3/12/09	1/19/10	313	1878
Compactor	815F	1	Graders	4/2/08	1/19/10	657	3942
Compactor	815F	1	Graders	5/7/08	1/19/10	622	3732

Compactor	963C	1	Graders	7/25/08	1/19/10	543	3258
Compactor	815F	2	Graders	3/9/09	1/19/10	316	1896
6-Wheel truck	TA30	1	Off-Highway Trucks	7/3/08	1/19/10	565	3390
6-Wheel truck	TA30	1	Off-Highway Trucks	6/24/08	4/21/09	301	1806
6-wheel Truck	TA30	1	Off-Highway Trucks	1/27/09	1/19/10	357	2142
Articulated Truck	730	2	Off-Highway Trucks	1/15/09	1/19/10	369	2214
Articulated Truck	A35D	2	Off-Highway Trucks	3/17/09	1/19/10	308	1848
Articulated Truck	730	2	Off-Highway Trucks	2/14/08	4/21/09	432	2592
Articulated Truck	730	2	Off-Highway Trucks	3/22/08	1/19/10	668	4008
Articulated Truck	730	2	Off-Highway Trucks	4/3/08	1/19/10	656	3936
Articulated Truck	730	2	Off-Highway Trucks	4/22/08	4/21/09	364	2184
Articulated Truck	730	2	Off-Highway Trucks	7/22/08	4/21/09	273	1638
Articulated Truck	730	2	Off-Highway Trucks	1/27/09	4/21/09	84	504
Articulated Truck	730	2	Off-Highway Trucks	1/27/09	4/21/09	84	504
Articulated Truck	730	2	Off-Highway Trucks	1/27/09	4/21/09	84	504
Articulated Truck	730	2	Off-Highway Trucks	1/27/09	4/21/09	84	504
Articulated Truck	730	2	Off-Highway Trucks	1/27/09	1/19/10	357	2142
Articulated Truck	30 TN	3	Off-Highway Trucks	6/26/08	1/19/10	572	3432
Articulated Truck	31 TN	3	Off-Highway Trucks	9/23/08	1/19/10	483	2898
Articulated Truck	32 TN	3	Off-Highway Trucks	9/23/08	1/19/10	483	2898
Articulated Truck	730	3	Off-Highway Trucks	1/27/09	1/19/10	357	2142
Articulated Truck	730	3	Off-Highway Trucks	1/27/09	4/21/09	84	504
Articulated Truck	730	3	Off-Highway Trucks	1/27/09	1/19/10	357	2142
Articulated Truck	730	3	Off-Highway Trucks	1/27/09	4/21/09	84	504
Articulated Truck	730	3	Off-Highway Trucks	1/27/09	1/19/10	357	2142
Articulated Truck	730	3	Off-Highway Trucks	1/27/09	1/19/10	357	2142
Articulated Truck	730	3	Off-Highway Trucks	2/18/09	4/21/09	62	372
Articulated Truck	730	3	Off-Highway Trucks	2/19/09	1/19/10	334	2004
Articulated Truck	730	3	Off-Highway Trucks	4/9/09	1/19/10	285	1710
Articulated Truck	730	3	Off-Highway Trucks	5/20/09	1/19/10	244	1464
Articulated Truck	730	3	Off-Highway Trucks	5/20/09	1/19/10	244	1464
Articulated Truck	730	3	Off-Highway Trucks	5/20/09	1/19/10	244	1464

Articulated Truck	730	3	Off-Highway Trucks	5/20/09	1/19/10	244	1464
Articulated Truck	730	3	Off-Highway Trucks	5/20/09	1/19/10	244	1464
Articulated Truck	730	3	Off-Highway Trucks	7/10/09	1/19/10	193	1158
Articulated Truck	730	3	Off-Highway Trucks	7/10/09	1/19/10	193	1158
Concrete Finisher	4800	2	Other Construction Equipment	2/11/08	1/19/10	708	4248
Gradail	XL4200S-II	1	Other General Industrial Equipment	1/27/09	1/19/10	357	2142
Track Grinder	6600	1	Other General Industrial Equipment	7/3/08	4/21/09	292	1752
Track Grinder	6600	1	Other General Industrial Equipment	1/27/09	4/21/09	84	504
Power Broom	CR350	2	Other General Industrial Equipment	10/17/08	1/19/10	459	2754
Straw Blower	B260	3	Other General Industrial Equipment	11/13/07	1/19/10	798	4788
Chipper	WCL23	1	Other Material Handling Equipment	11/14/07	1/19/10	797	4782
Hydo-Buncher	260HP	1	Other Material Handling Equipment	1/5/08	4/21/09	472	2832
Hydro seeder	*not given*	3	Other Material Handling Equipment	9/17/07	1/19/10	855	5130
Feiler Buncher	643J	3	Other Material Handling Equipment	5/11/07	4/21/09	711	4266
Roller	SD100D	0	Rollers	4/25/08	4/21/09	361	2166
Roller	SD100D	0	Rollers	7/25/08	4/21/09	270	1620
Roller	SD115D	0	Rollers	7/25/08	1/19/10	543	3258
Roller	SD115D	0	Rollers	1/27/09	1/19/10	357	2142
Roller	SD115D	0	Rollers	1/27/09	1/19/10	357	2142
Roller	SD122DX	0	Rollers	8/5/08	1/19/10	532	3192
Roller	SD100D	0	Rollers	1/27/09	1/19/10	357	2142
Roller	SD100D	1	Rollers	5/29/08	1/19/10	600	3600

Roller	SD122DX	1	Rollers	1/27/09	4/21/09	84	504
Roller	SD110D 84"	1	Rollers	8/10/09	1/19/10	162	972
SD Roller	50"	2	Rollers	4/9/08	1/19/10	650	3900
SD Roller	50"	2	Rollers	5/22/08	1/19/10	607	3642
SD Roller	50"	2	Rollers	3/13/09	1/19/10	312	1872
66" SD Roller	66"	2	Rollers	8/1/08	1/19/10	536	3216
SD Roller	66"	2	Rollers	8/6/08	1/19/10	531	3186
Roller	CS323C	2	Rollers	10/31/08	1/19/10	445	2670
Roller	SD-122	2	Rollers	3/12/09	1/19/10	313	1878
Compactor	CS563E	2	Rollers	3/23/09	1/19/10	302	1812
Roller	CS533	3	Rollers	7/2/09	1/19/10	201	1206
Roller	CS563E	3	Rollers	4/28/09	1/19/10	266	1596
Roller	CS563E	3	Rollers	6/17/09	1/19/10	216	1296
Dozer	D8R	1	Rubber Tired Dozers	6/13/08	4/21/09	312	1872
Dozer	D8R	1	Rubber Tired Dozers	6/13/08	1/19/10	585	3510
Dozer	550 J	2	Rubber Tired Dozers	8/6/08	1/19/10	531	3186
Dozer	D5GLGP	2	Rubber Tired Dozers	7/3/08	1/19/10	565	3390
Dozer	D5GLGP	2	Rubber Tired Dozers	7/22/08	4/21/09	273	1638
Dozer	D5GLGP	2	Rubber Tired Dozers	1/27/09	4/21/09	84	504
Dozer	D5GLGP	2	Rubber Tired Dozers	1/27/09	4/21/09	84	504
Dozer	D5GLGP	2	Rubber Tired Dozers	4/14/08	1/19/10	645	3870
Dozer	D5GLGP	2	Rubber Tired Dozers	7/22/08	1/19/10	546	3276
Dozer	D6NLGP	2	Rubber Tired Dozers	2/11/09	1/19/10	342	2052
Dozer	D6NLGP	2	Rubber Tired Dozers	1/27/09	1/19/10	357	2142
Dozer	650J	2	Rubber Tired Dozers	1/27/09	1/19/10	357	2142
Dozer	850CX	2	Rubber Tired Dozers	1/27/09	1/19/10	357	2142
Dozer	D6N	2	Rubber Tired Dozers	8/27/09	1/19/10	145	870
Dozer	D3GXL	2	Rubber Tired Dozers	1/27/09	1/19/10	357	2142
Dozer	D5GLGP	2	Rubber Tired Dozers	1/27/09	1/19/10	357	2142
Dozer	D5GLGP	2	Rubber Tired Dozers	1/27/09	1/19/10	357	2142
Dozer	DN5	2	Rubber Tired Dozers	7/2/09	1/19/10	201	1206
Dozer	D4K	3	Rubber Tired Dozers	9/15/08	1/19/10	491	2946

Dozer	D-6N	3	Rubber Tired Dozers	2/11/09	1/19/10	342	2052
Dozer	750J	3	Rubber Tired Dozers	9/7/08	4/21/09	226	1356
Dozer	D6N XL	3	Rubber Tired Dozers	6/25/09	1/19/10	208	1248
Dozer	D6N	3	Rubber Tired Dozers	5/13/09	1/19/10	251	1506
Dozer	*D6NLGP*	3	Rubber Tired Dozers	7/2/09	1/19/10	201	1206
Wheel Loader	962G	1	Rubber Tired Loaders	7/2/09	1/19/10	201	1206
Scraper	621G	2	Scrapers	1/27/09	1/19/10	357	2142
Scraper	621G	2	Scrapers	1/27/09	1/19/10	357	2142
Scraper	621G	2	Scrapers	1/17/09	1/19/10	367	2202
Scraper	621G	2	Scrapers	1/27/09	1/19/10	357	2142
Scraper	621G	2	Scrapers	1/27/09	1/19/10	357	2142
Tractor Scraper	627G	3	Scrapers	5/14/08	1/19/10	615	3690
Tractor Scraper	627G	3	Scrapers	1/27/09	4/21/09	84	504
Skidder	460D	1	Skid Steer Loaders	11/2/08	4/21/09	170	1020
Loader	950G	1	Skid Steer Loaders	4/14/09	1/19/10	280	1680
Track Loader	T-250	1	Skid Steer Loaders	4/22/09	1/19/10	272	1632
Loader	963C	1	Skid Steer Loaders	1/9/09	1/19/10	375	2250
Log Loader	535	2	Skid Steer Loaders	3/24/08	4/21/09	393	2358
Skidder	648G	2	Skid Steer Loaders	4/22/08	1/19/10	637	3822
Dozer	D65	2	Skid Steer Loaders	8/17/09	1/19/10	155	930
Loader wheel	950G	3	Skid Steer Loaders	10/17/07	1/19/10	825	4950
Loader	963C	1	Tractors/Loaders/Backhoes	3/13/08	1/19/10	677	4062
Loader	963C	1	Tractors/Loaders/Backhoes	7/22/08	1/19/10	546	3276
Loader	963C	1	Tractors/Loaders/Backhoes	7/22/08	1/19/10	546	3276
Loader	963C	1	Tractors/Loaders/Backhoes	1/27/09	4/21/09	84	504
Loader	IT38G	1	Tractors/Loaders/Backhoes	11/7/07	4/21/09	531	3186
Loader	644G	1	Tractors/Loaders/Backho	7/22/08	4/21/09	273	1638

			es				
Track Loader	963C	2	Tractors/Loaders/Backhoes	1/14/09	1/19/10	370	2220
Loader	IT3B	2	Tractors/Loaders/Backhoes	10/23/08	1/19/10	453	2718
Backhoe	410 J	2	Tractors/Loaders/Backhoes	9/6/07	1/19/10	866	5196
Backhoe	411 J	2	Tractors/Loaders/Backhoes	10/22/07	1/19/10	820	4920
Backhoe 4x4	412 J	2	Tractors/Loaders/Backhoes	11/23/07	1/19/10	788	4728
Tractor Tracked	550 J	2	Tractors/Loaders/Backhoes	10/8/07	1/19/10	834	5004
Tractor Tracked	550 J	2	Tractors/Loaders/Backhoes	11/12/07	1/19/10	799	4794
Loader	963C	2	Tractors/Loaders/Backhoes	5/23/08	1/19/10	606	3636
Wheel Loader	930H	3	Tractors/Loaders/Backhoes	3/3/09	1/19/10	322	1932
Wheel Loader	950H	3	Tractors/Loaders/Backhoes	10/22/07	1/19/10	820	4920
Wheel Loader	950H	3	Tractors/Loaders/Backhoes	4/22/08	1/19/10	637	3822
Wheel Loader	950H	3	Tractors/Loaders/Backhoes	11/14/08	1/19/10	431	2586
Track Loader	953C	3	Tractors/Loaders/Backhoes	1/21/09	1/19/10	363	2178
Loader	963	3	Tractors/Loaders/Backhoes	12/4/07	1/19/10	777	4662
Loader	IT3B	3	Tractors/Loaders/Backhoes	9/15/08	1/19/10	491	2946

Table M- 2. Results from emissions calculation of the ICC equipment fleet.

Est. Equip Type	Tier	Est. Hp	Year	EM (MT)							EM (MT CO2e)
				CO2	CO	CH4	NOx	ROG	SOX	PM	
Rollers	2	120	2004	78.161	0.573	0.017	1.146	0.192	0.0009	0.097	435.54
Off-Highway Trucks	1	500	1998	460.245	1.597	0.044	4.822	0.485	0.0045	0.178	1960.64
Off-Highway Trucks	1	500	1998	245.193	0.851	0.023	2.569	0.258	0.0024	0.095	1044.52
Off-Highway Trucks	1	500	1998	290.810	1.009	0.028	3.047	0.306	0.0029	0.112	1238.85
Off-Highway Trucks	3	250	2008	194.624	0.561	0.019	2.176	0.213	0.0022	0.077	871.15
Off-Highway Trucks	3	250	2008	164.342	0.474	0.016	1.837	0.180	0.0018	0.065	735.60
Off-Highway Trucks	3	250	2008	164.342	0.474	0.016	1.837	0.180	0.0018	0.065	735.60
Off-Highway Trucks	2	250	2004	151.919	0.465	0.016	1.824	0.176	0.0017	0.065	719.01
Off-Highway Trucks	2	500	2004	207.351	0.720	0.020	2.172	0.218	0.0020	0.080	883.31
Off-Highway Trucks	2	250	2004	177.857	0.544	0.019	2.135	0.206	0.0020	0.076	841.77
Off-Highway Trucks	2	250	2004	275.019	0.842	0.029	3.302	0.319	0.0031	0.117	1301.62
Off-Highway Trucks	2	250	2004	270.079	0.826	0.028	3.242	0.313	0.0030	0.115	1278.24
Off-Highway Trucks	2	250	2004	149.861	0.459	0.016	1.799	0.174	0.0017	0.064	709.27
Off-Highway Trucks	2	250	2004	112.396	0.344	0.012	1.349	0.130	0.0013	0.048	531.95
Off-Highway Trucks	3	250	2008	121.470	0.350	0.012	1.358	0.133	0.0014	0.048	543.70
Off-Highway Trucks	3	250	2008	28.581	0.082	0.003	0.319	0.031	0.0003	0.011	127.93
Off-Highway Trucks	2	250	2004	34.583	0.106	0.004	0.415	0.040	0.0004	0.015	163.68
Off-Highway Trucks	3	250	2008	121.470	0.350	0.012	1.358	0.133	0.0014	0.048	543.70
Off-Highway Trucks	2	250	2004	34.583	0.106	0.004	0.415	0.040	0.0004	0.015	163.68
Off-Highway Trucks	3	250	2008	28.581	0.082	0.003	0.319	0.031	0.0003	0.011	127.93
Off-Highway Trucks	2	250	2004	34.583	0.106	0.004	0.415	0.040	0.0004	0.015	163.68
Off-Highway Trucks	2	250	2004	34.583	0.106	0.004	0.415	0.040	0.0004	0.015	163.68

Off-Highway Trucks	3	250	2008	121.470	0.350	0.012	1.358	0.133	0.0014	0.048	543.70
Off-Highway Trucks	3	250	2008	121.470	0.350	0.012	1.358	0.133	0.0014	0.048	543.70
Off-Highway Trucks	3	250	2008	21.096	0.061	0.002	0.236	0.023	0.0002	0.008	94.42
Off-Highway Trucks	3	250	2008	113.644	0.327	0.011	1.270	0.124	0.0013	0.045	508.68
Off-Highway Trucks	2	250	2004	146.979	0.450	0.015	1.764	0.171	0.0017	0.063	695.63
Off-Highway Trucks	3	250	2008	96.972	0.279	0.010	1.084	0.106	0.0011	0.038	434.05
Off-Highway Trucks	3	250	2008	83.022	0.239	0.008	0.928	0.091	0.0009	0.033	371.61
Off-Highway Trucks	3	250	2008	83.022	0.239	0.008	0.928	0.091	0.0009	0.033	371.61
Off-Highway Trucks	3	250	2008	83.022	0.239	0.008	0.928	0.091	0.0009	0.033	371.61
Off-Highway Trucks	3	250	2008	83.022	0.239	0.008	0.928	0.091	0.0009	0.033	371.61
Off-Highway Trucks	3	250	2008	83.022	0.239	0.008	0.928	0.091	0.0009	0.033	371.61
Off-Highway Trucks	3	250	2008	65.669	0.189	0.006	0.734	0.072	0.0007	0.026	293.94
Off-Highway Trucks	3	250	2008	65.669	0.189	0.006	0.734	0.072	0.0007	0.026	293.94
Tractors/Loaders/Backhoes	2	50	2005	53.691	0.705	0.027	0.581	0.298	0.0007	0.069	236.57
Tractors/Loaders/Backhoes	2	50	2005	50.839	0.668	0.025	0.550	0.282	0.0007	0.065	224.01
Tractors/Loaders/Backhoes	2	50	2005	48.855	0.641	0.024	0.529	0.271	0.0006	0.063	215.27
Other Material Handling Equipment	1	500	1998	456.826	1.798	0.036	5.171	0.486	0.0045	0.186	2065.92
Graders	2	250	2004	134.448	0.454	0.015	1.678	0.163	0.0015	0.063	656.33
Graders	1	250	1999	338.235	1.141	0.037	4.222	0.410	0.0038	0.158	1651.16
Graders	1	250	1999	320.217	1.081	0.035	3.997	0.389	0.0036	0.149	1563.20
Graders	1	175	1999	201.273	1.225	0.030	2.641	0.337	0.0023	0.147	1024.16
Rollers	2	175	2004	80.737	0.478	0.012	1.060	0.131	0.0009	0.056	410.92
Air Compressors	2	50	2005	35.945	0.473	0.019	0.398	0.211	0.0005	0.047	161.24
Air Compressors	2	50	2005	35.945	0.473	0.019	0.398	0.211	0.0005	0.047	161.24
Air Compressors	2	50	2005	18.655	0.246	0.010	0.207	0.109	0.0002	0.024	83.68
Air Compressors	2	50	2005	18.655	0.246	0.010	0.207	0.109	0.0002	0.024	83.68
Other Construction	2	50	2005	40.485	0.472	0.018	0.426	0.196	0.0005	0.047	174.18

Equipment											
Cranes	3	250	2008	188.583	0.652	0.021	2.332	0.234	0.0021	0.090	913.80
Cranes	3	250	2008	164.523	0.569	0.018	2.034	0.204	0.0019	0.078	797.21
Cranes	1	250	1999	218.065	0.801	0.026	2.851	0.287	0.0025	0.111	1104.87
Cranes	2	250	2004	173.842	0.638	0.021	2.273	0.229	0.0020	0.088	880.80
Cranes	3	250	2008	78.137	0.270	0.009	0.966	0.097	0.0009	0.037	378.62
Cranes	1	250	1999	217.730	0.800	0.026	2.847	0.287	0.0024	0.111	1103.17
Cranes	2	250	2004	164.415	0.604	0.020	2.150	0.217	0.0018	0.084	833.04
Cranes	3	250	2008	121.444	0.420	0.014	1.502	0.151	0.0014	0.058	588.47
Cranes	3	250	2008	46.516	0.161	0.005	0.575	0.058	0.0005	0.022	225.40
Cranes	1	500	1998	323.765	1.525	0.034	3.784	0.381	0.0032	0.147	1502.11
Cranes	2	250	2004	174.674	0.641	0.021	2.284	0.230	0.0020	0.089	885.02
Rubber Tired Dozers	3	175	2008	129.880	0.889	0.024	1.963	0.261	0.0015	0.112	741.47
Rubber Tired Dozers	2	175	2004	169.957	1.177	0.032	2.684	0.356	0.0019	0.153	1006.32
Rubber Tired Dozers	2	175	2004	180.840	1.252	0.034	2.856	0.379	0.0020	0.163	1070.76
Rubber Tired Dozers	2	175	2004	87.379	0.605	0.017	1.380	0.183	0.0010	0.079	517.37
Rubber Tired Dozers	2	175	2004	26.886	0.186	0.005	0.425	0.056	0.0003	0.024	159.19
Rubber Tired Dozers	2	175	2004	26.886	0.186	0.005	0.425	0.056	0.0003	0.024	159.19
Rubber Tired Dozers	2	175	2004	206.445	1.429	0.039	3.261	0.432	0.0023	0.186	1222.37
Rubber Tired Dozers	2	175	2004	174.758	1.210	0.033	2.760	0.366	0.0020	0.157	1034.75
Rubber Tired Dozers	3	175	2008	90.466	0.619	0.016	1.367	0.182	0.0010	0.078	516.46
Rubber Tired Dozers	2	175	2004	109.464	0.758	0.021	1.729	0.229	0.0012	0.098	648.14
Rubber Tired Dozers	2	175	2004	114.265	0.791	0.022	1.805	0.239	0.0013	0.103	676.57
Rubber Tired Dozers	1	250	1999	171.238	0.825	0.026	2.613	0.293	0.0019	0.115	984.43
Rubber Tired Dozers	1	250	1999	321.070	1.547	0.050	4.900	0.549	0.0036	0.216	1845.80
Rubber Tired Dozers	2	175	2004	114.265	0.791	0.022	1.805	0.239	0.0013	0.103	676.57
Rubber Tired Dozers	3	175	2008	59.782	0.409	0.011	0.903	0.120	0.0007	0.052	341.29
Rubber Tired Dozers	2	175	2004	114.265	0.791	0.022	1.805	0.239	0.0013	0.103	676.57
Rubber Tired Dozers	2	175	2004	46.410	0.321	0.009	0.733	0.097	0.0005	0.042	274.80
Rubber Tired Dozers	3	175	2008	55.020	0.377	0.010	0.831	0.111	0.0006	0.048	314.10

Skid Steer Loaders	2	120	2004	16.385	0.112	0.003	0.201	0.032	0.0002	0.017	79.21
Rubber Tired Dozers	2	175	2004	114.265	0.791	0.022	1.805	0.239	0.0013	0.103	676.57
Rubber Tired Dozers	2	175	2004	114.265	0.791	0.022	1.805	0.239	0.0013	0.103	676.57
Rubber Tired Dozers	2	175	2004	114.265	0.791	0.022	1.805	0.239	0.0013	0.103	676.57
Rubber Tired Dozers	3	175	2008	66.395	0.455	0.012	1.003	0.133	0.0007	0.057	379.04
Rubber Tired Dozers	3	175	2008	53.169	0.364	0.010	0.803	0.107	0.0006	0.046	303.53
Rubber Tired Dozers	2	175	2004	64.334	0.445	0.012	1.016	0.135	0.0007	0.058	380.92
Excavators	3	120	2009	85.284	0.623	0.016	1.042	0.176	0.0010	0.097	410.53
Excavators	3	175	2008	195.566	1.174	0.026	2.250	0.292	0.0022	0.130	897.24
Excavators	3	175	2008	128.161	0.769	0.017	1.475	0.191	0.0014	0.085	587.99
Excavators	3	175	2008	97.210	0.583	0.013	1.119	0.145	0.0011	0.065	445.99
Excavators	1	250	1999	281.464	0.823	0.028	3.292	0.306	0.0032	0.114	1305.01
Excavators	3	250	2008	162.419	0.448	0.015	1.767	0.166	0.0018	0.061	711.73
Excavators	3	250	2008	266.807	0.735	0.025	2.902	0.272	0.0030	0.100	1169.17
Excavators	3	250	2008	259.027	0.714	0.024	2.817	0.264	0.0029	0.097	1135.07
Excavators	3	250	2008	187.381	0.516	0.017	2.038	0.191	0.0021	0.070	821.12
Excavators	3	250	2008	180.897	0.499	0.017	1.968	0.185	0.0020	0.068	792.70
Excavators	3	250	2008	146.858	0.405	0.014	1.597	0.150	0.0017	0.055	643.54
Excavators	3	250	2008	138.104	0.381	0.013	1.502	0.141	0.0016	0.052	605.18
Excavators	3	250	2008	111.521	0.307	0.010	1.213	0.114	0.0013	0.042	488.69
Excavators	2	120	2004	64.973	0.486	0.014	0.909	0.158	0.0008	0.085	348.67
Excavators	2	175	2004	187.810	1.131	0.027	2.326	0.300	0.0021	0.133	912.74
Excavators	2	250	2004	265.174	0.776	0.026	3.101	0.288	0.0030	0.107	1229.47
Excavators	2	250	2004	140.040	0.410	0.014	1.638	0.152	0.0016	0.057	649.29
Excavators	3	250	2008	177.007	0.488	0.016	1.925	0.181	0.0020	0.066	775.66
Excavators	3	250	2008	97.905	0.270	0.009	1.065	0.100	0.0011	0.037	429.03
Excavators	1	250	1999	128.154	0.375	0.013	1.499	0.139	0.0014	0.052	594.19
Excavators	1	250	1999	39.870	0.117	0.004	0.466	0.043	0.0004	0.016	184.86
Excavators	1	250	1999	259.156	0.758	0.025	3.031	0.282	0.0029	0.105	1201.57
Excavators	2	175	2004	44.941	0.271	0.006	0.557	0.072	0.0005	0.032	218.41

Excavators	2	250	2004	98.852	0.289	0.010	1.156	0.108	0.0011	0.040	458.32
Excavators	3	250	2008	70.025	0.193	0.006	0.762	0.071	0.0008	0.026	306.85
Excavators	3	250	2008	95.636	0.264	0.009	1.040	0.098	0.0011	0.036	419.08
Other Material Handling Equipment	3	175	2008	177.327	1.078	0.027	2.301	0.302	0.0020	0.133	894.40
Forklifts	3	120	2009	54.351	0.396	0.010	0.654	0.115	0.0006	0.065	258.49
Forklifts	3	120	2009	30.812	0.224	0.006	0.371	0.065	0.0004	0.037	146.54
Forklifts	3	120	2009	45.484	0.331	0.009	0.547	0.096	0.0005	0.054	216.32
Forklifts	2	120	2004	15.747	0.118	0.004	0.220	0.040	0.0002	0.022	84.31
Forklifts	2	120	2004	14.897	0.112	0.003	0.208	0.038	0.0002	0.020	79.77
Forklifts	2	120	2004	15.206	0.114	0.003	0.212	0.038	0.0002	0.021	81.42
Generators	2	50	2005	19.582	0.197	0.007	0.204	0.083	0.0003	0.020	83.70
Other General Industrial Equipment	1	175	1999	102.440	0.628	0.016	1.390	0.182	0.0012	0.080	535.48
Other Material Handling Equipment	1	175	1999	172.353	1.051	0.027	2.329	0.304	0.0019	0.133	898.02
Other Material Handling Equipment	3	175	2008	213.242	1.296	0.033	2.767	0.363	0.0024	0.160	1075.54
Tractors/Loaders/Backhoes	3	175	2008	160.943	0.937	0.020	1.780	0.223	0.0018	0.101	715.91
Tractors/Loaders/Backhoes	3	175	2008	101.703	0.592	0.013	1.125	0.141	0.0011	0.064	452.40
Tractors/Loaders/Backhoes	2	175	2004	113.536	0.663	0.015	1.353	0.169	0.0013	0.075	535.38
Tractors/Loaders/Backhoes	1	175	1999	205.310	1.198	0.028	2.447	0.306	0.0023	0.136	968.14
Tractors/Loaders/Backhoes	2	175	2004	151.883	0.887	0.020	1.810	0.227	0.0017	0.101	716.20
Tractors/Loaders/Backhoes	1	175	1999	165.582	0.967	0.022	1.974	0.247	0.0019	0.110	780.80
Tractors/Loaders/Backhoes	1	175	1999	165.582	0.967	0.022	1.974	0.247	0.0019	0.110	780.80
Tractors/Loaders/Backhoes	1	175	1999	25.474	0.149	0.003	0.304	0.038	0.0003	0.017	120.12

Tractors/Loaders/Backhoes	1	175	1999	161.033	0.940	0.022	1.920	0.240	0.0018	0.107	759.35
Tractors/Loaders/Backhoes	1	175	1999	82.791	0.483	0.011	0.987	0.124	0.0009	0.055	390.40
Skid Steer Loaders	1	120	1999	35.814	0.245	0.006	0.440	0.070	0.0004	0.038	173.14
Skid Steer Loaders	1	120	1999	47.965	0.328	0.009	0.590	0.094	0.0006	0.051	231.88
Skid Steer Loaders	3	120	2009	72.074	0.481	0.010	0.754	0.114	0.0008	0.065	307.46
Skid Steer Loaders	2	120	2004	41.543	0.284	0.007	0.511	0.082	0.0005	0.044	200.84
Forklifts	2	120	2004	24.160	0.181	0.005	0.337	0.061	0.0003	0.033	129.36
Aerial Lifts	2	120	2004	16.188	0.109	0.003	0.217	0.035	0.0002	0.017	83.94
Aerial Lifts	2	120	2004	14.494	0.098	0.003	0.195	0.031	0.0002	0.015	75.15
Other General Industrial Equipment	2	120	2004	70.390	0.540	0.017	1.059	0.190	0.0008	0.099	400.75
Crushing/Proc. Equipment	2	120	2004	41.311	0.303	0.009	0.592	0.102	0.0005	0.053	226.07
Rollers	2	120	2004	64.891	0.476	0.014	0.952	0.160	0.0008	0.081	361.59
Rollers	2	175	2004	83.678	0.495	0.012	1.098	0.135	0.0009	0.058	425.89
Rollers	0	120	1997	63.697	0.467	0.014	0.934	0.157	0.0007	0.079	354.94
Rollers	1	120	1999	105.867	0.776	0.023	1.552	0.260	0.0012	0.132	589.92
Rollers	0	120	1997	47.640	0.349	0.011	0.699	0.117	0.0006	0.059	265.47
Rollers	0	175	1997	175.651	1.039	0.026	2.305	0.284	0.0020	0.121	894.00
Rollers	0	175	1997	115.483	0.683	0.017	1.516	0.187	0.0013	0.080	587.77
Rollers	0	175	1997	115.483	0.683	0.017	1.516	0.187	0.0013	0.080	587.77
Rollers	0	175	1997	172.092	1.018	0.025	2.259	0.278	0.0019	0.119	875.89
Rollers	1	175	1999	27.172	0.161	0.004	0.357	0.044	0.0003	0.019	138.30
Rollers	1	175	1999	52.404	0.310	0.008	0.688	0.085	0.0006	0.036	266.72
Rollers	3	120	2009	24.223	0.173	0.005	0.320	0.053	0.0003	0.028	123.90
Rollers	3	175	2008	58.771	0.345	0.008	0.730	0.090	0.0007	0.039	286.28
Rollers	3	175	2008	47.724	0.280	0.007	0.593	0.073	0.0005	0.032	232.46
Rollers	0	120	1997	62.991	0.462	0.014	0.924	0.155	0.0007	0.078	351.00
Scrapers	2	250	2004	184.861	0.760	0.024	2.560	0.269	0.0021	0.105	981.34

Scrapers	2	250	2004	184.861	0.760	0.024	2.560	0.269	0.0021	0.105	981.34
Scrapers	2	250	2004	190.039	0.781	0.025	2.632	0.276	0.0021	0.108	1008.83
Scrapers	2	250	2004	184.861	0.760	0.024	2.560	0.269	0.0021	0.105	981.34
Scrapers	2	250	2004	184.861	0.760	0.024	2.560	0.269	0.0021	0.105	981.34
Rollers	2	50	2005	34.504	0.456	0.018	0.383	0.202	0.0004	0.045	155.00
Rollers	2	50	2005	32.222	0.426	0.017	0.358	0.189	0.0004	0.042	144.74
Rollers	2	50	2005	16.562	0.219	0.009	0.184	0.097	0.0002	0.022	74.40
Rollers	2	120	2004	77.431	0.568	0.017	1.135	0.190	0.0009	0.096	431.47
Skid Steer Loaders	2	120	2004	67.336	0.460	0.012	0.828	0.132	0.0008	0.072	325.53
Skid Steer Loaders	1	120	1999	21.744	0.149	0.004	0.267	0.043	0.0003	0.023	105.12
Other General Industrial Equipment	3	120	2009	101.138	0.765	0.023	1.405	0.251	0.0012	0.135	539.54
Forklifts	3	120	2009	52.246	0.380	0.010	0.629	0.111	0.0006	0.062	248.48
Other General Industrial Equipment	1	1000	2002	403.940	2.003	0.047	5.627	0.526	0.0041	0.179	2155.20
Other General Industrial Equipment	1	1000	2002	116.202	0.576	0.014	1.619	0.151	0.0012	0.051	619.99
Tractors/Loaders/Backhoes	3	120	2009	38.362	0.272	0.007	0.450	0.074	0.0005	0.041	178.89
Tractors/Loaders/Backhoes	2	175	2004	92.734	0.541	0.012	1.105	0.138	0.0010	0.061	437.29
Skid Steer Loaders	1	120	1999	34.791	0.238	0.006	0.428	0.068	0.0004	0.037	168.19
Crawler Tractors	3	250	2008	100.125	0.383	0.012	1.305	0.136	0.0011	0.053	505.99
Scrapers	3	500	2008	403.857	2.251	0.045	4.775	0.500	0.0040	0.193	1891.82
Scrapers	3	500	2008	55.161	0.307	0.006	0.652	0.068	0.0005	0.026	258.39
Tractors/Loaders/Backhoes	2	120	2004	106.646	0.773	0.022	1.439	0.243	0.0013	0.131	555.49
Tractors/Loaders/Backhoes	2	120	2004	102.171	0.740	0.021	1.379	0.233	0.0012	0.125	532.18
Tractors/Loaders/Backhoes	3	120	2009	34.029	0.241	0.006	0.399	0.065	0.0004	0.036	158.68
Tractors/Loaders/Backhoes	3	175	2008	169.849	0.989	0.021	1.878	0.235	0.0019	0.106	755.53

Tractors/Loaders/Backhoes	3	175	2008	131.944	0.768	0.017	1.459	0.183	0.0015	0.083	586.92
Tractors/Loaders/Backhoes	3	175	2008	89.275	0.520	0.011	0.987	0.124	0.0010	0.056	397.11
Rubber Tired Loaders	1	175	1999	63.919	0.386	0.010	0.833	0.106	0.0007	0.046	323.40
			Total	21960.5	105.2	3.0	274.7	33.3	0.244	13.46	107483.4

Appendix N: ICC input data & emissions calculation for site-preparation component of CFET.

DEFORESTATION EMISSIONS:

Type of trees	Area Trees		EF (MT C/ha)	C Conversion	EM (MT of CO_2)
	Acres	ha			
All	247	100	118.2	3.67	43395
1 unit C = 3.67 unit CO_2					

SOIL MOVEMENT EMISSIONS:

Type of Organic soil	Volume of Soil		Area (assuming 1 m depth removed)		EF (MT of C/ha)	C Conversion	EM (MT of CO_2)
	Cubic yds	cubic meters	square meter	ha			
All	2347301	1795685	1795685	180	69.7	3.67	45934
1 unit C = 3.67 unit CO_2							

Total Site-preparation emissions	89328	MT of CO_2

Appendix O: ICC input data & emissions calculation for materials component of CFET.

Cement Type	Portland
Fraction of Clinker (since Portland)	0.96
Clinker Blend (assumed)	65% $CaCO_3$
Emission Factor Used (for $CaCO_3$ blend)	0.51 tons CO_2/ton clinker

Constructed Structure	Quantity of Structure Used (Cubic Yds)	Cement Content in Structure	Quantity of Cement	
			lbs	MT
Place Substructure Concrete	17302	377 lbs/Cubic yd	6522854	2961.38
Place Superstructure Concrete	10203	459 lbs/Cubic Yd	4683177	2126.16
Culvert Wingwalls/Headwalls	2639	459 lbs/Cubic Yd	1211301	549093
Bridge Approach Slabs	11750	459lbs/Cubic Yd	5393250	2448.54
TOTAL			17810582	8086.0

Emissions from cement use	**3958.91**	**MT of CO_2**
Emissions from concrete use on-site (assumed to be 1% of cement emissions)	**0.01(3958.91) = 39.59**	**MT of CO_2**
Emissions from coatings/solvents & fertilizers use on-site (assumed to be 2% of cement emissions)	**0.02(3958.91) = 79.18**	**MT of CO_2**
Total Materials Production Emissions	**118.77**	**MT of CO_2**

Appendix P: ICC input data & emissions calculation for environmental impact mitigation of CFET.

Tree Type	Analogous Tree Type	Quantity	% of Total
Red Maple	Maple/Beech/Birch	144	
Black Gum	Maple/Beech/Birch	144	
River Birch	Maple/Beech/Birch	144	
Silver maple	Maple/Beech/Birch	144	
Sycamore	Maple/Beech/Birch	144	
Musclewood	Maple/Beech/Birch	144	
Red Maple	Maple/Beech/Birch	463	
Black Gum	Maple/Beech/Birch	463	
Sycamore	Maple/Beech/Birch	463	
Red Maple	Maple/Beech/Birch	514	
Sycamore	Maple/Beech/Birch	514	
Black Gum	Maple/Beech/Birch	513	0.38
Swamp White Oak	Oak/Hickory	143	
Northern Red Oak	Oak/Hickory	462	
White Oak	Oak/Hickory	462	
Northern Red Oak	Oak/Hickory	513	
White Oak	Oak/Hickory	513	0.21
Pin Oak	Oak/Pine	144	
Sassafras	Oak/Pine	463	0.06
Yellow Poplar	Spruce/Fir	144	
Eastern Red Cedar	Spruce/Fir	463	
Eastern Redbud	Spruce/Fir	463	
Yellow Poplar	Spruce/Fir	463	
Yellow Poplar	Spruce/Fir	514	
Eastern Red Cedar	Spruce/Fir	513	
RedBud	Spruce/Fir	513	0.36

Persimmon	Spruce/Fir	513	

	Acres	ha
Total Area of Reforestation (1:1)	206	83.43
Tree spacing used for reforestation	(10'x12')	0.0011
Number of trees reforested	75845	

Tree Type	**Percentage of Reforestation Population (%/100)**	**Number of Trees estimated to be planted *[a]** (Total number of trees x Percent population)	**Non-Soil EF (MT of C/ha)**	**EM (MT of CO_2) *[b]**
Maple/Beech/Birch	0.38	28547	2.1	242.02
Oak/Hickory	0.21	15748	2.1	133.51
Oak/Pine	0.06	4567	4.2	77.44
Spruce/Fir	0.36	26982	2.1	228.75
TOTAL	**1.00**	**75845**		**681.72**
*[a] *Rounded up to whole numbers*				
*[b] *Coversion factor used: 1 unit C = 3.67 units* CO_2				

Total area resoiled (assuming 1m depth)	**Acres**	**ha**
	206	83.43
Average soil EF(MT C/ha)	56.26	
C Conversion	3.67	
EM Resoil (MT CO2)	17226.14	

Total Environmental Impact Mitigation	17907.86 MT CO_2

Appendix Q. List of selected equipment given by solution of *OESP* with the given Ω and t=21.

Ω=1 (and Ω=0.9)		Ω=0.1		Ω=0	
Equipment ID*	Quantity	Equipment ID	Quantity	Equipment ID	Quantity
0.ArtA35D	3	0.ArtA35D	3	-	
0.Cr165TN	3	0.Cr165TN	3	-	
0.TGrind6600	1	0.TGrind6600	1	3.ArtT730	17
1.ArtA35D	11	1.ArtT730	13	3.Com815F	1
1.Com815F	1	1.ConcF4800	1	3.ConcF4800	1
1.ConcF4800	1	1.DozD5GLGP	3	3.Cr165TN	3
1.Doz650J	1	1.DozD6N	7	3.DozD65	11
1.DozD5GLGP	2	1.Ex315CL	1	3.Ex315CL	1
1.DozD6N	7	1.FB643J	1	3.Ex325DL	1
1.Ex315CL	1	1.L410J	2	3.Ex330CL	5
1.Ex345CL	4	1.L644G	4	3.FB643J	1
1.FB643J	1	1.Rol50	2	3.Fork10054	6
1.L644G	4	1.Scrap621G	9	3.HB260HP	1
1.Scrap621G	9	1.Skid460D	1	3.L410J	2
1.Skid460D	1	2.Com815F	1	3.L644G	4
2.HB260HP	1	2.Ex345CL	4	3.Rol66	11
2.L410J	2	2.HB260HP	1	3.RolSD110D	1
2.RolSD100D	11	2.RolSD100D	9	3.Scrap621G	9
3.Fork10054	6	3.Fork10054	6	3.Skid648G	1
3.Rol50	2	3.RolSD100D	2	3.TGrind6600	1

***The number that precedes the equipment name indicates the equipments tier level.**

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