ABSTRACT

AROCO ROSA, INGRID DEL MAR. The Impact of Transportation Construction Projects and Activities on Emissions. (Under the direction of William Rasdorf and Joseph Hummer.)

Construction equipment is an important contributor to emissions from construction projects. EPA develops emissions regulations that are followed by equipment manufacturers when producing new equipment. However, there are no national regulations that address emissions related to equipment use or fleet management. The objective of this research is to model emissions from construction projects and to analyze and understand the impact of equipment and activity characteristics in the total emissions. The study will focus on the exhaust pollutants that are included in the EPA NONROAD model for equipment used on construction sites.

The first part of the study included the estimation of construction equipment emissions for various transportation construction projects. The projects included road and utility projects, and highway projects. The calculations included emissions per day, emissions per construction activity, and emissions per equipment. Total project emissions were used to determine emissions metrics including emissions per dollar of bid cost, emissions per day of construction, and emissions per unit of work, that for the transportation projects was emissions per foot of road length. The results were compared to the total emissions and the emissions metrics for a commercial building project that was completed previously.

The data needed to complete these calculations was collected from different sources. Actual construction data was collected from the contractors for all projects. Data collected during construction vary between projects. The contractor’s data was supplemented with data from the RS Means Construction Data publication. Basic equipment characteristics were collected from the Caterpillar Performance Manual. Emissions factors for all the equipment were collected from the EPA NONROAD model.

The second part of the study included the development of an optimization model to select equipment fleet composition to minimize emissions or cost. This part also included a sensitivity analysis that was used to identify the effect of equipment characteristics and schedule changes on construction emissions. The model was developed with multiple
objectives: minimize emissions, minimize cost, or minimize cost with a cap on emissions. The results showed that equipment cost increase if the emissions are minimized. The minimum cost solution includes all Tier 1 equipment while the minimum emissions solution requires all the equipment to be Tier 3. Changing the emissions limit results on a mixed fleet that includes items of different tiers.

The last part of the study included the identification and assessment of the emissions regulations and the incentive programs that are in use currently. Future and possible policies were also identified. Current and future policies were assessed based on the lessons learned from the first two sections of this study and the unique construction industry characteristics.
The Impact of Transportation Construction Projects and Activities on Emissions

by

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1.0 INTRODUCTION

Construction projects produce pollutants that can affect the environment and human health. In 2002 the construction industry emitted 1.7% of the total US greenhouse gases and 6% of the total industry related greenhouse gases [EPA, 2009]. Fuel consumed by on-road and nonroad equipment produced 67% of the greenhouse gas from the construction sector [EPA, 2008b]. Nonroad equipment refers to the equipment and vehicles that are only used on the construction site. On-road equipment refers to vehicles that are operated on the road such as dump trucks.

When studying the environmental effects during the life cycle of a building, the construction phase comprise 1% of the carbon dioxide (CO₂) emissions, 7% of carbon monoxide (CO) emissions, 8% of nitrogen oxide (NOₓ) emissions, 8% of particulate matter (PM₁₀) emissions, and 1% of sulfur dioxide (SO₂) emissions [Guggemos and Horvath, 2006]. When the construction phase is compared with the operations, maintenance, and end-of life the environmental impact seems minimal. However, the construction phase offers many opportunities to decrease the environmental impact and improve the efficiency of the construction industry. Reduction on construction emissions will reduce the exposure for workers and operators that are regularly exposed. The communities surrounding construction projects will also benefit from emissions reductions during the construction phase.

1.1 Study Focus

This study will focus on the environmental impact caused by the nonroad equipment used on construction sites. The most prominent pollutants from construction equipment are emitted through the exhaust and include:

- Hydrocarbons (HC)
- Nitrogen oxide (NOₓ)
- Carbon monoxide (CO)
- Particulate matter (PM$_{10}$)
- Fine particulate matter (PM$_{2.5}$)
- Sulfur dioxide (SO$_2$)
- Carbon dioxide (CO$_2$)

Other pollutants are emitted by other parts of the equipment beside the exhaust. For example, particulate matter can be produced when the tires carry dust outside of the construction site or simply when vehicles travel over unprepared or unpaved runways. Other pollutants can be emitted by other parts of the vehicle like the crankcase or the fuel tank. For this study, I will be focusing on the pollutants emitted by the engine exhaust system.

1.2 Emissions Measurements and Estimates

Air pollutant emissions are measured in different ways. One way is to measure emissions produced by the engine while it is running. These field measurements are taken using a portable emissions measurement system (PEMS). This measurement system is installed on the vehicle and it will measure emissions from the exhaust and the work done by the engine. Data collected by this instrument can be used to calculate the amount of emissions from each item of equipment and to relate emissions to equipment workload and duty cycles.

Emissions from construction equipment may be estimated using computer simulation programs. The simulation of equipment use offers the opportunity to estimate emissions for different equipment types and working conditions. This technique is used to estimate emissions from a construction activity or a construction project without installing a PEMS on every item of equipment used on the project.

Emissions may also be estimated using emissions rates from the EPA NONROAD model. The emissions rates in the model are produced using engine dynamometer tests. However, during these tests, the engine is not in the equipment chassis and the measurements may not
accurately represent the workloads that construction equipment experience while at work in the field. However, these published and widely available emissions rates can be used to estimate emissions from particular items of equipment or to determine total emissions for a construction activity or project.

Another technique used to estimate construction emissions is life-cycle models. A life-cycle model includes all of the different phases of the construction project. A typical life-cycle model includes material manufacturing and transportation, construction activities, facility use, operation and maintenance, and end-of-life components. The result of a life-cycle model represents the expected total environmental impact of a structure. Thus, it should be mentioned that the study proposed here will focus on emissions produced by construction equipment on the construction site.

This thesis uses the emissions rates generated by the EPA NONROAD model as a basis for the results derived herein.

1.3 Problem

Emissions from construction equipment are harmful to humans and to the environment. EPA regulations have the objective of reducing the amount of pollutants emitted from construction equipment diesel engines. These regulations apply to equipment manufactured after the regulation is in place. However, it is important to have an accurate estimate of the amount of pollutants emitted by construction equipment or an equipment fleet on a construction activity or construction project basis. The emissions rates for each engine are controlled by the engine specifications, but the total amount of pollutant emissions is controlled by the activities performed by the equipment on a specific site.

The emissions factors presented by EPA in the NONROAD model can be used to estimate total emissions from each item of equipment based on its engine characteristics. However, one drawback is that these emissions factors do not take into consideration the characteristics
of each construction project and the particular fleet of equipment used for each activity. A model can be developed to estimate the quantity of emissions based on construction activities performed and the specific equipment used. The development of such a model was one of the key objectives of this thesis.

Having an accurate emissions model would enable contractors, designers, and government agencies to quantify pollutants produced on a variety of construction sites. Designers can use the emissions estimation to make decisions between preliminary design alternatives taking into consideration the environmental and health effect of each one. Contractors can use the emissions estimation to select construction techniques or materials that would reduce the amount of emissions produced by critical construction activities. New regulations can be drafted by local and federal agencies to regulate the quantity of emissions produced by a construction site or by an equipment fleet. An accurate estimation model is imperative to make these types of regulations possible.

A sensitivity analysis can be performed based on a well-understood knowledge base and model to determine the effects of different factors on the emissions quantities. Emissions production can be affected by the characteristics of both the equipment used and the construction project. Characteristics of the equipment include type of equipment, engine power, manufacture year, and EPA regulation tier. Characteristics of the construction project include project size, project type, cost, and duration. Other factors that can have an effect on emissions are the experience of the operator, terrain conditions, and weather conditions. Having a better understanding of the effects of each characteristic could help construction professionals make well-founded decisions to reduce emissions on a particular project.

1.4 Research Tasks

This study has four research tasks.
1. Estimate emissions from different transportation construction projects using information about construction activities collected from contractors.

2. Calculate emissions rates as emissions per day, emissions per construction activity, and emissions per unit of production (e.g., length of road paved). These emissions rates were used to compare different transportation and a commercial building construction projects.

3. Develop an optimization model to determine the equipment fleet needed to minimize emissions, equipment cost, or a combination of the two factors.

4. Make policy recommendations based on the findings from this study, taking into consideration characteristics of the industry and the incentives and regulation policies that are currently in place.

Completing these objectives will result in a better understanding of the factors that affect total emissions from construction projects.

1.5 Scope

The pollutants considered in this study include only those characterized by the EPA NONROAD model as exhaust pollutants. The EPA NONROAD model includes emissions rates for pollutants produced in different parts of the engine, but only the rates for exhaust pollutants will be studied herein. Exhaust pollutants include NO\textsubscript{x}, PM, CO, HC, CO\textsubscript{2}, and SO\textsubscript{2}.

This study will include construction equipment with diesel engines that are not on-road vehicles. Some on-road trucks are commonly used on construction projects to deliver materials; however, these trucks are not included in the emissions calculation. This study will focus particularly on equipment with diesel engines, which generally are the major pollutants on a construction project. The following list shows some examples of the equipment types that will be used in this study.
• Backhoes
• Bulldozers
• Cranes
• Excavators
• Front-end loaders
• Motor graders
• Paving equipment
• Rollers
• Scrapers

Emissions are estimated for different types of construction equipment. Estimates from a variety of projects help to identify project characteristics that directly affect emissions. The construction project types used during this study include commercial buildings and transportation infrastructure projects. Project schedules are studied to identify the effect of schedule delays or adjustments and activity performance on emissions quantities.

The emissions estimated during this study will only include those emitted from activities performed on the construction site. Emissions will be estimated for nonroad vehicles and equipment directly used to perform a construction activity on the construction site. This study will not include a life-cycle analysis of other activities that take place outside of the construction site such as material manufacturing and transportation.

The data used for this study comes from four different sources, three of which are currently available to construction engineers and contractors. The emissions factors for each item of equipment were obtained from the EPA NONROAD model. This model is available online at no cost. Construction activity information was acquired from RS Means [Means, 2014]. RS Means is a resource readily available for contractors. The Caterpillar Performance manual [CAT, 2013] provided otherwise unavailable information about specific items of equipment.
including engine horsepower. Using easily obtainable and familiar data sources helps contractors, policy analysts, and other professionals use the estimation model more easily. The fourth source of data is field measurements. These data are used to develop improved emissions factor models.

Research was conducted at the construction company and equipment fleet levels. Emissions can be regulated by limiting emissions rates from individual items of equipment or by limiting the total amount of pollutants by construction project or by the equipment fleet. Fleet regulation will require additional management to ensure that emissions are allocated in the most efficient way.
2.0 LITERATURE REVIEW

The following sections summarize the literature relevant to pollutant emissions from construction equipment. The literature review was divided according to the equipment, pollutants, pollutant’s effect on human health, analysis techniques, and available data sources that could be used to perform the study. Numerous other topics are mentioned and addressed in the primary literature related to emissions. Some additional topics are also presented at the end of the Literature Review Section so that the reader can gain a full understanding of the scope of this subject matter.

2.1 Equipment

Studies of construction equipment emissions have focused on different types of equipment. Table 2.1 summarizes the most relevant papers by equipment types presented in each study. The “Reference” column in Table 2.1 show the reference used in the text for each paper and the year of publication. “Research Group” presents the name of the institution where the study was performed: North Carolina State University (NCSU), Columbia University (CU), University of California – Berkeley (UCB), or Carnegie-Melon University (CMU). The “Equipment” columns present the equipment types used for each study. An X means that the equipment type was studied and a dash means that the equipment type was not used for the study.

Studies performed by NCSU measured emissions from eight different equipment types. Rasdor et al. [2010b] presented a methodology to measure emissions from construction equipment during real-world activities. The methodology was used to collect data from backhoes, bulldozers, excavators, generators, motor graders, off-highway trucks, rubber tire loaders, track loaders, and skid-steer loaders. The papers by Frey et al. [2010] and Lewis et al. [2009b] presented results from emissions measured from backhoes, bulldozers, excavators, generators, motor graders, nonroad trucks, and skid-steer, track, and wheel loaders.
## Table 2.1. Summary of Papers by Equipment Used for the Study

<table>
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<tr>
<th>Reference</th>
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</table>
Other studies focused on emissions from backhoes, front-end loaders, and graders. In Frey et al. [2008b] 15 items of equipment from different tiers were measured twice, one with petroleum diesel and one with B20 biodiesel. Emissions from bulldozers, nonroad trucks, excavators, Backhoes, front-end loaders, and skid-steer loaders were used in Frey et al. [2007] to present the real-world measurement methodology and the emissions by task mode. Lewis et al. [2009a] presented a methodology to create an emissions inventory using emissions from backhoes, front-end loaders, graders. The inventory included information about emissions rates, average annual fuel use, and estimated average annual emissions. A life cycle analysis was performed by Pang et al. (2009) that measured emissions from 15 items of equipment including backhoes, front-end loaders, and motor graders.

The NCSU research group also presented studies that focus on a specific type of equipment. Abolhasani et al. [2008] studied emissions from excavators and used task-oriented modes. The task-oriented mode included idling, using the bucket, and moving. In Frey et al. [2008a] emissions from motor graders were used to study differences between petroleum diesel and biodiesel. Emissions were also measured using duty cycles to characterize the work done by the equipment. Bulldozers were used in Lewis et al. [2011] to present the effect of operational efficiency on construction equipment emissions. Rasdorf et al. [2010a] used data from RS Means and the NONROAD model to estimate emissions from 200- and 300-horsepower bulldozers while performing a topsoil stripping activity.

The Columbia University research team used simulation to estimate emissions from bulldozers, excavators, graders, and nonroad trucks [Ahn et al. 2009]. Another simulation was created to estimate emissions from an operation that included nonroad trucks, bulldozers, graders, and excavators [Anh et al. 2010a]. Results from this study showed that the bulldozer emitted the largest amount of all the equipment tested. The study presented in Ahn et al. [2010b] measured carbon footprint and energy consumption during tunneling construction activities. The equipment used for this study was a tunnel-boring machine, a train, and a crane. Hajibabai and Peña-Mora [2009] presented a study where emissions from a
construction activity that included concrete mixer trucks and concrete pumps were estimated. The objective of the study was to present greenhouse gas emissions according to the location at the job site where they were emitted using GIS visualization.

The research group at Carnegie Mellon University (CMU) studied energy consumption for generators used on a construction site [Sharrard et al. 2007]. The study included gasoline and diesel generators. Other researchers at CMU developed a life-cycle assessment of the construction process [Bilec et al. 2006]. The assessment included emissions and fuel use of excavators, backhoes, skid-steer loaders, and cranes.

Studies from the University of California at Berkley focused on emissions from heavy-duty highway trucks. The first study measured the emissions of PM and hydrocarbons from all vehicles driving through a tunnel in California [Miguel et al. 1998]. The vehicles driving through the tunnel included light duty vehicles and heavy-duty diesel trucks. Another study measured VOC and NOx emissions while heavy-duty trucks were driving through the same tunnel in California [Ban-Weiss et al. 2008a]. Ban-Weiss et al. [2008b] performed a study comparing PM2.5 and NOx emissions from light duty vehicles, medium duty vehicles, and heavy-duty on-road trucks measured in 2006 with measurements from previous years. The measurements used for comparison were collected at the same location, a tunnel in California. Ban-Weiss et al. [2009] presented a study that measured PM emissions from 226 individual heavy duty trucks while driving through the California tunnel. Marr et al. [1999] measured the amount of hydrocarbon in the fuel and exhaust emissions from gasoline light duty vehicles and heavy duty diesel trucks.

In 2010, Millstein and Harley presented a study that analyzed the effects of retrofitting emissions controls on on-road heavy duty diesel trucks. A study from West Virginia University [Clark et al. 2002] looked at emissions of heavy duty diesel vehicles and how different factors affect emissions during real world activities. The study included tractor trucks, transit buses, telephone trucks, box trucks, line haul tractors, and refuse trucks.
Other studies looked at the life cycle analysis of the construction phase. These studies included emissions produced during material production and transportation to the construction emissions. Guggemos and Horvath [2005] and Guggemos and Horvath [2006] identified cranes, air compressors, concrete mixers, concrete pumps, forklifts, power saws, and backhoes as the equipment types used on the construction site. In 2003, Park et al. looked at the life cycle of highway construction projects. The equipment used for the construction phase analysis included bulldozers, nonroad trucks, excavators, graders, backhoes, cranes, air compressors, concrete mixers, and concrete pumps.

In 2005, Muleski et al. measured PM from earth moving activities that were performed by bulldozers, scrapers, and nonroad trucks. The PM measured in this study only included dust carried out by the equipment tires and not PM emissions from the exhaust.

2.2 Pollutants

The pollutants addressed in this study are those identified by the NONROAD model as exhaust pollutants and include HC, CO, NOx, PM, CO2, and SO2. The literature presents numerous studies that investigate some combination of these pollutants. Tables 2.2 and 2.3 present a summary of the papers included in the literature review by the pollutants examined for each study. The first two columns present the reference, year of publication, and the institution where the study was performed. The following columns present the pollutants. The pollutants examined for each paper are marked by an X. The pollutants not examined in the study are marked with a dash.

The majority of the papers included in this literature review deal with emissions for the six primary pollutants emitted by the exhaust system of diesel engines. These pollutants are particularly important for studies that include measuring emissions during equipment use because they can be measured directly from the exhaust air. CO2 is produced when...
carbonaceous fuel is burned and its emissions quantity is directly correlated with fuel use [Abolhasani et al. 2008].

Engine and equipment characteristics affect the quantity and type of pollutants emitted by each item of equipment. The manifold absolute pressure (MAP) of the engine is highly correlated with NO, PM, CO, HC, and CO₂ emissions [Frey et al. 2007, Frey et al. 2008b]. A study by Guggemos and Horvath [2005] shows that age of the equipment affects the quantity of emissions. Increasing the age of the equipment from 2 to 10 years increased CO, NO₂, and HC emissions between 30% and 68%.

Emissions rates can be different for different equipment types. In a study that compared backhoes, front-end loaders and motor graders, Lewis et al. [2009a] showed that front-end loaders have the highest emissions rates for NO; backhoes have the highest emissions rates for PM and CO; and motor grades have the highest emissions rates for HC. The study also showed that equipment with engines that comply with recent regulations has a lower emissions rate than equipment with older engines.

Particulate matter will be included in this study as an exhaust pollutant. However, PM can also be produced by mechanical activities that create dust. Kinsey et al. [2004] studied the creation of PM by the carryout of mud or dirt outside of the construction site. Muleski et al. [2005] presented five studies that identified sources of PM emitted by a construction project. Emissions were measured during different activities including controlled earthmoving, uncontrolled earthmoving, and truck loading and dumping. Mud and dirt carryout emissions were also measured and ideas were presented to control these emissions. The control technique studied was the watering of the travel routes on the construction site. Results show that watering becomes counterproductive if the moisture content of the soil is greater than 10%. Watering can reduce dust but it can also increase the amount of dirt and mud carried off the site by trucks.
A major contributor to greenhouse gases is CO₂ [IPCC 2013]. However, other gases can contribute to the greenhouse effect and to the climate change situation. Baouendi et al. [2005] presented a measure called global warming potential (GWP) as a way to demonstrate the effect of gases including CO₂, NO₂, and nitrous oxide (N₂O) as the equivalent effect of CO₂ for the construction of houses in Canada. The GWP coefficient compares the greenhouse effect of one gram of a given gas compared with the effect of one gram of CO₂. The GWP coefficients for NO₂, and N₂O are 23 and 275, respectively, when looking at a 100-year period.

During a life-cycle assessment of building construction, Bilec et al. [2006] used GWP to compare the effect of pollution from construction to the equivalent greenhouse effect of CO₂. Transportation of materials was the heaviest producer of CO₂ equivalent pollution followed by construction equipment.

Hendrickson and Horvath [2000] developed an assessment of the environmental emissions from construction in the US divided into four sectors: highway, commercial, residential, and other new construction. The GWP as ton CO₂ equivalent was presented for the construction activities of these four sectors that included emissions from the supply chain. Junnila and Horvath [2003] completed a life-cycle assessment of an office building. This study presented emissions in terms of their possible effects on different aspects of the environment: climate change, acidification, summer smog, eutrophication (which Cloern [2001] describes as the addition of nitrogen and phosphorus to surface and ground water that can stimulate plant growth and affect the balance of organic matter in coastal zones ), and heavy metals. Each one of these effects was presented as an equivalent to one pollutant. For example, climate change was presented as tons of CO₂ equivalent. Results from this paper showed that when construction is compared to all the other activities during the life cycle of the building the climate change effect is not significant.
### Table 2.2 Summary of Papers by Pollutants Studied

<table>
<thead>
<tr>
<th>Reference</th>
<th>Research Group</th>
<th>Pollutant</th>
<th>Fuel/Energy</th>
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<tr>
<td>Abolhasani et al. (2008)</td>
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<td>Guggemos &amp; Horvarth (2005)</td>
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<td>Park et al. (2003)</td>
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Table 2.3 Summary of Papers by Pollutants Studied

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<th>HC</th>
<th>CO</th>
<th>NOx</th>
<th>PM</th>
<th>CO2</th>
<th>SO2</th>
<th>CO2 Equivalent/ G</th>
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Lee et al [2009] presented a methodology to measure greenhouse gas emissions in real time using a wireless sensor. No specifics are offered about which pollutants were measured to determine the amount of greenhouse gas produced. The objective of the study was to develop a measuring system that can be used for emissions trading programs where areas with low emissions can trade with areas with high emissions.

Emissions from transportation facilities were studied by Matthews et al. [2001] using a life-cycle approach. Emissions were presented for CO, NOx, SO2, PM, VOC, and CO2 equivalents as global warming potential. In a study by Shiftehfar et al. [2010a], a visualization system was proposed to understand the quantity of GHG emitted by construction activities. The visualization system calculated the quantity of CO2 and represented this amount using the number of trees needed to compensate for this quantity.

Volatile organic compounds (VOCs) are also included in some studies, particularly the life-cycle studies. Guggemos and Horvath [2005] presented a comparison between the
construction of steel frame and concrete frame buildings. Results showed that when looking at the life-cycle, steel frame buildings are higher in VOC emissions. In Guggemos and Horvath [2006], the life-cycle tool showed that even when equipment use was responsible for 50% of the environmental effects from the structural frame, equipment is not a significant contributor to VOC emissions. The life-cycle analysis presented by Bilec et al. [2006] was used for a case study that showed that the major contributor of VOC emissions is the transportation of material to the construction site (1,420 kg) followed by the use of equipment with diesel engines (445 kg) on the construction site. Matthews et al. [2001] included VOC emissions in the life-cycle analysis of transportation systems. Hendrickson and Horvath [2000] included VOC emissions in their emissions analysis of the US construction sector. Sharrard et al. [2007] presented VOC emissions from on-road and nonroad trucks and equipment, focusing on emissions from generators used on the construction site. Sharrrad et al. [2008] included VOC emissions when comparing the environmental effects of construction activities for case studies.

Fuel and energy use is an important component when studying diesel engine emissions. The quantity of emissions for some of the pollutants is directly related to the amount of fuel or energy used during an activity. Engine MAP is highly correlated with fuel use as presented in Frey et al. [2008b]. Frey et al. [2008a] studied the effect of changing petroleum diesel with B20 biodiesel. They concluded that using B20 will result in a reduction of PM, CO, and HC emissions but NOx emissions will not change. The study by Lewis et al. [2009a] showed that the use of B20 fuel combined with newer cleaner engines will result in a significant reduction of pollutant emissions. Fuel-based emissions rates are less variable when comparing items of equipment from different models and tiers. For this reason, it is preferable to create emissions inventories that use fuel use rather than operation time to quantify emissions [Frey et al. 2010].

Pang et al. [2009] created a life cycle inventory for soy-based biodiesel to calculate a change in total emissions when compared with petroleum diesel. Life cycle emissions were higher for NOx and HC and lower for PM and CO.
2.3 Effects of Pollutants Emitted by Construction Equipment

Air pollutants emitted to the atmosphere can have effects on the environment and on human health. The effect of each pollutant depends on the chemical characteristics and the processes that produce each pollutant. The following subsections describe the effect on human health and the environment of some of the pollutants emitted by construction equipment.

This section and the proposed study focus on pollutants listed in Tables 2.2 and 2.3. The first six pollutants (HC, CO, NOx, PM, CO2, and SO2) are addressed in the subsections below. Tables 2.2 and 2.3 also list other pollutants that were addressed in the literature although those are not addressed directly in this section of the study.

2.3.1 Hydrocarbons

Hydrocarbons (HC) are produced by incomplete combustion or by the evaporation of organic liquids. One of the effects of HCs is that they react with NOx in the presence of sunlight to form ozone. Ground level ozone is a pollutant that can irritate eyes, nose, and throat. Ozone can also damage vegetation and other materials such as paint and textiles. Hydrocarbons are sometimes called volatile organic compounds (VOCs). The majority of VOCs do not have negative effect on human health. However, some VOCs can affect the growth of plants. A few VOCs are carcinogenic and odoriferous VOCs can cause displeasure because of the smells [Cooper & Alley, 2011].

2.3.2 Carbon Monoxide

Carbon monoxide (CO) is released into the environment when fuel is not burned completely during combustion. The majority of CO emissions come from vehicle engines but it is also produced during forest fires, residential wood burning, and industrial processes. When CO enters the lungs, it can get into the bloodstream and affect other internal organs. People with heart conditions can be particularly affected by CO causing chest pain and affecting the ability
to exercise. Exposure to high concentrations of CO cause vision problems, reduce ability to work, reduced manual dexterity, and difficulty performing difficult tasks. Very high concentrations of CO can cause death (EPA 2008a).

2.3.3 Nitrogen Oxide

The nitrogen oxide (NOX) family includes nitric oxide (NO) and nitrogen dioxide (NO2). NO is emitted when fuel is burned at high temperatures. NO2 is formed when NO is oxidized in the atmosphere. NO2 affects the respiratory system by decreasing lung function to individuals with pre-existing conditions when exposed for a short term. Long-term exposure can cause permanent damage to the lungs [EPA 2008a].

Environmental effects of NOX are related to its interaction with other substances to produce different chemical compounds that can be prejudicial to human health and the environment. NOX reacts with organic volatile compounds in presence of sunlight to produce ground level ozone. The reaction of NOX with ammonia and moisture produces nitric acid and particle nitrates. NOX also affects visibility and aids to the formation of acid rain [EPA 2008a].

2.3.4 Particulate Matter

Particulate matter (PM) is the term used to identify solid or liquid particles present in the air. Particulates with aerodynamic diameter of 2.5 micrometers or less are known as PM2.5. PM10 refers to particulates with aerodynamic diameter of ten micrometers or less. PM2.5 particulates are small and are usually formed in the atmosphere when gases such as sulfur dioxide (SO2), NO2, and volatile organic compounds react with each other. Larger particles, PM10, are directly emitted from sources such as construction sites and fires [EPA 2008a].

Some of the environmental effects of PM include reduced visibility and damage to ecosystems. Some particulates can be small enough to enter into the respiratory system and the lungs. Some possible health effects associated with PM [EPA 2008a] include:
• Respiratory symptoms like irritation, coughing, and difficulty breathing,
• Decreased lung function,
• Aggravated asthma,
• Chronic bronchitis,
• Irregular heartbeat,
• Heart attack, and
• Premature death.

2.3.5 Carbon Dioxide

Carbon dioxide (CO₂) is the main greenhouse gas and is released to the environmental both by natural and human activities. CO₂ is released while exhaling during the human respiration process and by burning gasoline, coal, oil, or wood. Even while CO₂ has a negative effect on humans and the environment, cases of CO₂ poisoning are rare. However, because CO₂ is a colorless and odorless gas, poisoning can occur without much notice. High concentrations of CO₂ can cause headaches, dizziness, and nausea. At extremely high concentrations, CO₂ can cause death by asphyxiation because it can replace oxygen in the blood [MDH 2010].

2.3.6 Sulfur Dioxide

Sulfur dioxide (SO₂) is produced when fuel that contains sulfur is burned. Other processes that produce SO₂ are extracting metals from ore and extracting gasoline from oil. Health effects caused by SO₂ are particularly problematic for individuals in sensitive groups like children, the elderly, asthmatics, and people with heart and lung diseases. SO₂ can gather in the lungs and produce respiratory disease, difficulty breathing, and premature death. SO₂ is the major cause of reduced visibility and is also a precursor of acid rain [EPA 2008a].
2.4 Analysis Technique

Different techniques are used to analyze pollutant emissions data. Table 2.4 presents a summary of the papers included in the literature review organized by the analysis technique used for each study. The first two columns present the reference and year of publication and the institution where the study was performed. The remaining columns present the analysis techniques. The techniques used for each paper are identified by an X. The techniques not used in the study are identified by a dash.

The analysis techniques used for emissions analysis can be grouped in three broad categories: simulation, statistical analysis, and life-cycle analysis. The following list presents how the techniques are divided between the major categories.

- Computer simulation
  - Discrete-element simulation
  - Bootstrap simulation
  - Monte Carlo simulation
  - GIS simulation model
  - Special model simulation
- Life-cycle analysis
  - Process-based life-cycle assessment
  - Input-output
- Community multiscale quality
- Statistical analysis
<table>
<thead>
<tr>
<th>Reference</th>
<th>Research Group</th>
<th>Analysis Technique</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Discrete-Event Simulation</td>
</tr>
<tr>
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<tr>
<td>Ahn et al. (2009)</td>
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<td>Ahn et al. (2010a)</td>
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<td>Ban Weiss et al. (2009)</td>
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<tr>
<td>Bilec et al. (2006)</td>
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<tr>
<td>Bilec et al. (2010)</td>
<td>CMU</td>
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<tr>
<td>Frey &amp; Bammi (2003)</td>
<td>NCSU</td>
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<tr>
<td>Guggemos &amp; Horvath (2005)</td>
<td>Other</td>
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<td>Guggemos &amp; Horvath (2006)</td>
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<td>Hajibabai &amp; Peña-Mora</td>
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<td>Ochoa et al. (2002)</td>
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<td>Pang et al. (2009)</td>
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<td>Park et al. (2003)</td>
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<td>Shiftehfar et al. (2010a)</td>
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<tr>
<td>Zapata &amp; Gambatese (2005)</td>
<td>Other</td>
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</table>
The analysis techniques used for emissions analysis can be grouped in three broad categories: simulation, statistical analysis, and life-cycle analysis. The following list presents how the techniques are divided between the major categories.

- **Computer simulation**
  - Discrete-element simulation
  - Bootstrap simulation
  - Monte Carlo simulation
  - GIS simulation model
  - Special model simulation
- **Life-cycle analysis**
  - Process-based life-cycle assessment
  - Input-output
- **Community multiscale quality**
- **Statistical analysis**

Computer simulations can be used to predict the quantity of emissions produced during an activity. Discrete-event simulation (DES) was used in Ahn et al. [2009] to more accurately determine equipment operating time and to make a more realistic estimate of duty cycles. An earthmoving activity was used by Ahn et al. as a case study to estimate emissions by using the emissions factors for each duty cycle (moving, idling, digging, hauling, and dumping). The simulation was used to estimate emissions for different scenarios with different numbers of trucks and different routing strategies. In another study by Ahn et al. [2010a], a topsoil stripping activity was used as a case study in to calculate total activity emissions quantities. These quantities were compared to emissions calculated using the emissions factors from the NONROAD model. The emissions quantity estimated by the simulation was less than the quantities calculated using the NONROAD model.
DES was also used to estimate emissions from a tunneling activity [Ahn et al. 2010b]. The tunneling activity included a crane and a tunneling machine. Emissions from the crane were calculated using the NONROAD model. Emissions from the tunneling machine were calculated using the electrical energy consumption.

A Monte Carlo simulation technique was used in Pang et al. [2009] to calculate the uncertainties for the inputs and outputs of a life-cycle inventory of biodiesel and petroleum diesel.

The framework for managing emissions presented in Peña-Mora et al. [2009] included special purpose simulation modeling (SPS) to be used by construction professionals to simulate every day equipment operations like waiting time and different parameters that affect working time.

Life-cycle modeling was used to analyze the effect of a construction project taking into consideration every activity needed to complete the project from conceptualization through operation and salvage. Studies have been developed to estimate the environmental effect of building and infrastructure construction projects. In Bilec et al. [2006], a life-cycle model was used to study building a concrete parking deck. The study included the environmental effects from material transportation, construction equipment, on-site activities, construction services, production and maintenance of construction equipment, and on-site electricity and water consumption. The authors presented the possibility to include an emissions cost factor in the bid process to account for environmental impacts. In Bilec et al. [2010], the model was used to study a steel frame building. The author concluded that even when construction is responsible for only a small part of the total emissions, PM emissions due to construction are significant when compared with the other life cycle phases.

The environmental impact of a concrete structural frame building and a steel frame building were compared in Guggemos and Horvath [2005]. Results from a life-cycle analysis show that a concrete building has higher energy use and a higher production rate for CO₂, CO, NO₂, PM₁₀, SO₂, and HC. A steel building is associated with more volatile organic compounds and
heavy metals. Emissions from the construction phase were compared with emissions from the other life-cycle phases in another building case study [Guggemos and Horvath, 2006]. The construction phase was responsible for 2% of the energy consumption, 1% of CO\textsubscript{2} emissions, 7% of CO emissions, 8% of NO\textsubscript{x}, 8% of PM\textsubscript{10}, and 1% of SO\textsubscript{2}. The low percentage is due to the long operation phase compared with the short construction period.

A life-cycle analysis of a commercial building in Finland showed that the construction phase is not a significant impact category [Junnila and Horvath, 2003]. However, it was determined that the use of construction equipment is the only element with significant impact in the construction phase. In Junnila et al. [2006], the analysis of the Finnish building was compared with an office building in the United States. The emissions distribution was the same for both buildings, however, the total quantity of emissions and energy used were different. The Finnish building used a third of the energy and emitted half the CO\textsubscript{2}, a third of the NO\textsubscript{x}, and a fifth of the PM. The difference is due to the energy sources used during the operation phase.

The residential building sector was studied in Ochoa et al [2002]. The life-cycle analysis included the whole supply chain of materials and services. The study found that the construction phase had the largest contribution to toxic air emissions and hazardous waste while the usage phase has the largest energy use and greenhouse gas emissions. Baouendi et al. [2005] used life-cycle analysis was used to study the operation and construction of a house exterior. This study found that 6% of the energy was used, and 9% of the equivalent CO\textsubscript{2} emissions were produced, during construction.

The environmental impact of a highway project life cycle was studied in Park et al. [2003]. The study focused on energy use that was calculated in tons of oil equivalent (TOE). The results showed that manufacturing of construction materials used the highest amount of energy. During the construction phase, it was found that the fuel used by dump trucks represented 94.5% of the energy used during earthwork. Based on this numbers, the study showed that efficient management of the dump truck operations can impact energy use.
The studies that measured emissions from construction equipment collected a large amount of data about emissions quantities, engine load data, and specific tasks. Statistical analysis was used to identify correlations and other statistical relations between engine loads and emissions factors. In Abolhasani et al. [2008], coefficients of determinations (R²) were calculated to determine the correlations of pollutants emissions with engine characteristics such as the manifold average pressure (MAP), engine speed, intake air temperature, and fuel use. Results showed that the correlation between NO and fuel use was very strong with a R² between 0.91 and 0.97 for the three excavators studied.

2.5 Data Sources

Tables 2.5 and 2.6 present a summary of the papers included in the literature review organized by the data sources used for each study. The first two columns present the reference and year of publication, and the institution where the study was performed. The remaining columns present the data sources. The sources used for each paper are identified by an X. The sources not used in the study are identified by a dash.

The majority of the papers presented in this literature review used real-world measurements to collect data and then to analyze emissions. These included emissions quantities measured during daily activities and other information from construction projects and the construction industry. The NCSU research group measured emissions from equipment of different sizes and tiers. The equipment used to measure emissions also measures engine characteristics. The data can be used to correlate emissions with engine characteristics.

NCSU developed a procedure to measure emissions from real-world activities of construction equipment [Rasdorf et al. 2010b, Frey et al. 2007]. Data collected with this procedure included emissions data, visual data, construction site information, and vehicle activity data. Information collected during real-world measurements was used to create an emissions inventory. Emissions information was combined with fuel use and vehicle characteristics to
create an inventory that can be used to calculate emissions rates [Lewis et al., 2009a]. In-use equipment emissions and fuel use measurements were made using a portable emissions monitoring system (PEMS) that can measure second-by-second emissions for NO, CO, CO₂, HC, and PM. PEMS was also used to collect information about the engine as manifold absolute pressure (MAP), intake air temperature (IAT), and revolutions per minute (RPM) [Lewis et al., 2009b].

The methodology developed to collect data during construction activity was used to measure emissions from different equipment types. PEMS was used to measure emissions from dump trucks [Frey and Kim, 2006], excavators [Abolhasani et al., 2008], and motor graders [Frey et al., 2008a]. In Frey et al. [2008b], emissions were measured for backhoes, front-end loaders, and motor graders of different engine tiers and using both diesel and biodiesel fuel. A study of 39 items of equipment that included backhoes, bulldozers, excavators, generators, motor graders, trucks, skid-steer loaders, track loaders, and wheel loaders was develop to create a large data base of emissions information [Frey et al., 2010]. The database was used to calculate time-based fuel use and emissions rates, and fuel-base emissions rates. Measurements from bulldozers were used to assess the effect of operational efficiency on emissions from construction equipment [Lewis et al., 2011]. Results showed a difference in emissions rates for idle and non-idle modes but few other differences.

Equipment is not the only source of PM on a construction site. The dust produced by other activities is also considered PM emissions. The dust and mud on on-road construction equipment tires can be transported outside the construction site. Muleski et al [2005] and Kinsey et al [2004] measured particles produced by the mud and dust carryout by construction equipment. Mulesky et al [2005] tested the PM emissions during a loading and dumping activity using a dump truck and small loader. The results showed that emissions were 100 times greater during loading. The study by Kinsey et al. [2004] measured PM on the road outside a construction site. The data collected showed that emissions of PM_{2.5} were minimal. However, PM_{10} emissions were about 6 grams per vehicle.
The NONROAD model is an important source of emissions information. The emissions factors presented by the model can be used to estimate emissions using different techniques including computer simulation, statistical analysis, and life-cycle analysis as discussed in the previous section. The NONROAD model can be downloaded from the internet and used by contractors and other construction professionals to estimate emissions for different construction projects. A detailed explanation of the NONROAD model will be given in a following section.

Measurements from real-world activities have been compared with emissions estimations developed using emissions factors from the NONROAD model. Emissions factors estimated from field measurements were comparable with emissions factors derived from the NONROAD model [Lewis et al., 2009b, Abolhasani et al., 2008]. Emissions estimation from NONROAD was also compared with estimates from DES [Ahn et al., 2010a]. Results showed that estimates from the NONROAD model are higher than estimates from the simulation method. The reason for the difference is that the simulation method used emissions rates that were different from the ones in the NONROAD model. Emissions estimates can also be developed by multiplying the NONROAD emissions rates by the activity duration estimates from RS Means [Rasdorf et al., 2010a]. Emissions estimates for all activities can be summed up to obtain an estimate of emissions for an entire construction project.
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<thead>
<tr>
<th>Reference</th>
<th>Research Group</th>
<th>Data Source</th>
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<tbody>
<tr>
<td>Abolhasani et al. (2008)</td>
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<td>Lewis Dissertation</td>
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<td>Other EPA Reports</td>
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<td>CU</td>
<td>EPA Highway Vehicles:</td>
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<td>UCB</td>
<td>Real World Measurements</td>
</tr>
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<td>UCB</td>
<td>RS Means</td>
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<tr>
<td>Baouendi et al. (2005)</td>
<td>Other</td>
<td>Surveys</td>
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<td>Clark et al. (2002)</td>
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<td>Frey &amp; Kim (2006)</td>
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<td>Frey et al. (2007)</td>
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<td>Frey et al. (2008a)</td>
<td>NCSU</td>
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<td>Frey et al. (2008b)</td>
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<td>Frey et al. (2010)</td>
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<tr>
<td>Guggemos &amp; Horvarth (2005)</td>
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<tr>
<td>Junnila et al. (2006)</td>
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Table 2.6. Summary of Papers by Data Source (cont.)

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<td>Zapata &amp; Gambatese (2005)</td>
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</table>

Emissions estimates created using the NONROAD model can be used to create more complex estimation tools. For example, simulation can be used to estimate time of work and NONROAD emissions factors are multiplied by the time to estimate total emissions [Ahn et al., 2010b]. An emissions inventory for California was created using the emissions rates from the NONROAD model combined with information from the local construction industry, population data, fuel sale data, and other emissions rates from the OFFROAD model developed by the California Air Resource Board (CARB) [Millstein and Harley, 2009].

Lewis [2009] presented emissions rates calculated from duty cycle information measured from 34 items of equipment. The emissions rates calculated by Lewis were included in the simulation model presented in Ahn et al. [2010a] and Ahn et al. [2010b].

RS Means is a commonly used information source for activity and productivity data. Activity cost information can be used to calculated cost-based emissions rates. A study by Ahn et al. [2009] combined RS Means labor cost data with emissions data to determine the optimal equipment fleet both for emissions and for cost. In Rasdorf et al. [2010a], RS Means data were used to calculate cost-based and productivity-based emissions rates.
Life-cycle analysis can also benefit from RS Means data. Examples of this are the use of equipment type and activity duration [Junnila et al., 2006], or quantities and cost of materials [Guggemos and Horvath, 2006, Guggemos and Horvath, 2005].

2.6 Other Topics

This section presents other topics related to construction emissions but which do not fit in the categories of equipment, pollutants, analysis techniques, or data sources. Regulations and incentives are in place to aid in reducing emissions from different sources and have been addressed by some research studies. Other topics presented here include green construction, operational efficiency, life-cycle, duty cycle, visualization, and regulations and incentives.

Table 2.7 presents a summary of the papers that discuss other topics. The first two columns present the reference and year of publication and the institution where the study was performed. The remaining columns present the topics. The topics addressed by each paper are identified by an X. The topics not addressed in the study are marked with a dash.

2.6.1 Green Construction

Green construction is usually defined as building design and construction that includes sustainable and environmentally friendly techniques. There is no formal characterization of the types or quantity of these techniques that a construction project needs to be a green construction project. However, in the US Green Building Council developed a ranking system for green buildings. This system is called Leadership in Energy and Environmental Design (LEED). Detailed information about LEED certification is provided in Appendix 1. Refer to Section 2.6.6.5 for regulation.
2.6.2 Operational Efficiency

Lewis et al [2011] showed a methodology to calculate operational efficiency and to determine how it affects the emissions rates from construction equipment. Operational efficiency is defined as the amount of time that the equipment is doing productive work. If an item of equipment is idling, the operational efficiency is low because that equipment is not productive. Emissions were measured for six bulldozers as a case study. Results showed that lower operational efficiency resulted in higher total emissions for that activity. However, differences in emissions rates between items of equipment were more significant than changes in operational efficiency between activities. These differences in emissions rates are related to engine size, engine tier, and engine load.

2.6.3 Life-Cycle Analysis

A life-cycle analysis includes the study of the impact of a product or service from the beginning to the end of its life. When studying environmental effects of a construction project, a life-cycle model can range from the acquisition of the raw materials to the final disposal of the structure [Baouendi et al., 2005]. Two different techniques can be used to determine the life-cycle impact of an industry: economic input-output techniques or process-based techniques. The economic input-output technique is based on an input-output model that is developed by the U.S. Department of Commerce every year. The US model includes 480 services or commodities. The input-output model consists of tables that relate every sector with all the other sectors. These tables provide information on how the sections interact and the sales from one sector affect another [Ochoa et al., 2002]. The input-output model will identify all the direct and indirect suppliers for an activity.

For the process-based technique, the supply chain is identified by tracing back the processes that are necessary for the activity. After all the suppliers are identified, the effects are calculated using the inputs and outputs for each stage [Zapata and Gambatese, 2005]. The
The major difference between the two techniques is that the input-output method uses all the direct and indirect suppliers and the process-based method does not trace back to the indirect suppliers.

Results from life-cycle models generally show that the construction phase has a small emissions effect when compared with other phases like the use phase. One of the reasons for this is that the construction process time is short when compared to the life of a building that can be 50 years or more [Guggemos and Horvath, 2006].

However, the construction phase offers many opportunities for emissions improvement. A study by Ochoa et al. [2002] showed that the construction phase of a residential building project produced a similar amount of hazardous material waste to that produced during the operation phase. Construction also accounted for 57% of the total toxic air releases for the project. Emissions of PM are also significant during the construction process, particularly when dust is included in the calculation.

When the life-cycle studies concentrate on the construction phase, construction equipment use is a very significant factor. A case study of an office building in Finland showed that equipment use produced between 24 and 60% of the total emissions of the construction phase that included material transportation, energy used, and materials used during construction but not permanent to the structure [Junnila and Horvath, 2003].

The environmental effect of a construction project includes more than the direct effect of the onsite construction activities. Materials are manufactured and transported from different parts of the country and even overseas. The fabrication and transportation of these materials can produce additional emissions and sometimes even hazardous materials.
Table 2.7. Summary of Papers by Other Topics

<table>
<thead>
<tr>
<th>Reference</th>
<th>Research Group</th>
<th>Green Construction</th>
<th>Operational Efficiency</th>
<th>Life Cycle</th>
<th>Duty Cycle</th>
<th>Visualization</th>
<th>Regulations and Incentives</th>
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<td>Guggemos &amp; Horvarth (2005)</td>
<td>Other</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Guggemos &amp; Horvarth (2006)</td>
<td>Other</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hajibabai &amp; Peña-Mora (2009)</td>
<td>CU</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hendrickson &amp; Horvath (2000)</td>
<td>CMU</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Junnila &amp; Horvath (2003)</td>
<td>Other</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Junnila et al. (2006)</td>
<td>Other</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lee et al. (2009)</td>
<td>Other</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>Lewis et al. (2009b)</td>
<td>NCSU</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>Lewis et al. (2011)</td>
<td>NCSU</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Matthews et al. (2001)</td>
<td>CMU</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Millstein &amp; Harley (2009)</td>
<td>UCB</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>Ochoa et al. (2002)</td>
<td>CMU</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>Pang et al. (2009)</td>
<td>NCSU</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Park et al. (2003)</td>
<td>Other</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Peña-Mora et al. (2009)</td>
<td>CU</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>Rasdorf et al. (2010a)</td>
<td>NCSU</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>Sharrard et al. (2007)</td>
<td>CMU</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>Sharrard et al. (2008)</td>
<td>CMU</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Zapata &amp; Gambatese (2005)</td>
<td>Other</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
The study presented here will focus on the effects of the construction equipment used on the construction site and the particular actions that can be taken to reduce the air pollution from these activities. However, it is important to understand that these activities are part of a large industry that includes many other factors.

2.6.4 Duty Cycle

Duty cycle is the sum of the tasks that equipment perform to complete a construction activity. During a construction activity, equipment performs different tasks that create different loads on the engines. This difference in engine work can affect the quantity of emissions produced during different tasks.

In the study by Frey et al. [2010], emissions were measured for 39 items of equipment. The data collected included the duty cycle performed by each item of equipment during data collection. The engine loads for this equipment were estimated using the MAP data from the engine. Having the duty cycle, MAP, fuel use, and productivity data, emissions rates were calculated.

A study by Abolhasani et al. [2008] focused on excavators and identified four task-oriented modes (low idle, high idle, using bucket, and moving). The results showed that the “using bucket” and the “moving” modes have similar emissions rates and the modes can be simplified to idle and non-idle. This same conclusion was presented in Frey et al. [2008a] when studying motor graders. There the modes included idling, moving, and using the blade. The emissions rate for moving and using the blade were very similar. Finally, the idle and non-idle modes were also found to be appropriate to describe backhoes duty cycles as presented in Frey et al. [2008b].

In Lewis et al. [2011], task-oriented modes were used to determine the operational efficiency of construction equipment and how it affects emissions quantities. Operational efficiency is the amount of time that the equipment operation results in productive work. The study was
completed using idle and non-idle modes. Results showed that when equipment spends more
time in idle mode (lower operational efficiency) the total emissions for that activity increase.

Other studies have used different emissions factors for each task-oriented mode [Ahn et al.
2009 and Ahn et al. 2010a]. These emissions factors are based on the study by Lewis [2009].

2.6.5 Visualization

Visualization techniques can be used to identify the location of construction equipment when
emissions are produced. Construction professionals can use this information to manage
emissions not only using quantity but also location. A study by Hajibabai and Peña-Mora
[2009] showed a visualization model based on GIS data. The visualization model showed the
location of a concrete pump and a concrete truck on the construction site. The model focused
on CO₂ emissions for an activity and showed the emissions concentration while the equipment
moved throughout the site.

In a study by Shiftehfar et al. [2010b], wireless GPS sensors were used to locate construction
equipment during construction activities. The location data was used to identify the exact
location of the emissions and to keep historic data of where emissions were produced on the
construction site. The information was added to a building information model (BIM) to relate
emissions with construction activity and building locations.

Shiftehfar et al. [2010a] took a different approach when they used visualization to help
construction professionals had better understanding of the emissions quantities produced
during the construction process. In addition to showing the construction emissions location
during construction activities, the model also showed the number of trees that needed to be
planted to offset the CO₂ emissions produced.
2.6.6 Regulations and Incentives

The following sections present different environmental regulations and incentives that affect construction activities in the US. Regulations are created by law and are enforced by government agencies. Incentives are primarily created by the private sector but can be used on both private and public projects.

2.6.6.1 Clean Air Act

In 1963, Congress passed the original Clean Air Act (CAA) that allocated funds to the study and cleaning of the air. In 1970, Congress passed a stronger CAA to reduce air pollution nationwide [EPA 2007]. The U.S. Environmental Protection Agency (EPA), also created in 1970, is a federal agency responsible for enforcing the CAA. Over the years, amendments have been added to the CAA, particularly in 1977 and 1990.

The CAA identified six pollutants as priorities to be regulated because of their negative effect on human health and the environment. These six air pollutants are categorized as criteria pollutants and are listed below.

- Particulate matter
- Ground-level ozone
- Carbon monoxide (CO)
- Sulfur oxide (SO)
- Nitrogen oxides (NOx)
- Lead

EPA created the National Ambient Air Quality Standards (NAAQS) to regulate the quantity of criteria pollutants in the environment. Criteria pollutants are regulated by two standards. Primary standards are developed to protect human health. Secondary standards are created to prevent environmental and property damage [EPA 2007]. If an area does not comply with the
NAAQS it is called a nonattainment area and action is required to comply with the NAAQS by a certain date. The primary and secondary standards are presented in Table 2.8.

EPA regulates emissions produced by both stationary and moving sources. Stationary sources are major pollution sources like power plants. Moving sources include passenger vehicles, heavy-duty trucks, and nonroad vehicles. Technology-based standards are applied to new stationary sources and to new engines. This means that the new standards apply to all the sources created after the regulation but do not need to be followed by sources that were manufactured before the regulation was created. The nonroad moving source section of the CAA regulates construction equipment.

### Table 2.8. National Ambient Air Quality Standards for Criteria Pollutants [EPA, 2014d]

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Primary Standard</th>
<th>Secondary Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Level</td>
<td>Averaging Time</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>9 ppm</td>
<td>8-hour</td>
</tr>
<tr>
<td></td>
<td>35 ppm</td>
<td>1-hour</td>
</tr>
<tr>
<td>Lead</td>
<td>0.15 μg/m³</td>
<td>Rolling 3-month average</td>
</tr>
<tr>
<td>Nitrogen Dioxide</td>
<td>53 ppb</td>
<td>Annual (Arithmetic Average)</td>
</tr>
<tr>
<td></td>
<td>100 ppb</td>
<td>1-hour</td>
</tr>
<tr>
<td>Particulate Matter (PM₁₀)</td>
<td>150 μg/m³</td>
<td>24-hour</td>
</tr>
<tr>
<td>Particulate Matter (PM₂.₅)</td>
<td>12.0 μg/m³</td>
<td>Annual (Arithmetic Average)</td>
</tr>
<tr>
<td></td>
<td>35 μg/m³</td>
<td>24-hour</td>
</tr>
<tr>
<td>Ozone</td>
<td>0.075 ppm</td>
<td>8-hours</td>
</tr>
<tr>
<td>Sulfur Dioxide</td>
<td>75ppb</td>
<td>1-hour</td>
</tr>
</tbody>
</table>

#### 2.6.6.2 Engine Tiers

EPA regulates the quantity of pollutants that can be emitted by diesel and gasoline engines. The first regulation of pollutants emitted by nonroad engines was implemented between 1996 and 2005 depending on the horsepower range of the engine. The engines that comply with
this regulation are called Tier 1 engines. Engines manufactured before 1996 that do not comply with the regulation are called Tier 0 engines. Tier 2 regulation was implemented between 2003 and 2010. Tier 3 regulation was implemented between 2006 and 2012. Tier 4 regulation will be implemented in two parts. The first part will be called Tier 4 transitional and will be implemented between 2008 and 2014. Tier 4 final will be implemented after 2013 depending on the engine horsepower [EPA 2010]. Table 2.9 presents the emissions limits for Tier 4 engines based on engine horsepower. The blank spaces in the table show pollutants that are not regulated for that horsepower range.

**Table 2.9. Tier 4 Emissions Limits**

<table>
<thead>
<tr>
<th>Engine Power (hp)</th>
<th>Emissions Standards (g/hp-hr)</th>
<th>HC</th>
<th>NMHC + NOx</th>
<th>CO</th>
<th>NOx</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 11</td>
<td>5.6</td>
<td>6.0</td>
<td>0.30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≥ 11 to &lt; 25</td>
<td>5.6</td>
<td>4.6</td>
<td>0.30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≥ 25 to &lt; 50</td>
<td>3.5</td>
<td>4.1</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≥ 50 to &lt; 75</td>
<td>3.5</td>
<td>3.7</td>
<td>6.9</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>≥ 75 to &lt; 100</td>
<td>0.14</td>
<td>3.5</td>
<td>3.7</td>
<td>0.30</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>≥ 100 to &lt; 175</td>
<td>0.14</td>
<td>3.0</td>
<td>3.7</td>
<td>0.30</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>≥ 175 to &lt; 300</td>
<td>0.14</td>
<td>3.0</td>
<td>2.6</td>
<td>0.30</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>≥ 300 to &lt; 600</td>
<td>0.14</td>
<td>3.0</td>
<td>2.6</td>
<td>0.30</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>≥ 600 to &lt; 750</td>
<td>0.14</td>
<td>3.0</td>
<td>2.6</td>
<td>0.30</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>&gt; 750</td>
<td>0.14</td>
<td>3.0</td>
<td>2.6</td>
<td>0.30</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>

*Non-methane hydrocarbons and nitrogen dioxide

The tier regulations are technology standards imposed on engine manufacturers and not to the equipment owner of fleet manager. New equipment manufactured and sold in the U.S. will comply with the most recent regulation. However, older equipment will continue to be used until it needs to be replaced, even if it does not comply with newer regulations. The environmental benefits of Tier 4 engines will not be fully obtained until the majority of equipment in use meets the new regulation. It is expected that the entire inventory of
construction equipment will be replaced by 2030 with most equipment meeting Tier 4 final at that time [Lewis et al. 2009b]. Engine tier is further discussed in Section 2.6.6.2.

2.6.6.3 California Air Resource Board

The California Air Resource Board (CARB) was created by the California’s Legislature in 1967 [CARB 2011a]. The CAA stipulates that the CARB is the only state agency with the authority to create air quality standards. All the other states can comply with the Federal standards or the CARB standards. The CARB standards need to be at least as protective as the Federal standards.

CARB sets air quality standards for the state. In 2007, CARB approved a regulation to reduce NOₓ and PM emissions from nonroad diesel vehicles. The regulation includes a performance requirement based on fleet averages. The regulation does not only apply to individual items of equipment, like the EPA regulations, but particularly to the average emissions from fleets. Fleets are classified by size with large fleets having over 5,000 hp, medium fleets between 2,501 and 5,000 hp, and small fleets of less than 2,500 hp. The regulation required that every diesel vehicle was reported and labeled by August 1, 2009. A limit on unnecessary idling is also part of the regulation limiting idling to five consecutive minutes. Owners are also required to disclose if a vehicle is sold [CEPA 2011].

In December 2010 amendments were approved to delay the compliance dateline to January 1, 2014 for large fleets, January 1, 2017 for medium fleets, and January 1, 2019 for small fleets. The amendments also include that exhaust retrofits are not mandatory, simplification of the requirements by only using NOₓ emissions averages, and raising the threshold to 200 hours per year for low-use vehicles. These amendments are estimated to reduce the cost of compliance by more than 95% during the first five years [CEPA 2011].

When the fleet regulations phase-in in 2014, large fleets will need to meet the fleet average target or retrofit 4.8 to 10% of the fleet’s horsepower. Fleet managers have the different
options to “turn over” their fleets. They can replace older vehicles, repower with new engines, retire Tier 0 engines, move to electric or other alternative fuels, designate vehicles as low-use (less than 200 hours per year), or install NOx reduction retrofits [CARB 2011b].

The regulation is also expected to include restriction to vehicles added to the fleet. Tier 0 engines should not be added to any fleet. In March 1, 2011, large and medium fleets were not allowed to add any Tier 1 vehicle that was not registered before. In January 2013, large and medium fleets will not be allowed to add Tier 1 vehicles even if it was registered before. In January 2016, small fleets will need to follow the same rule. By January 2018 for large and medium fleets, and January 2023 for small fleets, no Tier 2 engine will be added to the fleet [CARB 2011b].

2.6.6.4 Air Pollution Regulation in Europe

In December 1987, the European Parliament approved a law to study the emissions from diesel engines. In 1997, the first regulation was approved creating Stage I and Stage II emissions regulations and implemented in 1999 and 2001, respectively. In 2004, Stage III and Stage IV regulations were approved and implemented in 2006 and 2013 respectively. Like the EPA Tier standards, the implementation depends on the engine power. Stages I – IV are similar to Tiers 1 – 4 from the EPA regulations. The European regulations for nonroad vehicles are comparable to US technology-based regulations. European regulations are limits to emissions rates that need to be followed by manufacturers according to the most recent regulation. Table 2.10 presents the maximum emissions rate for Stage IV engines [EP 2004]. Table 2.11 presents that Stage IV European regulations converted to horsepower and grams per horsepower hour.
Table 2.10. Stage IV Regulation for Diesel Engines in Europe

<table>
<thead>
<tr>
<th>Net Power (kW)</th>
<th>CO (g/kWh)</th>
<th>HC (g/kWh)</th>
<th>NOx (g/kWh)</th>
<th>PM (g/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>130 kW ≤ P ≤ 560 kW</td>
<td>3.5</td>
<td>0.19</td>
<td>0.4</td>
<td>0.025</td>
</tr>
<tr>
<td>56 kW ≤ P ≤ 130kW</td>
<td>5.0</td>
<td>0.19</td>
<td>0.4</td>
<td>0.025</td>
</tr>
</tbody>
</table>

Table 2.11. Stage IV Regulation with Conversion to Horsepower Units

<table>
<thead>
<tr>
<th>Net Power (hp)</th>
<th>CO (g/hp-h)</th>
<th>HC (g/hp-h)</th>
<th>NOx (g/hp-h)</th>
<th>PM (g/hp-h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>174 hp ≤ P ≤ 750 hp</td>
<td>2.6</td>
<td>0.14</td>
<td>0.30</td>
<td>0.019</td>
</tr>
<tr>
<td>75 hp ≤ P ≤ 174 hp</td>
<td>3.73</td>
<td>0.14</td>
<td>0.30</td>
<td>0.019</td>
</tr>
</tbody>
</table>

2.6.6.5 US Green Building Council and LEED Certification

As mentioned in Section 2.6.1 green building is the practice of creating structures while using processes that are environmentally responsible and resource-efficient throughout a building’s life cycle. Green buildings are designed to reduce the overall impact of the built environment on human health and the natural environment by attempting to achieve the following objectives [EPA 2011a]:

- Efficiently using energy, water, and other resources,
- Protecting occupant health and improving employee productivity, and
- Reducing waste, pollution, and environmental degradation.

Many times a building is considered green if it complies with the requisites presented by the Leadership in Energy and Environmental Design (LEED) rating system. The U.S. Green Building Council (USGBC) created LEED. The rating system focuses on seven major characteristics of the design:

- Sustainable site,
• Water efficiency,
• Energy and atmosphere,
• Material and resources,
• Indoor environment quality,
• Innovation credits and design/build process, and
• Regional priority.

Each one of these characteristics presents requirements that each building needs to follow to be identified as green. Buildings should also comply with other specifications that have a credit associated with it. The number of credits acquire by the building will determine if the LEED certification will be silver, gold, or platinum [USGBC 2008]. Presently LEED does not account for emissions during the construction process.

Frequently, the term “green building” is used synonymously in combination with the term “sustainable building.” Sustainable or green buildings are designed to efficiently use energy, water, and materials. Green buildings usually use more natural light and have better air quality, improving the comfort and health of the occupants [Kats 2003]. It is important to note that green building practices tend to focus on building operation and maintenance rather than on their construction.

Air pollutants emissions from construction equipment are not one of the criteria used by LEED to characterize a building as green. One of the requirements is titled Construction Activities Pollution Prevention, but focuses on erosion control. One pilot point was added to the rating system that focuses on the PM produced by construction equipment. The requirement to obtain the pilot point is to use vehicles that comply with 2007 EPA regulations. Green buildings are designed to be energy efficient (during the operation phase of the building) based on energy cost.
Presently, emissions play a small role in the LEED Certification rating system. However, an accurate model for quantifying emissions could be used to include construction emissions in the LEED rating system. Such a model would be particularly useful if results show a difference in emissions from construction projects with different characteristics.

2.6.6.6 Contract requirements

If an accurate emissions model is developed, it can be used to control pollutant emissions by enabling owners to add restrictive clauses to the contract knowing that the limitations can be determined and enforced. Contractors would be obligated by contract to monitor, report, and reduce the quantity of pollutants produced by the construction equipment. The owner can include clauses to limit emissions by equipment item, fleet, or activity. The owner can also control the engine tier and the type of equipment used, if desired. No literature was found that mentioned contract requirements as a method to control pollution.

2.7 Information Sources

The following sections offer detailed information about the sources that were used in this study to obtain equipment and emissions information. Detailed information about items of equipment were obtained from contractors, RS Means, and the Caterpillar Performance Manual. Emissions factors were obtained from the Environmental Protection Agency NONROAD model.

2.7.1 RS Means

RS Means is a widely available tool that can be used by contractors and estimators. The online database version was used for this study [RS Means 2014]. RS Means is a source of detailed information about construction activities. Data from RS Means includes costs, productivity, and crew composition for each activity. Table 3.1 shows an example of the data available for
each activity. The table shows three alternatives for the completion of a trench excavation activity. The three alternatives are defined by the size of the excavator.

Table 2.13 shows an example of the data that can be obtained for one of the crews of Table 2.12. Crew B-11C can be used to complete the trench excavation activity. The information provided in Table 2.13 includes the number of workers and the type and size of the construction equipment used by the crew. The cost information can be used to estimate the cost of each activity.

### Table 2.12. Example of RS Means Information for Trench Excavation Activities [Means, 2014]

<table>
<thead>
<tr>
<th>Activity</th>
<th>Crew</th>
<th>Daily Outputs</th>
<th>Labor-Hours</th>
<th>2009 Bare Cost (dollar per unit)</th>
<th>Total Incl. O&amp;P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common earth with no sheeting or dewatering included</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1' to 4'deep, 3/8 CY excavator</td>
<td>B-11C</td>
<td>150</td>
<td>.107</td>
<td>BCY 3.89 1.96 5.85 8.10</td>
<td></td>
</tr>
<tr>
<td>1/2 CY excavator</td>
<td>B-11M</td>
<td>200</td>
<td>.080</td>
<td>BCY 2.92 1.72 4.64 6.35</td>
<td></td>
</tr>
<tr>
<td>3/4 CY excavator</td>
<td>B-12F</td>
<td>270</td>
<td>.059</td>
<td>BCY 2.20 2.22 4.42 5.80</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2.13. Crew B-11C from RS Means [Means, 2014]

<table>
<thead>
<tr>
<th>Crew No.</th>
<th>Bare Costs</th>
<th>Incl. Subs O &amp; P</th>
<th>Cost per Labor-Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hr.</td>
<td>Daily</td>
<td>Hr.</td>
</tr>
<tr>
<td>1 Equipment Oper. (med)</td>
<td>$41.35</td>
<td>$330.80</td>
<td>$62.15</td>
</tr>
<tr>
<td>1 Laborer</td>
<td>31.60</td>
<td>252.80</td>
<td>49.00</td>
</tr>
<tr>
<td>1 backhoe Loader, 48 H.P.</td>
<td>293.80</td>
<td>323.18</td>
<td></td>
</tr>
<tr>
<td>16 L.H., Daily Totals</td>
<td>$877.40</td>
<td>$1212.38</td>
<td></td>
</tr>
</tbody>
</table>
The RS Means detailed data can be used to estimate cost and duration of each activity on a construction project. General contractors can use historic data and the experience from previous projects to develop an estimation of the cost and duration of each activity based on local conditions.

RS Means is used in this study for three reasons. The first reason is that detailed historic data was not available. Construction companies own their proprietary databases and these are not readily available to the public. The second reason is that RS Means is an easy to use tool that is readily available. Construction engineering students learn how to use it and construction professionals have easy access to it. The third reason is to allow other researchers to reproduce the results of this study. Any researcher can repeat the methodology presented in this study if they have access to the data sources. Cost and scheduling values can be updated if the researcher has detailed historic data for a specific project.

2.7.2 EPA NONROAD Model

The EPA NONROAD model was used in the present study to estimate emissions from construction equipment. The NONROAD model offers emissions factors that can be combined with particular equipment and construction activity characteristic to estimate total emissions. The emissions factors from the model were measured by testing the engine on a dynamometer. Previous work has been done to compare emissions determine by the NONROAD model to emissions measured from equipment during daily activities [Lewis et al., 2009b]. The correlation between the two was high.

The EPA NONROAD is available for download from the EPA web page. The equipment categories presented in the NONROAD model are as follows [EPA 2005]:

- Recreational vehicles
- Logging equipment
- Agricultural equipment
• Construction equipment
• Industrial equipment
• Residential and commercial lawn and garden equipment
• Recreational marine vessels

Each equipment category includes different equipment types. For example, a bulldozer is included in the construction equipment category. The NONROAD model provides emissions rates for each category and type of equipment. The model presents emissions rates as grams per hour, grams per day, and grams per horsepower-hour. The model can also be used to calculate total emissions in a year for a geographic area, for an equipment classification, or for a horsepower range.

The reminder of this section discussed the pollutants that are included in the NONROAD model. This study will focus on exhaust pollutants but there are other pollutants produced by non-road vehicles.

2.7.3 Exhaust pollutants

The NONROAD model estimated emissions produced by different parts of the engine. This study will focus on the exhaust pollutants that are expelled from the cylinder after the fuel combustion. The following list presents the six exhaust pollutants that are estimated by the EPA NONROAD model. A discussion of the effects of the exhaust pollutants is presented in section 2.3. Other pollutants are mentioned below.

• Hydrocarbons (HC)
• Nitrogen Oxides (NOₓ)
• Carbon Monoxide (CO)
• Carbon Dioxide (CO₂)
• Sulfur Oxides (SOₓ)
• Particulate Matter (PM)

2.7.4 Hydrocarbons

The EPA NONROAD model offers different categories to provide hydrocarbon emissions factors. In order to use the NONROAD model, we must specify which HCs are of interest. The different categories that can be used include:

- THC – total hydrocarbons,
- TOG – total organic gases,
- NMOG – non-methane organic gases,
- NMHC – non-methane hydrocarbons, and
- VOC – volatile organic compounds.

Volatile organic compounds (VOC) are a category used in the NONROAD model that excludes ethane and methane from the HC emissions. VOC are substances regulated for their ozone formation capabilities in addition to their toxic and carcinogenic effects. Ethane and methane have a low ozone formation capability compare with other HCs [EPA, 2004].

For the purpose of this study, hydrocarbons emissions factors will be presented as total hydrocarbons produced by the exhaust system. These measurements could be multiplied by different factors to estimate emissions for the other categories of HCs [EPA, 2004].

2.7.5 Other Pollutants

Hydrocarbons are emitted by numerous parts and processes in the equipment. The NONROAD model measures these emissions using total hydrocarbons (THC). The present study only considers hydrocarbons produced by the exhaust system and will not deal with THC emitted by other engine parts or processes. Some of these emissions include:
Crankcase THC
Diurnal THC
Vapor displacement THC
Spillage THC
Hot soak THC
Running loss THC
Tank permeation THC
Hose permeation THC

2.7.6 Caterpillar Performance Manual

The Caterpillar Performance Manual provides information about all equipment models manufactured by Caterpillar. The information includes engine size, maximum load, maximum speed, operational weight, and other characteristics. This information can be used to determine productivity rates. The manual also offers additional information about equipment operation in different site conditions. The manual was used to determine engine size and equipment type for the equipment used in this research. The manual also provides a cost estimation method that was used for the optimization model.

2.7.7 Field Data and Construction Documents

Project plans, specifications, project schedules, and project cost estimates were used to obtain information about the project and the construction equipment used. Plans and specifications provided information about project characteristics. Quantity take-offs provided material and productivity quantities that were used to calculate emissions rates.
2.8 Summary

The study of the literature available on the topic of air pollution emissions from construction equipment provided numerous lessons. EPA emissions regulations triggered a reduction on emissions for newer equipment. However, construction equipment has a long service life and benefits from newer tiers will not be seen until a large number of equipment items are replaced.

Measurements of emissions from construction equipment showed correlations between emissions and vehicle and engine characteristics. Vehicles that operate with B20 instead of petroleum diesel produce fewer pollutants, particularly PM, HC, and CO. Analyses of equipment duty cycles showed that there is a significant difference between idle and non-idle operations. However, there is no significant difference between non-idle activities. The manifold average pressure is the engine characteristics with the strongest correlation with fuel use and with emissions quantities.

An alternative to reducing emissions from construction equipment is to retrofit the exhaust systems with catalysts or other after treatment systems. Studies showed that using catalyst reduce PM emissions but increase NOx emission.

Besides engine size and tier, other characteristics determine the quantity of emissions from construction equipment. Operational efficiency can be a determining factor when calculating emissions per construction activity. If an item of equipment spends too much time idling between working activities, emissions will be higher for that activity. However, other vehicle characteristics like engine tier and engine load have a larger impact on emissions rate than operational efficiency.

After reviewing the available literature, some questions remain. Measurements of emissions from construction items and totals for construction activities are available. However, only a few studies concentrate on estimation of emissions at the project level.
There is little information about the characteristics of the construction equipment fleet in the US. No equipment inventories are available besides private fleet documentations and the one recently created in California. The EPA develops equations that can be used to estimate the engine tier of the equipment and estimate the impact of newer, higher tier equipment on total emissions rates from the construction industry.

California is the first state government to require that equipment owners to update equipment information when the equipment is sold or removed from the fleet. The regulations also require that equipment will be replaced with newer equipment following some timelines. These regulations can have a large impact on the quantity of total emissions from construction projects or from individual fleets. More research needs to be done to understand the impact of the regulation in California. Additional studies can be developed to calculate the effect of expanding the fleet regulations to the entire country.
3.0 TIME AND COST CHARACTERIZATION OF EMISSIONS FROM NON-ROAD DIESEL EQUIPMENT FOR FOUR INFRASTRUCTURE PROJECTS

3.1 Introduction

The construction industry is ranked third in greenhouse emissions compared to other industry sectors in the US [EPA 2008]. Emissions from construction are equivalent to six percent of the greenhouse emissions from all industries in the US. Of the 131 million metric tons of CO_2 equivalent that construction produced in 2002, 100 million tons (or 76%) are due to fossil fuel combustion. Thus, reducing emissions from construction equipment is an important step toward cleaner air on a national level.

Tatari and Kucukvar [2012] studied the ecological impact of the construction industry. From the 13 sectors in which the construction industry was divided, highway construction was ranked fifth in total industry output in dollars. However, highway construction and highway maintenance had the highest in CO_2 emissions per dollar of economic output.

Recent regulations by the US Environmental Protection Agency (EPA) for non-road vehicles and equipment have focused on the manufacturers of the engines used. However, the new regulations only apply to equipment that is manufactured after a specific regulation comes into effect. Each new set of emissions regulations is referred to as a tier and is used as means to identify the engines with respect to their emissions level. For example, engines that comply with the first regulation in 1996 are known as Tier 1 engines. Engines manufactured before the regulations were in place are classified as Tier 0 engines. Tier 4 regulation will be fully implemented in 2015 [EPA 2010b].

EPA developed the NONROAD model that provides emissions factors for non-road equipment according to engine size, engine tiers, and equipment type. These factors can then be used to derive emissions quantities for various need and uses. The pollutants that were used for this study are those classified as exhaust pollutants by the NONROAD model and
include hydrocarbons (HC), nitrogen oxide (NOx), carbon monoxide (CO), particulate matter (PM), sulfur dioxide (SO2), and carbon dioxide (CO2).

The Clean Air Act requires EPA to develop National Ambient Air Quality Standards for criteria pollutants; those pollutants that negatively affect human health and the environment [EPA 2013a]. Four of the pollutants (noted above) that we investigate herein (CO, NOx, PM, and SO2) are criteria pollutants. HC emissions are important because they participate in the atmospheric process that produces ozone, another of the criteria pollutants. CO2 is studied regularly because it is a greenhouse gas and contributes to climate change [IPCC 2013].

3.1.1 Problem Statement

Determining where and when construction produces emissions is important, necessitating that databases of project emissions by type, cost, and other characteristics be developed to quantify these emissions. In this paper, we use the term forecast to mean the use of our methodology to determine emissions from yet unbuilt future projects. We use the term estimate to mean the use of the methodology to determine emissions from existing data sources for work already completed. Estimation allows us to benchmark our work against actual field measurements and forecasting enables us to predict future emissions that are in line with the metrics already established. One of the contributions of this paper is that it adds much needed field data to this inventory. Highway construction, rehabilitation, and resurfacing have a significant environmental impact due to emissions from the use of both diesel and gasoline powered equipment. However, there has not been an established methodology for inventorying construction activity emissions at the project or activity levels for street and utility construction projects.

This paper contributes one such methodology – a direct link between street construction activities and emissions. Such a methodology can enable contractors and fleet managers to estimate the emissions from their equipment without the need to field measure emissions from
every item of equipment used and then knowing the environmental impact only after the fact. Instead, the key goal is to have a methodology to forecast project emissions during planning and preliminary engineering project stages.

The objective of this paper is to present a methodology to estimate the total emissions from a specific type of very common transportation construction project – street and utility projects. The use of this methodology is illustrated by its application to four projects, thereby providing quantified emissions predictions for various levels of detail that can be assessed and used for further study. Two of the projects include pavement rehabilitation and utility work on an existing street. The other two projects (two separate phases) include street construction and utility work for a new residential subdivision.

The projects studied herein are representative of the type of construction that is regularly completed by local governments and developers; thus, the results of the paper have broad practical applications. It is important to realize that all levels of government and private developers commonly perform this work, even during recessions. The literature search revealed that these prevalent project types have not previously been studied. It is our hope that with the data and methodology presented herein we have made a valuable contribution to the body of knowledge. Contractors and local agencies can use this work to forecast emissions from these types of projects.

3.2 Literature Review

Various studies have been performed to determine the effect of construction activities on the environment. The construction industry includes numerous project types that range from residential to industrial buildings and from large industrial projects to mega infrastructure projects. Those projects may range from small scale endeavors that cost only a few thousand dollars to large scale “megaproject” that exceeds one billion dollars in cost.
One of the ways to study the pollutants emissions of various construction projects is by analyzing the life cycle of the projects. The emissions are often calculated for all the phases of the life cycle of a project, including material manufacturing and transportation, construction, operation, maintenance, and demolition and disposal. One such study showed that the construction phase accounts for 6% of the total energy consumption and 9% of the total equivalent CO₂ emissions for residential projects in Canada. The operation phase accounted for the remaining 94% of the energy consumption and 91% of the equivalent CO₂ emissions [Baouendi et al, 2005]. Another study showed that asphalt and bridge repair projects produced 3.5 times more NOₓ than did building projects [Sharrard et al, 2008]. A study by Lee et al. [2011] concluded that projects that use recycled materials improved sustainability and reduced greenhouse gas emissions.

Kim et al. [2012] developed a methodology to estimate CO₂ emissions from road construction activities. The methodology had three basic steps: estimate working hours of the equipment, calculate fuel use for those hours, and calculate greenhouse gas quantities based on equipment fuel consumption. The activities were divided into earthwork, pavement, utility, and miscellaneous. It was determined that earthwork activities used more fuel than any of the other activities. For the majority of the cases dump trucks emitted the most pollutants.

Some studies directly measured emissions from equipment while working on site. The study by Lewis et al [2009a] presented an emissions inventory using actual emissions measurements from equipment fleets. This paper focused on emissions inventories for equipment but not project activities. The equipment was tested using both petroleum diesel and a biodiesel blend (B20). The results showed that emissions were lower for equipment using biodiesel as fuel. The inventory also showed that emissions were lower for higher-tier equipment. As a result of this study the NCDOT converted its entire fleet to biodiesel fuel.

The emissions inventory resulting from the Lewis study was used to develop a set of practices that the construction industry can use to reduce emissions [Lewis et al., 2009b]. The
recommended practices included the improvement of maintenance procedures, the use of alternative fuels, and the development of emissions inventories based on accurate emissions forecast. Other opportunities to reduce emissions were also presented by EPA [2009]. The actions by the contractors with the most influence in reducing greenhouse gases emissions were determined to be fuel selection, equipment maintenance, equipment idling, equipment selection, electricity used, and materials recycling.

Lewis et al [2012] also studied the effect of productivity and idling time on total emissions. The authors concluded that emissions were considerably lower during idle time. However, idling has a negative effect on productivity and results in an overall increase of emissions for a particular activity or project.

A methodology was presented by Marshall et al. [2012] to forecast emissions from building construction projects and was used to forecast emissions from a small commercial project. The authors calculated the emissions for each individual construction activity using project data (and a project schedule provided by the contractor) that were combined with crew, productivity, and cost data from RS Means [Means, 2013]. Results from this study showed that concrete work was responsible for 45% of the total CO emissions, that the most emissions were generated early in the construction process, and that those emissions were primarily due to earthwork and site preparation activities (thus verifying the findings of Kim et al. 2012).

Previous work had shown that emissions from road construction projects are significant. These emissions can be changed by taking equipment and fuel characteristics into consideration. It was also shown that equipment use (particularly idle time) has an impact on total emissions from infrastructure projects. What was missing in the previous literature was a methodology that contractors and local governments could use to forecast these emissions. It was our intention in this study to provide this methodology and we do so herein. This paper introduces emissions forecasts and metrics for street and utility infrastructure projects.
Furthermore, the data used herein are available for further study by other researchers for future project type comparisons.

3.3 Methodology

A methodology was previously developed and tested on a commercial building project [Marshall et al. 2012]. The methodology was initially designed to be easily implemented by construction professionals. Following that study, the authors sought herein to apply, test, refine, and assess the methodology in a transportation construction setting. Plans, specifications, equipment fleet composition, fuel use, and other data were obtained for the four transportation street construction projects described above.

3.3.1 Data Sources

The project data presented here were developed using both the EPA’s NONROAD Model and RS Means estimating data. The contractor that worked on the four projects described and analyzed herein provided basic project characteristics, schedule, cost, and equipment used for each activity as well as basic equipment characteristics. Additional data were collected from the equipment manufacturer’s manuals. An abundance of actual field data was available and was made use of. This section explains how these data sources were obtained for this project. For a further discussion of additional data sources see Marshall et al [2012].

EPA has developed a widely used NONROAD model to forecast emissions from all types of non-road equipment [EPA, 2005]. The model allows the user to select the different types of engines and different localities for their use. It supports equipment use classifications including agriculture, marine, construction, and others. The EPA NONROAD Model provides emissions factors for equipment based on differing equipment characteristics.

Pollutant emissions factors in the NONROAD model are dependent on equipment type, engine tier, and type of fuel. The pollutant emissions factors are provided in grams of
pollutant per horsepower hour. In addition to the factors themselves, we used further adjustments for each item of equipment that took into consideration the deterioration of the engine and the engine load. The adjustments were completed following the methodology provided by EPA [EPA, 2010a].

RS Means provides estimates of crew, cost, and productivity data for typical construction activities [Means, 2013]. These data items were used to estimate the project schedule, cost, and equipment needs of each project activity using data usually available to contractors during the early phases of the project.

A key goal of this paper is to present the results of using this published data in conjunction with field data to estimate emissions production on equipment and activity levels using the best information available. In doing so the results and insights gained can be used to provide more precise data as input to life cycle models. Presently life cycle models use estimates rather than detailed equipment emissions data.

3.3.2 Project Descriptions

Street construction projects can primarily be divided by project type into new construction, rehabilitation, and resurfacing. The four projects presented here focus on street and utility rehabilitation construction projects, including new pavement placement. These projects represent typical construction work regularly performed by construction companies for city streets and residential developments. This kind of construction is prevalent through the US, especially in rapidly growing areas.

Four projects were selected to represent different sizes of small street projects. These types of projects usually include work to improve or relocate utilities and curbs. A construction firm that specializes in street construction provided the plans and specifications, the schedule, and insight into the field construction methods used.
The projects consisted of two separate street rehabilitation projects and one other subdivision street construction project delivered in two phases (referred to herein as two separate projects). Table 3.1 shows basic characteristics of the four projects and Table 3.2 shows the construction activities associated with each project. The costs calculated for all the projects and activities were determined using RS Means 2013 cost data.

### Table 3.1. Project Characteristics

<table>
<thead>
<tr>
<th>Project</th>
<th>Acronym</th>
<th>Total Cost</th>
<th>Year Built</th>
<th>Construction Duration (days)</th>
<th>Length (ft)</th>
<th>Width (ft)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Little Street Roadway</td>
<td>LS</td>
<td>$179,000</td>
<td>2011</td>
<td>65</td>
<td>600</td>
<td>24</td>
<td>Street and utility improvement</td>
</tr>
<tr>
<td>W. Burkhead Street</td>
<td>WB</td>
<td>$103,860</td>
<td>2012</td>
<td>9</td>
<td>500</td>
<td>27</td>
<td>Street and utility improvement</td>
</tr>
<tr>
<td>Sutton Place Phase 1</td>
<td>SP1</td>
<td>$219,540</td>
<td>2009</td>
<td>49</td>
<td>930</td>
<td>20</td>
<td>New development</td>
</tr>
<tr>
<td>Sutton Place Phase 2</td>
<td>SP2</td>
<td>$622,660</td>
<td>2009</td>
<td>101</td>
<td>2,813</td>
<td>27</td>
<td>New development</td>
</tr>
</tbody>
</table>
### Table 3.2 Project Construction Activities

<table>
<thead>
<tr>
<th>Construction Activities</th>
<th>Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Little Street</td>
</tr>
<tr>
<td>Mobilization</td>
<td>X</td>
</tr>
<tr>
<td>Staking and layout</td>
<td>X</td>
</tr>
<tr>
<td>Clearing and grubbing</td>
<td></td>
</tr>
<tr>
<td>Demolition and removal of existing asphalt</td>
<td>X</td>
</tr>
<tr>
<td>Erosion control measures</td>
<td></td>
</tr>
<tr>
<td>Earthwork and grading</td>
<td></td>
</tr>
<tr>
<td>Demolition of sewer, storm, and water systems</td>
<td>X</td>
</tr>
<tr>
<td>Initial grading and excavation</td>
<td></td>
</tr>
<tr>
<td>Installation of new sanitary sewer system</td>
<td>X</td>
</tr>
<tr>
<td>Abandon existing sewer</td>
<td></td>
</tr>
<tr>
<td>Installation of water distribution system</td>
<td>X</td>
</tr>
<tr>
<td>Installation of storm sewer</td>
<td></td>
</tr>
<tr>
<td>Remove and replace curb on adjacent streets</td>
<td></td>
</tr>
<tr>
<td>Prepare subgrade</td>
<td>X</td>
</tr>
<tr>
<td>Paving</td>
<td>X</td>
</tr>
<tr>
<td>Final clean up, punch list, and demobilization</td>
<td>X</td>
</tr>
</tbody>
</table>

#### 3.3.3 Calculations Steps

The general methodology consists of performing a quantity takeoff, developing a cost estimate, assembling emissions factors, developing and undertaking an activity level emissions analysis, and developing overall project level emissions forecasts.

The first step was to benchmark the information supplied by the contractor. The project schedule is part of the contract documents and was determined to be reliable. The contractor identified the items of equipment used for the construction project. The hours of operation for the equipment were estimated using labor hours provided by the contractor for each construction activity. However, while labor hours provided an estimate of the amount of time the equipment was located at the job they did not necessarily provide a good estimate of the number of hours that the equipment was in use. In cases where contractor data was insufficient
to determine the characteristics of the equipment used for each activity, RS Means data [Means, 2013] was used to supplement the contractor’s data.

The activities in the contractor’s schedule were matched with a corresponding activity or group of activities from RS Means. Some of the activities were directly equivalent to an activity in RS Means, others required a grouping of similar or multiple activities.

In addition to cost and productivity data, RS Means also identifies a specific crew composition for each activity including the laborers and equipment operators as well as the items of equipment required to perform the activity. For most of the equipment identified, RS Means also provided its engine size (in horsepower) and its capacity (e.g. cubic yards).

A final project schedule was developed using the most reliable information from all the sources. The activities and total duration were determined using information from the contractor. The list of equipment and total hours of use, as well as the total cost, were determined using RS Means. The activity duration was adjusted to fit the actual field schedule provided by the contractor. Doing so reflected the actual delays and other situations that the contractor encountered during the construction process.

Once a final schedule was determined, the emissions factors for the items of equipment were obtained from the EPA NONROAD model. Table 3.3 shows the equipment that was determine using RS Means and used on all four projects. The table includes equipment type, horsepower, emissions factors, and the projects on which each item of equipment was used. The emissions factors were adjusted assuming that all the equipment used was Tier 2. Tier 2 equipment was produced during the years 2003 to 2007 and it is reasonable to assume that the typical equipment used by small contractors was obtained before the economic downturn of 2008. EPA default values were used for the other information needed to adjust the emissions factors for deterioration of the engine and variance on the actual use of the engine.
Factors obtained from the EPA NONROAD model were adjusted using the procedures, formulas, and data presented by EPA [EPA, 2010a and EPA, 2010b]. For example, the adjustment equation for HC, CO, and NO\textsubscript{x} is as follows:

\[
EF_{\text{adj}} = EF \times TAF \times DF
\]

where:

\begin{itemize}
  \item \(EF_{\text{adj}}\) = final emissions factor adjusted
  \item \(EF\) = steady-state emissions factor from the EPA NONROAD model
  \item \(TAF\) = transient adjustment factor
  \item \(DF\) = deterioration factor
\end{itemize}

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>HP</th>
<th>Emissions Factors (g/hp-hr)</th>
<th>Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>HC</td>
<td>CO</td>
</tr>
<tr>
<td>Asphalt Paver</td>
<td>130</td>
<td>0.48</td>
<td>4.0</td>
</tr>
<tr>
<td>Backhoe Loader</td>
<td>48</td>
<td>1.70</td>
<td>11.55</td>
</tr>
<tr>
<td>Brush Chipper</td>
<td>110</td>
<td>0.65</td>
<td>2.83</td>
</tr>
<tr>
<td>Concrete Pump</td>
<td>400</td>
<td>0.49</td>
<td>3.56</td>
</tr>
<tr>
<td>Curb Paver</td>
<td>130</td>
<td>0.60</td>
<td>5.25</td>
</tr>
<tr>
<td>Bulldozer</td>
<td>105</td>
<td>0.42</td>
<td>3.79</td>
</tr>
<tr>
<td>Front End Loader</td>
<td>80</td>
<td>1.70</td>
<td>11.55</td>
</tr>
<tr>
<td>Grader</td>
<td>138</td>
<td>0.39</td>
<td>2.77</td>
</tr>
<tr>
<td>Horizontal Directional Drill</td>
<td>100</td>
<td>0.49</td>
<td>3.55</td>
</tr>
<tr>
<td>Hydraulic Crane</td>
<td>130</td>
<td>0.42</td>
<td>1.63</td>
</tr>
<tr>
<td>Hydraulic Excavator</td>
<td>160</td>
<td>0.39</td>
<td>3.13</td>
</tr>
<tr>
<td>Pneumatic Roller</td>
<td>100</td>
<td>0.55</td>
<td>4.86</td>
</tr>
<tr>
<td>Self-Propelled Crane</td>
<td>200</td>
<td>0.42</td>
<td>1.72</td>
</tr>
<tr>
<td>Tandem Roller</td>
<td>125</td>
<td>0.55</td>
<td>4.86</td>
</tr>
<tr>
<td>Trencher</td>
<td>150</td>
<td>0.70</td>
<td>6.55</td>
</tr>
<tr>
<td>Vibratory Roller</td>
<td>174</td>
<td>0.55</td>
<td>4.86</td>
</tr>
</tbody>
</table>
The transient adjustment factor accounts for the differences in engine load between the steady-state test (upon which the original factors are based) and actual use during construction activities. This adjustment reflects the impact of varying equipment types. The deterioration factor accounts for differences in emissions due to the age of the engine.

Emissions factors are multiplied by the amount of time that the equipment was used to obtain the total emissions for each activity. The total emissions for the project were determined by summing the total emissions for each activity. The total quantity of emissions was then used to calculate productivity emissions rate factors (emissions per dollar and emissions per foot of street length) by dividing total emissions by the total length of the street constructed and total emissions by the total cost of the project as calculated using RS Means. If desired, it is also easily possible to determine emissions per day. Figure 3.1 is a visual representation of these calculations steps.

The cost emissions rate is an important early stage emissions indicator, enabling an unrefined emissions estimate to be obtained for a project based solely on knowing its preliminary cost. This is important because these totals represent the project’s overall environmental impact. Over time, such a preliminary forecast can be more precisely determined as more is learned about the details of the project such as the actual construction activities to be undertaken and details about the composition of the actual construction equipment fleet to be used.
3.4 Results

This section presents the emissions results for each entire project as well as for individual project activities. All four projects are compared. It is important to note that street construction projects have activities that include heavy equipment use which tend to produce large quantities of emissions throughout the entire project.

3.4.1 Project CO₂ Emissions

While our entire study encompassed six pollutants, we are presenting results here only for CO₂ because this pollutant is prevalently discussed in previous literature and because CO₂ is
linked to climate change. The total daily project emissions for CO₂ for the four projects are presented on Figures 3.2, 3.3, 3.4 and 3.5. The profiles for all the other pollutants follow a similar shape with different magnitudes of daily total emissions. These are discussed in later sections.

Figure 3.2. CO₂ Emissions per Day for the Little Street Project
Figure 3.3. CO₂ Emissions per Day for the West Burkhead Project

Figure 3.4. CO₂ Emissions per Day for the Sutton Place Project (Phase 1)
The CO$_2$ emissions distribution for the Little Street project is presented on Figure 3.2. The figure shows a high peak on day six of the construction project. The activities for day six included pavement demolition and the excavation needed during demolition and required the use of a backhoe and a front-end loader. The second highest quantity of emissions occurred on day 51 and corresponded with work for the connection of the new water system to the existing meters and the installation of storm water piping under the street. The crew for these activities included a backhoe loader and an excavator and consisted of trenching, backfilling, and other excavation activities. The total project CO$_2$ emissions were approximately 112 million grams and the average emissions per day were 1.7 million grams.

The CO$_2$ emissions distribution for the West Burkhead project is presented on Figure 3.3. This was an extremely short project. The figure shows a high peak on the second day of construction when the contractor was demolishing the existing street. The crews for these
activities required the use of a backhoe and a front-end loader working to demolish the street and load the material into dump trucks for disposal. The sanitary sewer was either abandoned or demolished and replaced during day six, resulting on another, but smaller, peak. The equipment utilized by the crews for these activities were self-propelled crane, bulldozer, vibratory roller, backhoe loader, and concrete pump. The total project CO\textsubscript{2} emissions were approximately 88 million grams and the average emissions per day were 9.7 million grams.

Figures 3.4 and 3.5 show the CO\textsubscript{2} emissions for the two phases of the Sutton Place project. The distributions of emissions were very similar in shape because both phases were comprised of the same activities with different quantities. The highest emissions production occurred during the installation of the water distribution system that included the use of a trencher. The water system installation occurred on days 32 to 36 for Phase 1 and days 61 to 75 for Phase 2. The second highest emissions quantities correspond to the stripping of top soil and the initial excavation. The crews for these excavation activities included a bulldozer and a front-end loader. The stripping and excavation activities occurred during days 16 and 17 on Phase 1 and days 15 to 29 on Phase 2. For Phase 1, the total project CO\textsubscript{2} emissions were approximately 147 million grams and the average emissions per day were 3 million grams. For Phase 2, the total project CO\textsubscript{2} emissions were approximately 356 million grams and the average emissions per day were 3.5 million grams.

3.4.2 Other Pollutants

To illustrate the collective impact of all six of the pollutants we introduce Figure 3.6 which presents the emissions from the Little Street Project study. These emissions are presented as a percentage of total emissions by days of construction. There were two distinctive groups of pollutants. HC, CO, and PM all start at a higher percentage than CO\textsubscript{2}, SO\textsubscript{2}, and NO\textsubscript{x}. The basic difference between these two groups was the front-end loader (used for the demolition activities) which tends to produce more HC, CO, and PM. The bulldozer and rollers tend to produce more of the other three pollutants and were used more often, for longer periods, and
at a later time in the project than the front-end loader was. As a result, the percentage of total emissions for HC, CO, and PM that is produced at the beginning of the project is much higher than the percentage of the other pollutants. The emissions for CO₂ and SO₂ (the bottom two overlapping lines) have nearly identical shapes because both factors are directly derived from fuel use.

The graph in Figure 3.6 also presents three slopes for emissions production. A large quantity of emissions is produced at the beginning of the project resulting in an almost vertical slope up to day 5. From day 6 to day 42, the emissions production is constant resulting on slope close to horizontal. From day 43 to 64 the emissions production increases resulting on a larger slope. The graph shows that by day 42, two thirds of the duration of the project, 66% of HC, PM, and CO was produced as well as 50% of NOₓ, CO₂, and SO₂.

The configuration presented in Figure 3.6 is opposite to the lazy S graphs that are usually shown on other construction related data. An example of this type of graph is the cash flow during a construction project. The cash flow at the beginning of the project is slow resulting in a small slope. Later during the project, the cash flow increases resulting on a more pronounce slope during the middle of the project. At the end of the project, the cash flow decreases resulting on a small slope. Emissions production seems to have a different pattern to what is normally expected for construction resources.

The other three projects that were studied had similar profiles for the six pollutants. For these projects, the CO and PM lines are again extremely close to each other. This also holds true for the CO₂ and SO₂ lines.
3.4.3 **Activity Emissions**

The emissions profiles for all four projects show that differing levels of emissions were produced over time for the entire duration of the project. The majority of all of the activities that are required to complete a transportation project include the use of non-road diesel powered equipment.

Table 3.4 shows the percent of total emissions for each project activity for the projects that have a demolition activity (and for each pollutant) as well as the average percentage of emissions for each pollutant. For both Little Street and West Burkhead, demolition was the activity that produced the largest amount of HC, CO, and PM emissions. Earthwork produced similar emissions amounts. The high emissions quantities for the peak activities of demolition and earthwork are directly linked to the equipment used and the high emissions factors for
that equipment. For the projects that did not have a demolition activity (Sutton Place Phases 1 and 2) earthwork was the activity with the highest quantity of emissions for both projects and for all the pollutants.

Table 3.4 provides the quantification of our research results, which could be made available to the research community. We have also included Figure 3.7 to illustrate the relative comparison between the different pollutant types and between the two projects with demolition. This chart allows for a quick comparison in terms of percent emissions.

Table 3.4. Percent of Emissions for Each Activity for Projects with Demolition

<table>
<thead>
<tr>
<th>Project</th>
<th>Pollutant</th>
<th>Percent of Total Emissions per Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Demolition</td>
</tr>
<tr>
<td>Little Street</td>
<td>HC</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>NOx</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>PM</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>CO2</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>SO2</td>
<td>19</td>
</tr>
<tr>
<td>West Burkhead</td>
<td>HC</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>NOx</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>PM</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>CO2</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>SO2</td>
<td>14</td>
</tr>
<tr>
<td>Average</td>
<td>HC</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>NOx</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>PM</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>CO2</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>SO2</td>
<td>17</td>
</tr>
</tbody>
</table>
Figure 3.7. Visual Representation of the Percent of Emissions for Each Activity for Projects with Demolition

An important factor affecting total project emissions is the amount of work that has to be completed over time. For example, demolition and earthmoving activities not only utilized highly polluting equipment (with high emissions factors) but they also required the movement of a large quantity of the material in a small amount of time. Demolition for Little Street was completed in two days and for West Burkhead in one day.

Demolition and earthwork activities both utilize front-end loaders. These have a large emissions factor for HC, CO and PM. The bulldozer and trenchers used for the earthwork (and other later activities) emit more NOx, CO2, and SO2. This is reflected on the emissions factors shown in Table 3.3.
3.4.4 Emissions by Equipment Type

The analysis of emissions per activity showed that demolition and earthwork are the most polluting type of activity. The main equipment types used for these activities were backhoes, front-end loaders, bulldozers, and trenchers. Table 2 showed that front-end loaders and backhoes are the equipment with the largest emissions factors for HC, CO, NOx, and PM from the NONROAD model.

Table 3.5 shows the percentage of emissions produced by each item of equipment for each pollutant. Front-end-loaders are the major contributor of HC, CO, NOx, and PM emissions while trenchers produced the highest average emissions for CO2, and SO2. As before, Figure 3.8 presents these data using a stacked bar chart.

The type of equipment used for each project was different. Trenchers were not used for Little Street and West Burkhead. Sutton Place Phase 1 and Sutton Place Phase 2 did not use backhoes. Table 3.4 clearly shows that front-end loaders and trenchers are the two equipment types with the largest effect on pollutant emissions followed by excavators and bulldozers.
Table 3.5. Percent Emissions by Equipment Type for the Projects

<table>
<thead>
<tr>
<th>Project</th>
<th>Pollutant</th>
<th>Percent Emissions per Equipment Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FE Loader</td>
<td>Bulldozer</td>
</tr>
<tr>
<td>Little Street</td>
<td>HC</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>NO&lt;sub&gt;x&lt;/sub&gt;</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>PM</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>SO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>15</td>
</tr>
<tr>
<td>West Burkhead</td>
<td>HC</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>NO&lt;sub&gt;x&lt;/sub&gt;</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>PM</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>SO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>8</td>
</tr>
<tr>
<td>Sutton Place Phase 1</td>
<td>HC</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>NO&lt;sub&gt;x&lt;/sub&gt;</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>PM</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>SO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>17</td>
</tr>
<tr>
<td>Sutton Place Phase 2</td>
<td>HC</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>NO&lt;sub&gt;x&lt;/sub&gt;</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>PM</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>SO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>11</td>
</tr>
</tbody>
</table>

NA signifies that the specified equipment was not used on that project.
3.4.5 Differences Between the Four Street Projects

The emissions profiles by day for the four projects shown in Figures 3.2-3.5 look different because of the different characteristics of each project. Both the Little Street and West Burkhead projects were rehabilitations that included removing the existing street and removing and reinstalling the utility system. The Sutton Place project was a new street for a subdivision and included only the installation of utilities and required no demolition and
removal. Tables 3.3 and 3.4 showed the emissions per activity that reflect the different
distribution of work per project.

The construction time for the West Burkhead project was only 9 days. The short duration of
the project affected its emissions profile (Figure 3.3) and was due not only to the short length
of the street but also to the circumstances surrounding the project. The construction was
categorized as an urgent project that needed to be fixed as soon as possible. The local
government acquired all the permits and documentation needed in an expedited manner and
construction proceeded at an accelerated pace.

The Sutton Place project was a new street. The project was completed in two phases, each
with different emissions profiles. The first phase lasted 49 days and the second phases lasted
101 days.

The differences between the four projects’ characteristics account for the differences between
their emissions per activity. However, a comparison of emissions by percent complete for the
four projects highlights similarities. Figure 3.9 shows the cumulative emissions over time for
the four street projects. For all the street projects, the first few days of construction were used
for mobilization and preparation without the use of non-road equipment. This is reflected in
the low emissions production rate shown. After that, the first activity included the preparation
of the entire area of construction (demolition and earthwork) producing a sharp initial jump
in emissions. Various items of equipment were continuously used, producing different but
nearly continuous amounts of emissions each day and resulting in similar emissions graphs
for all the projects.

Figure 3.9 also shows that even when all the projects have a similar behavior over time, the
two project that require demolition and repaving (West Burkhead and Little Street), have
higher emissions at the beginning of the project. The two projects that included new
construction, (Sutton Place 1 and Sutton Place 2), have a slower production of emissions at
the beginning of the project. This difference can be due to the large quantity of emissions that
are produced during the demolition activity and the effect of not having this activity in a
project.

For the Little Street and West Burkhead projects, half of the emissions were produced before
the projects were 40% completed. When the West Burkhead project was half way completed,
two thirds of the emissions had already been produced. For Sutton Place, 30% and 37% of
the emissions for phases 1 and 2, respectively, were produced at the midpoint of the project.

Figure 3.9. Comparison of Cumulative CO₂ as Percent Street Projects
Table 3.6 shows the emissions per thousand dollars and per foot of street length for the four street projects. The rates were calculated using the total cost resulting from the RS Means information.

Some of the differences in the percent-completed quantities shown in Figure 3.9 are related to the amount of time at the beginning of the project when there were no emissions. For SP1 there were no emissions for the first 14 days (33% complete). By contrast, the Little Street project started producing emissions on day 2 (3% complete).

### Table 3.6. Emissions Metrics for the Street Construction Projects

<table>
<thead>
<tr>
<th>Metric</th>
<th>Pollutant</th>
<th>Average Street</th>
<th>Little Street</th>
<th>West Burkhead</th>
<th>Sutton Place Phase 1</th>
<th>Sutton Place Phase 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grams per thousand dollars</td>
<td>HC</td>
<td>97</td>
<td>95</td>
<td>109</td>
<td>106</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>747</td>
<td>680</td>
<td>787</td>
<td>865</td>
<td>656</td>
</tr>
<tr>
<td></td>
<td>NO\textsubscript{x}</td>
<td>814</td>
<td>791</td>
<td>998</td>
<td>797</td>
<td>670</td>
</tr>
<tr>
<td></td>
<td>PM</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>CO\textsubscript{2}</td>
<td>680,000</td>
<td>629,000</td>
<td>845,000</td>
<td>673,000</td>
<td>572,000</td>
</tr>
<tr>
<td></td>
<td>SO\textsubscript{2}</td>
<td>119</td>
<td>110</td>
<td>148</td>
<td>118</td>
<td>100</td>
</tr>
<tr>
<td>Grams per foot of street length</td>
<td>HC</td>
<td>17</td>
<td>21</td>
<td>17</td>
<td>18</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>144</td>
<td>164</td>
<td>135</td>
<td>162</td>
<td>115</td>
</tr>
<tr>
<td></td>
<td>NO\textsubscript{x}</td>
<td>157</td>
<td>190</td>
<td>165</td>
<td>154</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>PM</td>
<td>0.5</td>
<td>0.57</td>
<td>0.5</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>CO\textsubscript{2}</td>
<td>1.62E+05</td>
<td>1.88E+05</td>
<td>1.76E+05</td>
<td>1.59E+05</td>
<td>1.27E+05</td>
</tr>
<tr>
<td></td>
<td>SO\textsubscript{2}</td>
<td>28</td>
<td>33</td>
<td>31</td>
<td>28</td>
<td>22</td>
</tr>
</tbody>
</table>

### 3.5 Conclusions

The fundamental questions addressed in this paper were how to quantify (and thus determine) the emissions produced for the construction of street and utility transportation construction projects, what factors resulted in higher or lower emissions (and how do these change over time), and how do different project types compare with respect to emissions production? The
objective of this work was to provide a methodology to both estimate and forecast emissions from street and utility infrastructure projects. No similar work had previously been done. Thus, we provide a greater understanding of the emissions from these projects.

The four street construction projects showed similar profiles of emissions. All four projects experienced a period without emissions at the beginning of the project followed by a short period with very high emissions production. After that, emissions were uniformly produced at a relatively steady rate throughout the rest of the project, with perhaps one more peak during the second half of the period. This uniform emissions production occurred, in part, because street construction requires the use of non-road equipment for the majority of the activities. As a result, it is clear that the profile is quite similar for the street projects. These results hold true for all pollutants.

This study showed that demolition and earthwork have a significant impact on the emissions produced during street construction. Those interested in emissions should pay close attention to these activities because changes in activity duration and productivity could have a significant impact on total project emissions. These activities would be particularly important to maintain and control if emissions regulations are put in place to regulate daily emissions peaks.

The equipment types for the four street construction project with the greatest influence on emissions were backhoes, front-end loaders, bulldozers, and trenchers. These types of equipment have high NONROAD model emissions factors. However, because of their versatility, these items of equipment will continue to be used for a wide variety of construction activities and thus, will continue to be large emissions producers.

When examining the emissions profiles for all the pollutants we observed that HC, CO, and NOx were produced at higher rates at the beginning of the project while CO2, SO2, and PM tended to be produced later. Furthermore, these two groupings of the six pollutants exhibit
similar characteristics and trend together tightly. This could have implications for those trying
to regulate particular types of pollutants.

It was also observed that the graph of cumulative emissions production during the project has
a different configuration than the one typically seen for construction factors. The graph does
not present the lazy-S shape but more of a lazy-Z shape. The graph shows a large growth at
the beginning of the project, slow growth during the middle of the project, and another section
of large growth at the end of the project.

Results also showed that some activities have a larger contribution of emissions for each
project. Future construction professionals and regulators can use this knowledge to
concentrate their pollution reduction efforts on the construction activities that have the largest
impact on total emissions.

Comparisons between the different projects were made using measures of emissions per dollar
of construction cost. This factor can be used in the future to develop forecasts for construction
projects during their planning or early construction phases. Being able to accurately forecast
emissions in an early planning or design stage will be beneficial for addressing future
environmental and emissions regulations and in achieving desired pollution reductions.

3.6 Future Work

The work presented herein utilized both contractor and RS Means data to forecast the total
quantity of emissions for four street construction projects using EPA emissions factors for
typical construction equipment types and sizes. The work does not, however, account for the
fact that any given contractor has a limited availability of equipment in his fleet for use on his
construction projects. Future work should include the forecasting of project emissions based
on the specific equipment type and tier actually used on site during the project. Hopefully,
data can be obtained from contractors who maintain a detailed equipment use record that
includes daily hours of operation and fuel use as well as basic specifications about the equipment used.

Future work should also be directed at determining the effects of different equipment characteristics on emissions factors. Having a better understanding of the effects of equipment type, engine size, and engine tier on the emissions can help contractors to make decisions on equipment usage to comply with future regulations. It can also aid in their selection of new equipment purchases. Additional work should also be done to determine the effect of engine tier on emissions. Calculating total emissions using equipment of different tier can help to determine the difference on emissions and assess the effect of the regulations.

In the future, different types of projects should be analyzed to see how their emissions profiles compare to projects analyzed to this point. This could include residential buildings, commercial buildings, high-rise buildings, and various types of transportation projects beside streets. The results presented here found clear similarities between street construction projects. A larger numbers of studies need to be undertaken. A larger emissions inventory needs to be assembled to better establish the generalizability of the results presented in studies such as this one.

Only non-road construction equipment was studied herein. Future studies should obtain detailed forecasts of pollutants for on-road vehicles such as dump trucks, flatbed trucks, and concrete mixer trucks. The EPA NONROAD model used here only offers emissions factors for equipment that does not travel on the road. The EPA also developed a model to estimate emissions from on-road vehicles called MOVES. However, the categories used by this model to determine emissions do not include ones that correspond to construction vehicles moving on the road. Future studies should be completed to find the best alternative for these emissions factors.

This paper focused on emissions from non-road heavy duty diesel powered equipment that is used on construction sites. The pollutants studied were the exhaust pollutants from
construction equipment; we did not include other emissions related to a construction projects such as fugitive particulate matter (e.g. from dust). Additional work should be done to assess the effects of all the emissions associated with the use of construction equipment on the construction site. This estimation would help to assess the effect of construction activities on the workers, operators, and the community.

Useful measures of emissions are critical for the proper assessment of their impact in the Architecture-Engineering-Construction and infrastructure markets. We presented measures of emissions per dollar and per foot of street length because these measures are clearly useful at all project stages and can be used for long term planning as well. Of course, additional research is needed to assess the variability of the emissions per dollar and per foot of street length metrics on projects of varying size and cost. A variety of other measures should be considered, studied, and quantified as well.

Finally, more research needs to be done to determine the effect of possible future regulations on emissions and the resulting productivity of construction activities. New and stricter regulation could have a significant impact on the construction methods currently used by contractors. Having an accurate forecasting model (and taking into consideration the unique characteristics of construction work) may enable government agencies to develop regulations that will help to reduce air pollution from construction projects. Construction professionals could themselves use more accurate forecasts to make decisions on what is the most efficient way to reduce emissions without negatively affecting productivity.
4.0 EMISSIONS ESTIMATION AND COMPARISONS FOR TRANSPORTATION CONSTRUCTION PROJECTS USING FIELD AND PUBLISHED DATA

4.1 Introduction

Typically, an infrastructure project is studied from different perspectives during the planning and design phases to assess the impact the project will have on the community, the existing infrastructure system, and the environment. Such analysis is particularly intense during the development of highly visible transportation projects, especially highway projects. The impacts of these types of projects on the community and infrastructure are visible and obvious to the general public. Air pollution emissions are one of the effects that are of special interest because of the dangers they pose. The impact of future emissions from passenger cars, heavy-duty trucks, and other vehicles using the facility is an important area of study during early phases of the project. However, such study does not typically include construction equipment emissions assessments leaving a full understanding of the emissions produced during the construction processes as an important void in the body of knowledge.

The operation and use phases of a facility (street, road, building, etc.) are of a significantly longer duration than the construction phase itself. However, the emissions produced during construction may be localized and strong and may have a direct effect on nearby workers and equipment operators as well as on communities surrounding the project.

Understanding and forecasting the emissions that are produced during the construction phase of a project would enable us to benchmark and eventually reduce the negative effect of these emissions. To achieve this end, construction professionals and regulatory agencies need an emissions estimation tool to quantify and assess the emissions produced by any particular construction project. Then, future industry and regulatory policies and guidelines could be developed taking into consideration the unique contributions of construction.
This paper first focuses on equipment emissions impacts during the road construction process. In doing so, it reports on road construction data collection, on the problems associated with the use of project and activity data, on the forecasting of emissions using that data, on the forecasting of emissions using RS Means data, and on a comparison between the two road projects. Next, the paper reports the results of four previous street and utility projects and one commercial building project. Finally, it presents a comparison of all seven projects and the conclusions that can be drawn from them.

4.1.1 Research Questions and Objectives

One research question to be addressed herein is, “how does contractor supplied field data compare with published data when used in an emissions forecast model?” This question is important to determine if emissions can be forecast when we do not have actual data, for example, during a project planning phase. To answer this question we investigated two different data sources. The first data source was information that the general contractor and the inspector collected in the field. The second data source was information from RS Means (Means 2013), a widely used construction activity database containing the type of project information that is commonly available to the construction community during early stages of a project. We compared emissions calculated using contractor data with emissions calculated using RS Means data. In doing so we are also able to address the research question of “can RS Means data be reliably used (in the event that field data are unavailable) as a surrogate to quantify emissions?” In a predictive mode we can also ask, “can RS Means data be used as a reliable source to forecast emissions prior to construction or in early planning and design stages?”

Another research question to be addressed herein is, “to what extent, if any, do different project types vary in their emissions during construction?” To answer this question we compared the emissions forecasts of the road projects presented herein to results from previous work that forecast emissions for four street and utility construction projects. The
results for all six transportation projects are then compared with results from a building construction project.

Results from the different types of projects can be used to understand how the emissions profiles change between different activities and schedules. These comparisons begin to reveal general patterns on emissions that should be helpful to all stakeholders. In the future, this information could be used to calculate emissions factors per dollar or per productivity unit that could then be used to forecast emissions for numerous other projects during their early planning stages. Early emissions forecasts can be used to improve design alternative selection. Thus, a third research question addressed in this paper is, “are there metrics by which emissions forecasts can be compared across various project sizes and types?”

We have investigated and reported on nonroad on-site construction emissions studies for some time. The projects that have been studied varied by size and type and included a commercial building, four street and utility installation projects, and two road projects. The purpose of this new paper is twofold. First, we present the data for, and results from, the highway construction projects. Second, we tie all of our work together by presenting a comparison between all seven projects. In doing so we address the research questions articulated above.

4.1.2 Scope

This paper focuses on forecasting emissions from the exhaust system of nonroad construction equipment during the construction process. The six pollutants studied are hydrocarbons (HC), nitrogen oxide (NOx), carbon monoxide (CO), particulate matter (PM), sulfur dioxide (SO2), and carbon dioxide (CO2). Emissions from other parts of the equipment such as the braking system are not included. This paper also does not include other air pollution produced during the construction project such as fugitive dust.

The equipment used for the calculations in this paper was categorized using the tier system derived from the US Environmental Protection Agency (EPA) regulations. Engine tier is a
categorization of equipment by age and by regulated emissions quantities for that age. Engines can be identified by the emissions levels that were in place for that model year with each subsequent tier being more restrictive with respect to allowable emissions quantities. For example, construction equipment diesel engines manufactured before the regulations were in place are called Tier 0 engines. Diesel engines that comply with the first regulation that was in place in 1996 are referred to as Tier 1 engines. Tier 4 regulations will be fully implemented by 2015 [EPA 2010].

Emissions were calculated for two highway construction projects. The first one, referred to as the Apex project, was the relocation of a road. The second project, referred to as the Wake Forest project, was the widening of an existing road. The two projects included different activities and had significantly different schedules. Emissions from these two projects are then compared to those from four street and utility construction projects [Arocho et al. 2015] and to one building construction project [Marshall et al. 2012].

4.2 Literature Review

The impact of the life cycle of various construction projects has been studied in the past. Such studies have demonstrated that the construction phase accounted for 9% of the CO2 emissions from residential projects in Canada [Baouendi et al, 2005]. Elsewhere it was shown that asphalt and bridge repair projects produced 3.5 times more NOx emissions than building projects [Sharrard et al, 2008], and that using recycled materials for transportation construction projects reduces greenhouse gas emissions and improves sustainability [Lee et al. 2011].

It has also been established that highway construction produces a large amount of waste [Gambatese 2005]. Lee et al. presented a rating system that quantitatively assessed highway designs with respect to their environmental impact [Lee et al., 2014]. In the building industry, Chiang et al. developed and optimization model to identify materials that reduce carbon
emissions, cost, and labor deployment [Chiang et al, 2014]. The collective results from life cycle studies show that emissions during the construction phase are significant, particularly when the duration of the construction phase increases compared to the operation phase. Still, a comprehensive framework enabling construction stakeholders to estimate, benchmark, and monitor the environmental impact associate with their construction operations has yet to be defined [Ahn et al. 2014].

One interesting recent study focused on greenhouse gas (GHG) emissions during the construction of transportation projects in Korea [Kim et al. 2012]. The paper focused on CO₂, methane, and nitrous oxide emissions presented as CO₂ equivalent. The first step included the estimation of GHG emissions for two highway projects. The key finding was that earthwork activities consumed more fuel than any other activity and that dump trucks (on-road equipment) are the highest emitters of pollutants. Using these results, the authors calculated emissions during earthwork activities. The optimal equipment fleet for each activity was determined using typical equipment combinations. The activities and emissions quantities were determined using the design documents for each project.

Other studies have centered on measuring the emissions from highway maintenance equipment during use. A study by Lewis et al. [2009a] presented a maintenance equipment emissions inventory that was developed by measuring emissions both petroleum diesel and biodiesel blend (B20) fuels. The results from this study quantified the degree to which the equipment that used biodiesel produced lower emissions. This study also verified that equipment of higher tier produced lower emissions. The study did not address the effects of B20 on engine wear.

Cui and Zhu [2011] surveyed the use of green contracting strategies by state DOTs. The survey was completed by 39 states of which 25 reported using some type of green strategy. The findings indicated that New York, California, Washington, Oregon, and Illinois have green strategy programs that are enforced by the state government or DOT. This paper also
mentioned that EPA recommends the Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) that can be used to calculate the economic and environmental effects of an existing, proposed, or hypothetical highway construction project. The output of the tool includes the energy use and emissions produced during the construction and maintenance phases of the project, including material transportation. This program is currently only applicable to roadway construction. It also focuses on life cycle environmental effects and cost. It operates at the project level and does not assess the impact of individual construction project activities, which is a critical element addressed in our current paper.

A paper by Avetisyan et al. [2012] presented a decision model to select construction equipment for construction projects of any type, location, and conditions. The inputs for the model are derived from information provided by the contractor and included the amount of work and time available for each activity, list of equipment with details about capacity and compatibility, operational and maintenance cost, engine tier specifications, and emissions rates for the equipment. The model can be used to optimize equipment selection by cost and emissions production. The result of the model is a list of equipment that should be used for the project and the tier for each item of equipment. One case study was used to test the model.

In summary, research has been conducted in auto emissions, other on road vehicle emissions, life cycle emissions, standards development, emissions regulations, sustainability, and green infrastructure. However, other than previous work examining four street and utility projects [Arocho et al. 2015] and the project by Kim et al. (2012) (that looked at GHG emissions during the earthwork activities of highway construction projects) little has been done in estimating and benchmarking emissions from nonroad construction equipment performing highway construction work. This paper makes a contribution toward filling a part of that void. Furthermore, it is worth noting that life cycle analyses estimate the quantity of emissions produced during the construction process. The work described herein provides quantification for the construction process to fill that void (replace the estimate) in existing life cycle models.
4.3 Project Descriptions

This section presents descriptions of the two highway projects analyzed herein. Basic project information and details about the equipment fleet used on each project is included.

4.3.1 Apex Construction Project

The Apex project consisted of relocating Lufkin Road at the intersection with Ten Ten Road in the town of Apex, North Carolina. The project included work to widen approximately 1,100 feet of Ten Ten Road and relocate approximately 1,500 feet of Lufkin Road. The project also included storm water pipe relocation.

Figure 4.1 shows one of the work progress pictures taken during construction, after completion of grading (activity 4 noted below). The picture shows the new alignment of Lufkin Road and the completed excavation. At this point, the road is ready for the subgrade installation.

Figure 4.1. Picture Showing the New Alignment of Lufkin Road
The equipment data obtained from the contractor for the Apex project included equipment type and model, when available. However, the level of detail did not include model year or engine tier. The general contractor reported that they are converting their fleet to Tier 3. The calculations for this study were therefore completed assuming that the general contractors’ fleet was Tier 3 and the subcontractors’ fleet was Tier 2. This assumption corresponds to information provided by the general contractor and the idea that subcontractors will be slower to upgrade all their equipment to the latest models and tier.

Table 4.1 shows the equipment that was used during the Apex project and the horsepower that were used for the calculations.

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>HP</th>
<th>Equipment Type</th>
<th>HP</th>
<th>Equipment Type</th>
<th>HP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Compressor</td>
<td>117</td>
<td>Excavator 4</td>
<td>140</td>
<td>Paver</td>
<td>174</td>
</tr>
<tr>
<td>Asphalt Distributor</td>
<td>5.5</td>
<td>Excavator 5</td>
<td>140</td>
<td>Pneumatic Roller</td>
<td>80</td>
</tr>
<tr>
<td>Backhoe</td>
<td>100</td>
<td>Excavator 6</td>
<td>169</td>
<td>Roller 1</td>
<td>145</td>
</tr>
<tr>
<td>Brush Chipper</td>
<td>85</td>
<td>Excavator 7</td>
<td>100</td>
<td>Roller 2</td>
<td>99</td>
</tr>
<tr>
<td>Bulldozer 1</td>
<td>130</td>
<td>Excavator 8</td>
<td>386</td>
<td>Roller 3</td>
<td>33</td>
</tr>
<tr>
<td>Bulldozer 2</td>
<td>121</td>
<td>Excavator 9</td>
<td>140</td>
<td>Roller 4</td>
<td>99</td>
</tr>
<tr>
<td>Bulldozer 3</td>
<td>140</td>
<td>Excavator 10</td>
<td>232</td>
<td>Rubber Tire Loader</td>
<td>196</td>
</tr>
<tr>
<td>Bulldozer 4</td>
<td>90</td>
<td>Front End Loader</td>
<td>200</td>
<td>Scaper 1</td>
<td>175</td>
</tr>
<tr>
<td>Bulldozer 5</td>
<td>90</td>
<td>Grader 1</td>
<td>135</td>
<td>Scraper 2</td>
<td>265</td>
</tr>
<tr>
<td>Bulldozer 6</td>
<td>121</td>
<td>Grader 2</td>
<td>135</td>
<td>Skid Steer 1</td>
<td>56</td>
</tr>
<tr>
<td>Bulldozer 7</td>
<td>90</td>
<td>Loader</td>
<td>128</td>
<td>Skid Steer 2</td>
<td>46</td>
</tr>
<tr>
<td>Compact Track Loader</td>
<td>84</td>
<td>Milling Machine</td>
<td>140</td>
<td>Straw Blower</td>
<td>125</td>
</tr>
<tr>
<td>Curb Machine</td>
<td>130</td>
<td>Mini Excavator</td>
<td>39.4</td>
<td>Tandem Roller</td>
<td>100</td>
</tr>
<tr>
<td>Excavator 1</td>
<td>100</td>
<td>Mixer</td>
<td>25</td>
<td>Trench Roller</td>
<td>18</td>
</tr>
<tr>
<td>Excavator 2</td>
<td>140</td>
<td>Mulch Blower</td>
<td>33.5</td>
<td>Trencher</td>
<td>120</td>
</tr>
<tr>
<td>Excavator 3</td>
<td>140</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.3.2 Wake Forest Project

The Wake Forest project consisted of widening Royal Mill Avenue in the town of Wake Forest, NC. The work included grading, installing a missing curb, and paving as well as minor utility relocation work. The original road was half the width of the new one and had curb on one side only.

Figure 4.2 shows a picture taken during one of the visits by the authors to the construction site. The picture illustrates the project during the paving activity (activity 6 noted below). Note that the new curb has already been installed and is visible where the work is being undertaken.

![Figure 4.2. Picture of the Paving Activity on Royal Mill Avenue](image-url)
The estimated cost of the project was $203,000 and it was completed in 13 construction days. The project included approximately 1,300 feet of road. The activities completed for the Wake Forest project included:

1. Grading  
2. Gravel subgrade installation  
3. Utilities  
4. Curb  
5. Backfill outside the curb  
6. Paving

The equipment data obtained from the general contractor included equipment type and engine size, model, and year. This information was used to determine the emissions factors based on the EPA NONORAD model. Table 4.2 shows the equipment that was used during the project with the engine size in horsepower.

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>HP</th>
<th>Equipment Type</th>
<th>HP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulldozer</td>
<td>90</td>
<td>Curb Machine</td>
<td>130</td>
</tr>
<tr>
<td>Motor Grader</td>
<td>150</td>
<td>Paver</td>
<td>205</td>
</tr>
<tr>
<td>Pan Scraper</td>
<td>175</td>
<td>Roller 2</td>
<td>137</td>
</tr>
<tr>
<td>Backhoe</td>
<td>94</td>
<td>Broom Tractor</td>
<td>50</td>
</tr>
<tr>
<td>Roller 1</td>
<td>145</td>
<td>Mini Excavator</td>
<td>20</td>
</tr>
</tbody>
</table>

### 4.4 Methodology

This section presents the methodology used to calculate total emissions for the construction projects mentioned in the previous section. Emissions were calculated using two data sources. The first method used the actual project and equipment data collected from the general contractor. The second method used RS Means data to forecast the project schedule and the equipment fleet required. The purpose was threefold: to benchmark field data with RS Means;
to compare different projects; and, to compare different project types using common construction metrics.

4.4.1 Apex Project Emissions Forecasting Using Field Data

The project and activity data for the Apex project were obtained from both the general contractor and the company that performed the contract administration, inspection, and material testing as an extension of the owner’s staff. The data collected included project plans, bid cost, proposed schedule, photos, and daily reports from the construction site. The daily reports documented the activities that were undertaken and completed each day including the labor hours and equipment use hours for each subcontractor. The basic project data and the daily reports were compiled, reconciled, and used by the authors to develop a project schedule that focused on the equipment used for each activity.

The emissions factors for each item of equipment were determined using the EPA NONROAD model. The equipment data from the daily reports was used to determine equipment type and model. The engine tier was determined as noted in Section 4.3.1 and was used to obtain the emissions factors as well as to adjust them for age and deterioration. The factors were multiplied by the horsepower of each item of equipment to obtain grams per hour factors. For a further discussion of the NONROAD model and how it obtains emissions rates see Marshall et al [2012].

The duration of each activity was obtained from the project schedule. The emissions factors were multiplied by the activity duration in hours to determine total emissions for that construction activity. Summing all activity total emissions results in total project emissions.

To determine emissions per day the project schedule was consulted to identify which activities were underway on each project day. The amount of daily total project emissions is the sum of all the different daily activity emissions occurring on that day. Emissions per dollar and
emissions per square foot of pavement were then calculated by dividing the total project emissions by the actual project cost and project size, respectively.

4.4.2 Wake Forest Project Emissions Forecasting Using Field Data

For the Wake Forest project a wealth of field data including basic project data, documentation of project activities, pictures, and equipment data were obtained during site visits. The foreman for the job also collected data on the hours of use for each item of equipment for each day as well as data on the subcontractors’ equipment.

Interviews with the foreman, project activity observations, and pictures were used by the authors to develop a field schedule for the project. The equipment use data came directly from the foreman’s reports that also included equipment model and year for the majority of the equipment. Emissions factors were determined using the equipment data and the factors from the EPA NONROAD model and were adjusted for equipment deterioration due to age and use per the formulas and procedures described by EPA [EPA 2010a, EPA 2010b]. All subsequent calculations (activity duration and emissions; total project emissions; and emissions per day, dollar, and square foot) were the same as those for the Apex project.

4.4.3 Emissions Forecasting from RS Means Data

The second data source used to calculate emissions for both construction projects was to determine the project schedule and to identify its equipment fleet using RS Means [Means, 2013]. However, RS Means cost data were not used to benchmark emissions because RS Means costs do not accurately reflect the project costs or bids reported to us by the contractors for these projects. Costs are often localized and are, at times, highly variable. Contractors tend to exclusively use their own cost metrics to determine bid cost. Thus, all costs used herein were the actual contractor’s costs or the bids reported by contractors.
The activities and quantity takeoffs were obtained from the project documents. Productivity and crews for each activity were obtained from RS Means. The crew data defined the labor and the equipment needed for each activity and included a description of the equipment using either its capacity (e.g., cubic yards) or its engine size (horsepower).

RS Means provides productivity data as units of production per day. The quantities provided by the contractor were divided by the productivity to determine the duration of each activity, which was then used to develop a schedule for the project.

Using the RS Means specified equipment data, the emissions factors were determined from the NONROAD model and adjusted for age and deterioration. The adjusted emissions factors were multiplied by horsepower to determine specific emissions factors. All emissions calculations were then performed as described earlier.

4.4.4 Project Comparison with Tier 3 Equipment

The equipment fleets that were used on the construction sites included engines of various tiers. The emissions forecast using RS Means were all based on Tier 3 equipment. Thus, the calculation of emissions using the actual fleet composition cannot be directly compared with the calculations using the RS Means fleets. To allow for a comparison the emissions were recalculated using Tier 3 for the field equipment.

The emissions calculation for the building that was presented in Marshall et al [2010] is herein included in this comparison to show the difference in emissions metrics for different types of projects. That building is a 13,400 square foot commercial structure with parking lot, sidewalks, and landscaping. The project was finished in 25 weeks at a total cost of $1.5 million. All calculations for it were completed using Tier 3 equipment.
4.5 Results

The following sections present the results for the emissions forecasts for the Apex and the Wake Forest projects.

4.5.1 Apex Project from Field Data

Total emissions for the six pollutants were calculated for the Apex project. Figure 4.3 shows the CO\textsubscript{2} emissions per day. Emissions for the other pollutants portray a similar emissions profile as for CO\textsubscript{2} but are omitted for space.

![Figure 4.3. Field CO\textsubscript{2} Emissions per Day for the Apex Project](image-url)
The graph shows two peaks of emissions, one on day 42 and other on day 117. The peak on day 42 corresponds to grading activities. The equipment used that day included two bulldozers, an excavator, two rollers, and a grader. The peak on day 117 corresponds to paving activities. The equipment used for paving included a paver, three rollers, a bulldozer, a loader, and a milling machine.

The largest bulk quantity of emissions was produced between days 20 and 48 which correspond to various simultaneous activities. The clearing and grubbing activity lasted from days 10 to 33 and storm drain pipe installation occurred during days 20 to 30. Grading started on day 28 and lasted until day 48. These three activities required the simultaneous use of multiple high emissions items of equipment including excavators, rollers, bulldozers, scrapers, and graders. Indeed, as expected, this equipment has the highest emissions factors and it produced the most pollution.

Table 4.3 shows the results in terms of the critical metrics of emissions per day, emissions per thousand dollars, and emissions per square foot for the Apex project for all six of the pollutants. The numbers show that CO₂ is the pollutant with the highest amount for the three metrics. Note again that the grams per dollar column is based on the total actual project cost provided by the contractor.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Pollutants</th>
<th>HC</th>
<th>CO</th>
<th>NOₓ</th>
<th>PM</th>
<th>CO₂</th>
<th>SO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grams per Day</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,270</td>
<td>1,500</td>
</tr>
<tr>
<td>Grams per Thousand Dollars*</td>
<td></td>
<td>183</td>
<td>1,240</td>
<td>1,310</td>
<td>209</td>
<td>1.23E+06</td>
<td>216</td>
</tr>
<tr>
<td>Grams per Square Foot</td>
<td></td>
<td>2.53</td>
<td>17.1</td>
<td>18.0</td>
<td>2.88</td>
<td>1.70E+04</td>
<td>2.99</td>
</tr>
</tbody>
</table>

* Based on bid cost as reported by the contractor
Table 4.4 shows the emissions per activity for the Apex project. The table shows that the individual activities producing the largest amount of emissions are clearing and grubbing, grading, and aggregate base course subgrade installation and paving. These activities correspond with the emissions peaks that are visible on Figure 5.4 for clearing and grubbing (days 10-33), grading (days 28-48), and paving (days 117-122).

<table>
<thead>
<tr>
<th>Activity</th>
<th>Pollutants (Thousands of Grams)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
</tr>
<tr>
<td>Mobilization</td>
<td>0.38</td>
</tr>
<tr>
<td>Clearing and Grubbing</td>
<td>36.7</td>
</tr>
<tr>
<td>Erosion Control</td>
<td>4.91</td>
</tr>
<tr>
<td>Grading</td>
<td>55.2</td>
</tr>
<tr>
<td>Storm Drain</td>
<td>17.0</td>
</tr>
<tr>
<td>Concrete Work</td>
<td>3.07</td>
</tr>
<tr>
<td>Guardrail and Fence</td>
<td>4.23</td>
</tr>
<tr>
<td>Markings and Signs</td>
<td>0.92</td>
</tr>
<tr>
<td>ABC and Paving</td>
<td>28.1</td>
</tr>
<tr>
<td>Traffic Signals</td>
<td>2.37</td>
</tr>
<tr>
<td>Utilities</td>
<td>4.88</td>
</tr>
</tbody>
</table>

4.5.2 Wake Forest Project from Field Data

Figure 4.4 shows the CO₂ emissions per day for the Wake Forest project. The graph shows two peaks of emissions, one on days 5 and 6 and one on day 13. The peak on day 6 corresponds with the placement of the gravel subgrade requiring the use of five items of equipment: bulldozer, motor grader, pan scraper, backhoe, and roller. The peak on day 13 corresponds to the paving operations requiring the use of a paver, a broom tractor, two tandem rollers, and a backhoe, all operating at once. Of these, the backhoe and the motor grader have the highest emissions factors. Table 4.5 shows the metrics calculated for each pollutant.
Table 4.5. Field Emissions Metrics for the Wake Forest Project

<table>
<thead>
<tr>
<th>Metric</th>
<th>Pollutants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
</tr>
<tr>
<td>Grams per Day</td>
<td>1,460</td>
</tr>
<tr>
<td>Grams per Thousand Dollars*</td>
<td>93</td>
</tr>
<tr>
<td>Grams per Square Foot</td>
<td>1.21</td>
</tr>
</tbody>
</table>

* Based on bid cost as reported by the contractor

Table 4.6 shows the emissions per activity for the Wake Forest Project. The individual activities with the highest emissions are the placement of the gravel subgrade and backfill. The gravel subgrade corresponds to one of the peaks presented on Figure 4.3 (days 5 to 7; bulldozer, motor grader, backhoe, scraper, and roller). While paving and grading activities are not the top emissions producers, they are close.
### Table 4.6. Field Emissions per Activity for the Wake Forest Project

<table>
<thead>
<tr>
<th>Activity</th>
<th>Pollutants (Thousands of Grams)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
</tr>
<tr>
<td>Grading</td>
<td>3.70</td>
</tr>
<tr>
<td>Gravel Subgrade</td>
<td>8.22</td>
</tr>
<tr>
<td>Utilities</td>
<td>0.02</td>
</tr>
<tr>
<td>Curb</td>
<td>0.74</td>
</tr>
<tr>
<td>Backfill</td>
<td>4.36</td>
</tr>
<tr>
<td>Paving</td>
<td>1.88</td>
</tr>
</tbody>
</table>

#### 4.5.3 Apex Project from RS Means Data

Figure 4.5 shows the CO\text{2} emissions per day for the Apex project. Days 5 through 12 included clearing and grubbing activities. Days 24 to 31 included various activities performed at the same time: erosion control, grading, and the installation of the storm drain. Emissions during days 50 to 55 are linked to the placement of base course for paving.

![Figure 4.5. RS Means CO\text{2} Emissions per Day for the Apex Project](image-url)
Table 4.7 shows the equipment fleet (compare with Table 4.1 for field equipment) that was used for the emissions determination using the RS Means data. The table shows equipment type and engine size in horsepower.

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>HP</th>
<th>Equipment Type</th>
<th>HP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate Spreader</td>
<td>203</td>
<td>FE Loader Wheel 2</td>
<td>196</td>
</tr>
<tr>
<td>Paver</td>
<td>130</td>
<td>Grader</td>
<td>158</td>
</tr>
<tr>
<td>Backhoe</td>
<td>48</td>
<td>Hydraulic Crane</td>
<td>315</td>
</tr>
<tr>
<td>Brush Chipper</td>
<td>130</td>
<td>Mulcher</td>
<td>275</td>
</tr>
<tr>
<td>Concrete Pump</td>
<td>77</td>
<td>Pavement Profiler</td>
<td>750</td>
</tr>
<tr>
<td>Concrete Saw</td>
<td>44</td>
<td>Pneumatic Roller</td>
<td>100</td>
</tr>
<tr>
<td>Crawler Crane</td>
<td>173</td>
<td>Crane 1</td>
<td>100</td>
</tr>
<tr>
<td>Crawler Loader</td>
<td>189</td>
<td>Crane 2</td>
<td>85</td>
</tr>
<tr>
<td>Curb Machine</td>
<td>99</td>
<td>Tandem Roller</td>
<td>129</td>
</tr>
<tr>
<td>Dozer</td>
<td>200</td>
<td>Trencher</td>
<td>12</td>
</tr>
<tr>
<td>FE Loader Wheel 1</td>
<td>96</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.8 shows the results for the emissions metrics for the Apex project using the RS Means data. The RS Means productivity data resulted on shorter project duration (87 days) than the actual duration (124 days) which is not surprising or significant given construction schedule variability for any number of reasons. This increases the grams per day by almost the same amount as the decrease in project duration. The grams per square foot with RS Means data is close to the same metric when calculated with field data (Table 4.3). As noted earlier this table does not include grams per dollar because the cost calculated from the RS Means data was not comparable with the actual cost presented by the contractor and thus it could not be reliably used herein.
Table 4.8. RS Means Emissions Metrics for the Apex Project

<table>
<thead>
<tr>
<th>Metric</th>
<th>HC</th>
<th>CO</th>
<th>NOx</th>
<th>PM</th>
<th>CO2</th>
<th>SO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grams per Day</td>
<td>1,690</td>
<td>11,500</td>
<td>11,700</td>
<td>46</td>
<td>1.08E+07</td>
<td>1,900</td>
</tr>
<tr>
<td>Grams per Square Foot</td>
<td>2.35</td>
<td>16.0</td>
<td>16.4</td>
<td>0.06</td>
<td>1.51E+04</td>
<td>2.65</td>
</tr>
</tbody>
</table>

Table 4.9 shows the emissions per activity for all the pollutants using the RS Means data. The activities with the highest total emissions are clearing and grubbing, erosion control, grading, and ABC and paving as marked on the table. These activities require the use of multiple items of equipment simultaneously. The larger contributor activities are concurrent with the activities identified as the larger contributors when emissions were calculated using field data.

Table 4.9. RS Means Emissions per Activity for the Apex Project

<table>
<thead>
<tr>
<th>Activity</th>
<th>Pollutants (Thousands of Grams)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
</tr>
<tr>
<td>Mobilization</td>
<td>0</td>
</tr>
<tr>
<td>Clearing and Grubbing</td>
<td>48</td>
</tr>
<tr>
<td>Erosion Control</td>
<td>50</td>
</tr>
<tr>
<td>Grading</td>
<td>13</td>
</tr>
<tr>
<td>Storm Drain</td>
<td>8</td>
</tr>
<tr>
<td>Concrete Work</td>
<td>0</td>
</tr>
<tr>
<td>Guardrail and Fence</td>
<td>4</td>
</tr>
<tr>
<td>Markings and Signs</td>
<td>0</td>
</tr>
<tr>
<td>ABC and Paving</td>
<td>21</td>
</tr>
<tr>
<td>Traffic Signals</td>
<td>0</td>
</tr>
<tr>
<td>Utilities</td>
<td>2</td>
</tr>
</tbody>
</table>

4.5.4 Wake Forest Project from RS Means Data

The calculation of project emissions using RS Means data requires the identification of equipment based on crew composition for each activity. Table 4.10 shows the items of
equipment (compare to table 4.2 for field equipment) that were needed for the Wake Forest project for each activity and the horsepower for each.

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>HP</th>
<th>Equipment Type</th>
<th>HP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paver</td>
<td>130</td>
<td>Vibratory Roller 1</td>
<td>180</td>
</tr>
<tr>
<td>Crawler Loader</td>
<td>189</td>
<td>Tandem Roller</td>
<td>129</td>
</tr>
<tr>
<td>Curb Machine</td>
<td>99</td>
<td>Vibratory Roller 2</td>
<td>156</td>
</tr>
<tr>
<td>Dozer</td>
<td>300</td>
<td>Pavement. Profiler</td>
<td>750</td>
</tr>
<tr>
<td>Front End Loader Crawler</td>
<td>90</td>
<td>F.E. Loader, Wheel 1</td>
<td>96</td>
</tr>
<tr>
<td>Grader</td>
<td>158</td>
<td>FE Loader, Wheel 2</td>
<td>69</td>
</tr>
<tr>
<td>Pneumatic Roller</td>
<td>100</td>
<td>Backhoe</td>
<td>48</td>
</tr>
</tbody>
</table>

Figure 4.6 shows the CO₂ emissions for the Wake Forest project as calculated using the crew and productivity data from RS Means. Note that the RS Means project duration is about the same as the actual duration. The graph shows a peak on day 3 that corresponds with the placement of gravel as a base for the pavement. The crew used for this activity included a grader, front-end loader, dozer, and vibratory roller.

The graph also shows a high concentration of emissions during days 6 to 8. These days represent the backfill activity that used a crawler loader during the entire day. The crawler loader is one of the items of equipment with the higher emissions factors, as can be seen in Table 4.10.

The emissions peak on day 11 includes the pavement activities that require various item of equipment to be working at the same time. The crew for the paving activity includes a paver, two tandem rollers, and a pneumatic wheel roller.
Table 4.11 shows the emissions metrics for the Wake Forest project as grams per construction day and grams per square foot. The emissions per construction day are higher for HC, but lower for CO, NOx, PM, CO\textsubscript{2}, and SO\textsubscript{2} compared with the emissions calculated with the equipment used by the contractor. The emissions per square foot are very similar to the emissions calculated before.

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Pollutants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
</tr>
<tr>
<td>Grams per Day</td>
<td>1.640</td>
</tr>
<tr>
<td>Grams per Square Foot</td>
<td>1.16</td>
</tr>
</tbody>
</table>
Table 4.12 presents total emissions per activity for the Wake Forest project. The table shows that backfill is the activity with the highest total emissions followed by gravel subgrade placement, corresponding with the peaks that are visible in Figure 4.6. The paving activity is one of the highest on total emissions and shows in the figure as a peak because of the short duration of the activity, which is around four hours. These activities are the same than the ones identified as the larger contributors when the field data was used.

**Table 4.12. RS Means Emissions per Activity for the Wake Forest**

<table>
<thead>
<tr>
<th>Activity</th>
<th>Pollutants (Thousands of Grams)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
</tr>
<tr>
<td>Grading</td>
<td>0.53</td>
</tr>
<tr>
<td>Gravel Subgrade</td>
<td>1.42</td>
</tr>
<tr>
<td>Utilities</td>
<td>0.38</td>
</tr>
<tr>
<td>Curb</td>
<td>0.20</td>
</tr>
<tr>
<td>Backfill</td>
<td>14.7</td>
</tr>
<tr>
<td>Paving</td>
<td>0.82</td>
</tr>
</tbody>
</table>

### 4.6 Comparison Between Projects

This paper presents results from a comprehensive emissions field study. It provides, for the research community, a plethora of actual and predicted emissions data that has not previously been available. In this section the paper compares the emissions from the three distinct project types (road, street and utility, and building) for the seven projects.

#### 4.6.1 Project Type Comparison with Tier 3 Equipment

This section shows the results from the comparison of the building, street and utility, and road projects using Tier 3 as the reference for all equipment used. In Table 4.13, the average daily emissions for the street and utility projects are lower than the average daily emissions for the building project. The emissions for the road projects (calculated using the field data) are
almost double the emissions for the street and utility and building projects for all the pollutants. The metrics for the road projects using published data are even higher than the emissions estimated using project data with the exception of PM.

Table 4.13. Average Grams per Day for All Tier 3

<table>
<thead>
<tr>
<th>Project Type</th>
<th>Pollutants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
</tr>
<tr>
<td>Building</td>
<td>538</td>
</tr>
<tr>
<td>Average Street with Utilities (4 Projects)</td>
<td>467</td>
</tr>
<tr>
<td>Average Field Roads (2 Projects)</td>
<td>1,010</td>
</tr>
<tr>
<td>Average RS Means Roads (2 Projects)</td>
<td>1,660</td>
</tr>
</tbody>
</table>

Table 4.14 shows the results for the metrics of grams of pollutant per square foot of pavement. The table does not include the building project because the units of square footage are not comparable. The table shows that the results for the average of the four street projects, the road projects with field data, and the road projects with RS Means data. The values for the pollutants are comparable, however, the results show that the road projects have higher emissions per unit of production than the street and utility projects and that the RS Means calculation results in a higher emissions metric.

Table 4.14. Grams per Square Foot of Pavement for Street and Road Projects Assuming Tier 3 Equipment

<table>
<thead>
<tr>
<th>Project Types</th>
<th>Pollutants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
</tr>
<tr>
<td>Average Street with Utilities (4 Projects) (Field and RS Means combination)</td>
<td>0.73</td>
</tr>
<tr>
<td>Average Field Roads (2 Projects)</td>
<td>1.51</td>
</tr>
<tr>
<td>Average RS Means Roads (2 Projects)</td>
<td>1.75</td>
</tr>
</tbody>
</table>
4.6.2 Road Project Comparison with Tier 3 Equipment

Table 4.15 shows the emissions per day for the Apex and Wake Forest projects for both the field and RS Means methodology when using Tier 3 for all the equipment. The RS Means results for the Apex project are more than double the results for the field calculation. The exceptions are PM and SO₂. The results for Wake Forest also show that the RS Means numbers are higher, however, the difference is smaller. The difference between the schedule obtained using RS Means productivity factors (88 days) and the actual schedule (124 days) accounts for some of the difference between the metrics for the Apex project.

<table>
<thead>
<tr>
<th>Projects</th>
<th>Pollutants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
</tr>
<tr>
<td>Apex Field</td>
<td>1,160</td>
</tr>
<tr>
<td>Apex RS Means</td>
<td>1,810</td>
</tr>
<tr>
<td>Wake Forest Field</td>
<td>866</td>
</tr>
<tr>
<td>Wake Forest RS Means</td>
<td>1,630</td>
</tr>
</tbody>
</table>

Table 4.16 shows the calculation of the metric of emissions per square foot for Apex and Wake Forest for both field and RS Means. The results of the calculation with RS Means resulted in higher emissions for both projects but the difference between the calculations for Apex is larger than the difference for Wake Forest. The real difference lies in the significantly higher emissions for Apex than for Wake Forest. This discrepancy is likely due to the difference in complexity and quantities between the projects.
Table 4.16. Grams per Square Foot of Pavement for Road Projects Assuming Tier 3 Equipment

| Projects             | Pollutants |  |
|----------------------|------------|--|---|---|---|---|---|
|                      | HC   | CO  | NOx | PM | CO₂  | SO₂ |
| Apex Field           | 2.31 | 16.1| 17.2| 2.76| 1.70E+04 | 2.99 |
| Apex RS Means        | 2.52 | 15.8| 16.1| 0.06| 1.23E+04 | 2.60 |
| Wake Forest Field    | 0.72 | 5.35| 5.75| 0.02| 5,890    | 1.08 |
| Wake Forest RS Means | 1.15 | 6.97| 4.71| 0.03| 3,990    | 0.70 |

4.6.3 Comparison Between Field and RS Means Results

The total emissions calculated using the field data were compared to the total emissions calculated using RS Means data. The difference in the equipment fleet between the two data sources is the largest contributor to the total emissions difference. Table 4.17 shows the field and RS Means fleets for the Apex project. The equipment fleet determined using the RS Means data (21 items) is significantly smaller than the actual fleet used on the project (46 items). The RS Means fleet includes one engine size of the majority of the items except for front-end loader and cranes that included two items with different engine sizes. The actual fleet used for the project included seven bulldozers, 10 excavators, and four rollers, many of them with different engine horse power.
Table 4.17. Comparison of Equipment Fleet for the Apex Project

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Field HP</th>
<th>Equipment Type</th>
<th>Field HP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Compressor</td>
<td>117</td>
<td>Front End Loader</td>
<td>200</td>
</tr>
<tr>
<td>Asphalt Distributor</td>
<td>5.5</td>
<td>Grader 1</td>
<td>135</td>
</tr>
<tr>
<td>Backhoe</td>
<td>100</td>
<td>Grader 2</td>
<td>135</td>
</tr>
<tr>
<td>Brush Chipper</td>
<td>85</td>
<td>Loader</td>
<td>128</td>
</tr>
<tr>
<td>Bulldozer 1</td>
<td>130</td>
<td>Milling Machine</td>
<td>140</td>
</tr>
<tr>
<td>Bulldozer 2</td>
<td>121</td>
<td>Mini Excavator</td>
<td>39.4</td>
</tr>
<tr>
<td>Bulldozer 3</td>
<td>140</td>
<td>Mixer</td>
<td>25</td>
</tr>
<tr>
<td>Bulldozer 4</td>
<td>90</td>
<td>Mulch Blower</td>
<td>33.5</td>
</tr>
<tr>
<td>Bulldozer 5</td>
<td>90</td>
<td>Paver</td>
<td>174</td>
</tr>
<tr>
<td>Bulldozer 6</td>
<td>121</td>
<td>Pneumatic Roller</td>
<td>80</td>
</tr>
<tr>
<td>Bulldozer 7</td>
<td>90</td>
<td>Roller 1</td>
<td>145</td>
</tr>
<tr>
<td>Compact Track Loader</td>
<td>84</td>
<td>Roller 2</td>
<td>99</td>
</tr>
<tr>
<td>Curb Machine</td>
<td>130</td>
<td>Roller 3</td>
<td>33</td>
</tr>
<tr>
<td>Excavator 1</td>
<td>100</td>
<td>Roller 4</td>
<td>99</td>
</tr>
<tr>
<td>Excavator 2</td>
<td>232</td>
<td>Rubber Tire Loader</td>
<td>196</td>
</tr>
<tr>
<td>Excavator 3</td>
<td>140</td>
<td>Scraper 1</td>
<td>175</td>
</tr>
<tr>
<td>Excavator 4</td>
<td>140</td>
<td>Scraper 2</td>
<td>265</td>
</tr>
<tr>
<td>Excavator 5</td>
<td>140</td>
<td>Skid Steer 1</td>
<td>56</td>
</tr>
<tr>
<td>Excavator 6</td>
<td>169</td>
<td>Skid Steer 2</td>
<td>46</td>
</tr>
<tr>
<td>Excavator 7</td>
<td>100</td>
<td>Straw Blower</td>
<td>125</td>
</tr>
<tr>
<td>Excavator 8</td>
<td>386</td>
<td>Trench Roller</td>
<td>18</td>
</tr>
<tr>
<td>Excavator 9</td>
<td>140</td>
<td>Trencher</td>
<td>120</td>
</tr>
</tbody>
</table>

The emissions per activity were also calculated for both data sources. The activities with the largest contribution to emissions were consistent for field and RS Means data with earthmoving and paving activities on the top of the list for both.

Figure 4.7 shows CO₂ emissions by day for both field and RS Means for the Apex Project. The RS Means calculation resulted in shorter project duration than the actual duration but matched up well in emissions quantities.
Table 4.18 shows the field and RS Means fleets for the Wake Forest project. The RS Means fleet was larger than the actual fleet used for the project. Wake Forest was a small project that was finished quickly. The contractor was able to use only a few items of equipment to complete a variety of different tasks for all the activities needed. Alternatively, the RS Means fleet composition results in more items of equipment used for that same limited number of activities.
Table 4.18. Comparison of Equipment Fleet for the Wake Forest Project

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Field HP</th>
<th>RS Means HP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulldozer</td>
<td>90</td>
<td>Paver</td>
</tr>
<tr>
<td>Motor Grader</td>
<td>150</td>
<td>Crawler Loader</td>
</tr>
<tr>
<td>Pan Scraper</td>
<td>175</td>
<td>Curb Machine</td>
</tr>
<tr>
<td>Backhoe</td>
<td>94</td>
<td>Dozer</td>
</tr>
<tr>
<td>Roller 1</td>
<td>145</td>
<td>Front End Loader Crawler</td>
</tr>
<tr>
<td>Curb Machine</td>
<td>130</td>
<td>Grader</td>
</tr>
<tr>
<td>Paver</td>
<td>205</td>
<td>Pneumatic Roller</td>
</tr>
<tr>
<td>Roller 2</td>
<td>137</td>
<td>Vibratory Roller 1</td>
</tr>
<tr>
<td>Broom Tractor</td>
<td>50</td>
<td>Tandem Roller</td>
</tr>
<tr>
<td>Mini Excavator</td>
<td>20</td>
<td>Vibratory Roller 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pavement. Profiler</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F.E. Loader, Wheel 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FE Loader, Wheel 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Backhoe</td>
</tr>
</tbody>
</table>

Figure 4.8 shows field and RS Means CO₂ emissions for the Wake Forest project. Emissions and project duration for Wake Forest were not very different because the project was relatively simple and completed quickly.
4.7 Conclusions

The projects compared in this paper have differences not only in type but also in size and complexity. The Wake Forest road project was a simple and small widening project that lasted 13 days. The Apex road project included the relocation of a road and an intersection and lasted 124 days. The street and utility projects included the installation of water distribution, sewer, and storm water systems, while the building project was a medium-sized commercial structure. These projects are typical of different construction projects types. One of our goals was to determine the extent to which project type affects the total quantity of emissions produced. The comparison presented on this paper shows that it is possible to calculate emissions metrics to compare different types of projects.

One research question addressed herein was aimed at determining if there are differences between emissions forecasts when using field activity data versus published data. The results showed that the differences were small and that it is possible to forecast emissions for a project.
using published data as a surrogate for actual field data. This is especially true when field data is simply not available, for example, at the beginning of the project or in early project planning stages. A forecast can also be made by incorporating a general contractor’s historical data, which could result in more accurate forecasts. As with any forecast, the accuracy of the results can be improved when additional data is available.

Another question of interest is to what extent do different project types vary in their emissions during construction. The results showed that the Apex and Wake Forest projects had similar emissions profiles with large amounts of emissions produced during earth movement and paving activities. This emissions pattern was similar to the one presented by the street and utility projects. The road and street projects both produced pollutant emissions throughout the entire duration of the project. In contrast, the building project produced the majority of its emissions at the beginning of the project with almost all the emissions produced during the first two thirds of the project and two thirds of the emissions were produced before the project was one half completed. More work is needed to increase the number of projects for which forecasts have been produced. However, this very small sample shows that it is possible to identify patterns of emissions production for different types of projects, thus enabling us to begin to develop a hierarchy of project type emissions production thereby alerting designers, in early project stages, of estimated total emissions quantities that are a function of project type.

The third research question addressed whether or not emissions metrics could be used to compare different project types. One metric used to compare emissions between the building, street and utility, and road projects was emissions per day. The results showed that road projects have the highest emissions followed by the building. However, emissions per day may not be a good method to compare different project because this metric can vary depending on schedule changes that do not affect total emissions. A different metric for comparison is emissions per unit, but the building project did not have a production unit comparable with the road and street projects. When the street and utility and the road projects are compared
using emissions per square foot the results showed that road construction produced more emissions than street and utility projects.

More work is needed to increase the database of projects of different types and emissions forecasting. Emissions metrics by unit of production could be determined for each project type. Emissions metrics by project type allow both the forecasting of total emissions during the early planning stages of a project and the comparison of different alternatives based on emissions per unit for different projects. An additional metric of emissions per gallon of fuel use can be calculated if fuel use data is available. This metric could be linked to contractor’s records on fuel use quantities and fuel cost information for each project.

Calculations presented here included total emissions, emissions per activity, and emissions per equipment type. The activities with a larger contribution to total emissions include earth movement and paving. The activities with the largest contribution for the Apex project were clearing and grubbing, grading, and aggregate base course (ABC) and paving. Gravel subgrade and backfill were the activities with the largest emissions for the Wake Forest project. The emissions for these activities were the highest for both the field and RS Means estimation methods.

The equipment types with the largest contribution to total emissions were motor graders, backhoes, front-end loaders, and bulldozers. The large contribution of some of these types of equipment is linked to their high emissions factors. For other equipment types, such as bulldozers, their large quantity of emissions is due to the long hours of use of the equipment for different activities.

The emissions for the road construction projects were calculated using two different data sources: data provided by the contractors and published data. The results show that emissions calculated using published data were higher than those from field data for the majority of the pollutants. This difference could be caused by the differences in equipment type and engine size between the actual fleet and the ones specified by RS Means. These differences in
equipment fleet result in differences in schedule due to the different productivity of different equipment. Contractors use the equipment that is available (depending on the fleet that they own) or the equipment that is available for rent. One related problem is that contractors do not always keep a detailed as-built schedule. Furthermore, they also often do not collect specific equipment use data as they do for labor. Because of this reality, it was critical to benchmark an independent data source such as RS Means. A further study could also assess the value of proprietary historical project data for emissions forecast.

This study shows that it is possible to use published data to obtain a forecast of total emissions at the early stages of the project. An early forecast can be used during the planning process to compare alternatives or to estimate the environmental impact of a potential project. As with any forecast, the accuracy of the numbers can be improved when additional information is available.

Contractors can use a forecasting model during the construction process to assess their actual emissions production. The actual equipment type and hours of use can be used as inputs rather than a planned (and potentially highly variable) schedule. Contractors could use the forecast to monitor their equipment use and productivity in addition to monitoring emissions produced, thus enabling them to see if the actual construction emissions match the forecast. Improving productivity could reduce hours of operation for each item of equipment and could result on lower total emissions for the project.

The data collected during construction could be used to calculate a final total emissions quantity for the entire project. This total could be viewed as an equivalent to an “as-built” emissions total that owners can use to evaluate total effect or future activities to offset this effect. Researchers could use the equipment use and total emissions information to improve emissions metrics for different equipment types.
5.0 CONSTRUCTION EQUIPMENT FLEET EMISSIONS REDUCTIONS OPTIMIZATION

5.1 Introduction

The US Environmental Protection Agency (EPA) regulates pollution produced by both mobile and stationary sources. Construction equipment is classified as a mobile nonroad source and regulations have been developed during the years to reduce exhaust emissions from such equipment. The first regulation was put in place in 1998 and subsequently more strict regulations were developed in later years. Engines are classified as Tier 0 if they were manufactured before regulations were in place and Tier 1 through Tier 4 corresponding to the regulation that was active during these years of manufacturing. Tier 4 regulations are now in place and will be required for all engine sizes in 2015 [EPA 2010]. Manufacturers are responsible for producing equipment that complies with these exhaust pollution regulations. However, there is no EPA regulation for the quantity of emissions produced by this same equipment during use.

This paper discusses a study of the selection of construction fleet components as a method to reduce total emissions from a project. It describes an optimization model that can be used by contractors to select a construction fleet composition at the beginning of a project to control the quantity of emissions produced during the project. The model can be used to select different equipment types depending on the activity, as well as engine tier. The methodology could also be used during early planning phases to calculate emissions quantity ranges that could be used during the process of selecting different project alternatives. Total emissions could be used as one of the factors for selecting a project in a similar way than cost, schedule, and traffic effects are used now.

The pollutants analyzed in this paper are the exhaust pollutants provided by the EPA NONROAD model [EPA 2005], including hydrocarbons (HC), nitrogen oxide (NOx), carbon monoxide (CO), particulate matter (PM), sulfur dioxide (SO2), and carbon dioxide (CO2).
Reduction of the four pollutants that are considered to be criteria pollutants by the EPA (CO, NO\textsubscript{x}, PM, and SO\textsubscript{2}) can substantially help improve air quality. Criteria pollutants are regulated to protect against their effect on human health, the environment, and private property [EPA 2007]. The large amount of CO\textsubscript{2} in the atmosphere is due in large part to the burn of fossil fuels and is one of the direct causes of the greenhouse effect and climate change [IPCC 2013]. Regulations and incentive programs to reduce CO\textsubscript{2} emissions could be enforced in the near future and having a methodology to estimate their total quantity can help contractors to prepare to comply with these regulations. Reducing the amount of HC in the atmosphere can help to reduce the production of ozone [EPA 2008a]. Ozone is a criteria pollutant with negative effects on the respiratory system.

Reducing emissions can reduce the effect of the construction industry on the environment. In addition, reducing emissions would minimize the exposure of construction workers and the communities surrounding the construction site to potentially harmful substances. Even if the emissions produced during the construction phase are relatively small when compared to the life cycle emissions for the completed structure, operators and workers are exposed to these emissions daily, perhaps in high concentrations and sometimes for an extended period of time.

The methodology presented here can also be used to estimate total emissions per day. This number can be useful for complying with daily regulations for some of the pollutants. Daily quantity regulations could be developed to address environmental problems that depend on the quantity of pollutants in the atmosphere at a particular time, such as the formation of ozone at lower levels of the atmosphere. Ozone is created when NO\textsubscript{x} reacts with HCs in the presence of ultra-violate light. This problem is more intense during sunny and warm days. Reducing the quantities of NO\textsubscript{x} and HC during problematic days could help to reduce ozone formation and could help localities stay in the compliance with EPA regulations.
5.2 Previous Work

A study by Miller-Hooks et al. [2010] for the Maryland State Highway Administration studied the greenhouse gas emissions from transportation projects and provided the only known previous example of an optimization model aimed at pollutants during construction projects. The first part of the study included the development of an estimation tool for the net greenhouse production from a project. The second part included the development of a decision support methodology to minimize emissions and cost by selecting the construction fleet for a project.

The estimation tool included emissions during four steps of a project: site preparation, equipment use, materials production, and environmental impact mitigation. The site preparation component included emissions produced during clearing activities and the CO₂ sequestration component that is lost when trees are cut. The equipment component included the emissions produced by equipment during construction activities. The material production component included the emissions produced during the production of cement, concrete, asphalt, solvents, fertilizers, and steel. The environmental impact mitigation component accounted for the effects of reforestation after the construction is completed.

The estimation tool included a user interface that provided for user project data input. The site preparation section required information on the location of the construction site, the type of forest, and the area of each type of forestland that would be cleared. Input data for equipment usage included the number of items, hours of operation, age, model, year, and engine horsepower. The user can also add the EPA tier if known and select a maximum horsepower. The user also needs to select the type of fuel and the retrofit technology from a list of EPA approved technologies.

The output of this tool is the net emissions of greenhouse gases in metric tons of CO₂ equivalent for a project. The CO₂ equivalent quantity included reactive organic gases (ROG), nitrous oxides (NO₂), sulfur oxides (SO₂), carbon monoxide (CO), carbon dioxide (CO₂), and
methane (CH₄). The tool also provides totals for other pollutants such as SOₓ, volatile organic compounds (VOC), and reactive organic gases (ROG).

The second part of the study consisted of the development of a decision support methodology that uses a multi-period, bi-objective mixed integer program [Avetisyan et al., 2012]. The methodology can be used to select a fleet for construction activities that would minimize the CO₂ equivalent emissions or minimize cost. A weighting system can be used to change the importance of these two criteria and minimize both accordingly. The constraints used in the program are the following.

1. The number of items used is less than or equal to the total items of items of equipment available.
2. The equipment is used for enough time to complete the activity.
3. The capacity of the selected equipment is appropriate to complete the activity.
4. The equipment used is compatible. For example, a loader and trucks have compatible cycles.
5. The number of items of equipment does not cause congestion.
6. The fleet composition complies with the Maryland’s Tier System Guidelines as shown in Table 5.1.
7. The number of items of equipment is an integer.

<table>
<thead>
<tr>
<th>EPA Tier</th>
<th>Limitations on number of pieces of equipment on site per tier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tier 0</td>
<td>Must not exceed 10%</td>
</tr>
<tr>
<td>Tier 1</td>
<td>Must not exceed 70% (when combined with Tier 0)</td>
</tr>
<tr>
<td>Tier 2</td>
<td>Must not exceed 90% (when combined with Tier 0 and 1)</td>
</tr>
<tr>
<td>Tier 3</td>
<td>Must be no less than 10%</td>
</tr>
</tbody>
</table>
In the Miller-Hooks et al. study two different methods were used to solve the program. The first one, a weighting method for developing a Pareto-Frontier, was used when the optimization was done for both cost and emissions. For this method, an assumed value was used for the price of a metric ton of carbon in a carbon market. The cost of equipment use and operation was calculated using Tier 2 equipment as a base and assuming that Tier 0 is 15% less expensive, Tier 1 is 10% less expensive, and Tier 3 is 20% more expensive. The second method consisted of minimizing costs with a cap on emissions that was added as an additional constraint.

An assumption was made that the equipment under consideration was available for every tier because of the possibility of renting, buying, or leasing equipment. This assumption enables the program to include equipment of every tier in the solution if needed.

The authors applied the model to a case study. The results showed that 55% of the emissions were produced by equipment use, 45% by site preparation, and 0.06% by material production. The equipment with the largest emissions was off-highway trucks with 19%, excavators with 17%, and rubber-tire dozers with 15% of the emissions from construction equipment.

The decision model was also used on the same case study project. The weight of the cost and emissions factors was changed to determine the effect on the solution. The results showed that when cost had a higher weight, the fleet included lower tier equipment. When reducing emissions was the priority, higher tier equipment was selected. However, the authors did not compare the equipment selected by the model to the original equipment used by the contractor in the case study.

The solution for the emissions cap procedure was also used to determine the effect of changes on the limits. The emissions cap was set to an initial value of 160,000 metric tons of CO$_2$ equivalent. The model was used to see the difference in cost for different emissions caps by reducing the initial value. The results showed that emissions could be reduced by 78% without
a notable increase in equipment cost. It was also found that when seeking a reduction in emissions of 89% it is difficult to comply with the limit at any cost.

5.3 Research Questions

The objective of this paper is to present a methodology to select the construction equipment fleet that would produce a lower amount of emissions per activity resulting in a lower total project emissions production. Various questions need to be answered to achieve this objective.

The first research question addressed herein is, “can an effective model be created to select an equipment fleet that will produce the minimum amount of emissions?” The model should be design to use known equipment characteristics and the project information to calculate total emissions. One of the steps needed to answer this question included performing a sensitivity analysis to determine how emissions change when other factors are changed such as equipment type, engine size, or construction schedule.

The second research question is, “what are the effects on fleet equipment selection when equipment cost is used as a selection factor?” Construction cost is estimated from the early stages of project planning. Bid cost is the most important factor when selecting contractors to complete a construction project, particularly for public work. Equipment cost, in addition to labor and materials, is one of the major categories of costs used to determine construction cost. Using equipment cost as one of the selecting criteria could help to determine the consequences of emissions reduction on the construction budget. However, this impact can be predetermined, assessed, and planned for.

The third research question is, “what is the effect on schedule of selecting a minimum emissions fleet composition?” The schedule for a construction project is directly related to the productivity that can be achieved for each activity and for the project as a whole. Selecting different equipment types and engine sizes can change the productivity of the equipment, thus
affecting the duration of each activity and of the project. Information on project duration can help contractors to have an accurate schedule during the bidding phases and to inform the owner of the effects of any schedule changes during the construction phase to accommodate for emissions regulations and limits or to meet green construction goals.

The model presented here is different from the Maryland study in various ways. The first one is the pollutants used on the study. The previous study concentrated only on greenhouse gas emissions (GHG) emissions as CO₂ equivalents. The present study focus on emissions for all six exhaust pollutants available in the EPA NONROAD model. The model can be used to minimize emissions for any of these pollutants or for a combination of them. In addition, the model can be used to minimize cost after a limit has been set for one or more of the pollutants.

The second difference is the assumption of the equipment available for use. The Maryland study assumes that equipment is available in every tier because contractors can use their own equipment or rent additional equipment. Information obtained by the authors from rental equipment companies shows, however, that available rental equipment is usually newer and has an average age of 3 years. This information supports the idea that rental equipment will typically be Tier 4 and is in fact not generally available in every tier. Our model uses fleet information provided by a contractor who might supplement their existing fleet with rented higher tier equipment as needed (Rasdorf). The possibility of using different equipment fleet configurations (and tiers) allows contractors to select the best solution based on their actual situation. The model can produce more accurate and useful solutions when actual fleet composition information is known and used.

The final difference is that our methodology also includes the development of a preliminary schedule for the activities used. Previous work showed that earthmoving, excavation, grading, and paving activities are the major producers of emissions. The methodology can be used to calculate a basic schedule that includes these four activities with a basic logic relationship. More activities could be included in the future to represent more complicated schedules or
different types of projects (such as commercial or residential construction). The schedule was also used to calculate daily quantities of emissions and maximum daily quantity of emissions throughout the project. Maximum daily quantity of emissions can also be used as one of the factors to determine the environmental effects of the project.

5.4 Methodology

The following sections present the methodology used to develop the optimization model, perform the sensitivity analysis, and make the fleet composition selection. The information used to do so was collected from various sources including information provided by contractors, RS Means [Means 2014], the Caterpillar Performance handbook [CAT 2013], and the EPA NONROAD model [EPA 2005].

Two transportation construction projects were used to develop the sensitivity analysis and the optimization model. For these projects, the general contractor offered field information that included bid price, construction schedule, and activities performed. This information was used to determine construction quantities for the earthmoving, excavation, grading, and paving activities.

RS Means [Means 2014] is one source of cost and productivity information that can be used to determine construction activity total cost and duration. RS Means also includes the equipment fleet for each activity. In some cases, the RS Means offers different fleet alternatives for the same activity. Some of these cases were used during the sensitivity analysis process discussed later.

The Caterpillar Performance handbook [CAT 2013] offers detailed information for all the equipment models that are currently produced by the company. The information includes basic characteristics such as engine size, weight, and dimensions. The handbook also offers methods to determine productivity for some of the equipment types and a methodology to estimate ownership and operating cost for each item that were used as input to the optimization
model. This methodology used only equipment models manufactured by Caterpillar. Caterpillar produces a large number of different equipment models that are used by numerous companies. Data from Caterpillar equipment was available through the handbook, a local dealer and rental company, and through the numerous Caterpillar equipment that were used to complete the construction projects used for previous studies. The model can be extended to include other manufacturers and models corresponding with local availability and the fleet owned by the contractor.

The emissions factors for each item of equipment are obtained from the EPA NONROAD model [EPA 2005]. The NONROAD model offers emissions factors, based on type of equipment and engine size, expressed as grams of pollutant per horsepower hour. The emissions factor is multiplied by the horsepower of each item and the duration in hours of each activity to determine total emissions per activity. The sum of all the individual activity emissions resulted in total emissions per project.

The optimization model was developed using two transportation projects as case studies. The first one was a project in Wake Forest, NC that consisted of a road widening and curb construction. The second project was in Apex, NC and included the relocation of a road and the widening of an intersection. The projects were completed in 2013 and 2014, respectively. The quantity take-off for the Apex and the Wake Forest projects were used to calculate solutions for the optimization model. The sensitivity analysis was develop using the construction activities and quantities from the Wake Forest project.

5.4.1 Sensitivity Analysis

A sensitivity analysis was completed to observe how changes in equipment and project characteristics affected total emissions. The equipment characteristics included equipment type, engine size, and engine tier. The equipment fleet composition was changed to represent the different yet realistic options the contractors had for the same activity. The project
schedule was also changed to determine if activity starting time and duration variations could be used to reduce daily peaks of emission.

5.4.2 Optimization Model

The following sections describe the steps to develop a linear programming model to minimize either total emissions or equipment cost by selecting the construction fleet and specifying the project schedule. The decisions were based on the lessons learned from the sensitivity analysis as well as previous work completed on emissions production and estimation.

5.4.2.1 Optimization Factors

The model can be used to minimize total emissions for any of the six exhaust pollutants. The optimization could be done separately for each pollutant or for any subset of the pollutants depending on the objective. The model can also be used to minimize equipment cost for the construction activities. Finally, the model can be used to select a construction fleet that would identify the minimum cost after adding a limit to the total project emissions for one or more of the pollutants.

5.4.2.2 Optimization Model Selection

The optimization model used is a mixed integer linear program. The model adopted for the work and presented herein was solved using the open source program OpenSolver that can be added to Microsoft Excel [Mason, 2012]. This program offers the opportunity to find solutions for models with a larger number of variables and factors than the basic solver normally available in Excel. The open source nature of the program and its easy implementation in Excel makes it convenient for contractors, other construction professionals, and academia to use the methodology in the future.
The calculations were completed using three different optimization formulas to correspond to the three different optimization scenarios studied: minimize emissions of each pollutant, minimize equipment cost, and minimize equipment cost after capping total project quantities for some of the pollutants. The number of items of equipment (in bold in the equations below) are the decision variables and the solutions for each model. The solutions for minimum emissions and minimum equipment cost present the extreme solutions. The solution for minimum equipment cost with cap presents intermediate solutions and the constraint can be changed to present more practical solutions.

The elements of the model with total quantity of emissions as the objective function are as follows. The model can be used to minimize one pollutant at a time. A simplified presentation is used here.

\[
\text{Minimize Total Emission} = \sum_{a \in A} \sum_{m \in M} \sum_{t \in T} \text{item}_{amt} \times EF_{mt} \times HP_{mt} \times D_a
\]

Constraints:

- Number of item for activity a = number of items needed for activity a
- Number of items of each equipment model m <= number of items available for each equipment model m
- Units of production for each activity = units of production specify for the project
- Number of items is a positive integer

Where:

- \( \text{item}_{amt} \) = number of items of model m and tier t used during activity a
- \( EF_{mt} \) = emissions factor for the item of model m and tier t
- \( HP_{mt} \) = horsepower of the engine in model m tier t
- \( D_a \) = duration of activity a
The elements of the model with total equipment cost as the objective function are as follows. Emissions were not constraint to present the extreme solution.

\[
\text{Minimize Total Equipment Cost} = \sum_{a \in A} \sum_{m \in M} \sum_{t \in T} \text{item}_{amt} \times \text{cost}_{mt} \times D_a
\]

Constraints:
Same as above

Where:
\(\text{cost}_{mt} = \) owning and operating cost per hour for item of model \(m\) and tier \(t\)

The model with total equipment cost as the objective function with emissions cap for one or more pollutants is presented below. The combination formula for multiple pollutants depends on the preferences and priorities of the user.

\[
\text{Minimize Total Equipment Cost} = \sum_{a \in A} \sum_{m \in M} \sum_{t \in T} \text{item}_{amt} \times \text{cost}_{mt} \times D_a
\]

Constraint:
Total quantity of emissions \(\leq\) maximum quantity of emissions allowed (cap for each pollutant)

Additional constraints as above

Solving the model results in the number of items of each equipment model that should be used to produce the optimal quantity of emissions. The number of items of equipment selected is limited by the number of items available in the contractor’s fleet (total, per model, per equipment type) and the number of items that need to be used for each activity. The constraint on the number of items used for each activity can be changed to account for construction site
configuration and congestion. Rental equipment can be used to supplement the available equipment fleet.

5.4.2.3 Equipment Cost Calculations

Equipment cost information is included in the model to enable that variable to serve as one of the selection factors. Equipment cost is usually presented as cost per hour of the item of equipment including both ownership and operation cost. The Caterpillar Performance Handbook [CAT 2013] includes a methodology that can be used to calculate the cost per hour for different equipment types. This section describes the methodology and the data sources used to determine equipment cost for our optimization model. Clearly, any cost estimation can be made more accurate by using both actual and historical data for the particular equipment fleet in use on a given project. Figure 5.1 shows a flowchart with the methodology used to calculate equipment cost. The text that follows describes the graphical presentation represented in the figure.

A compilation of prices posted on the Construction Equipment Guide website [CEG 2014] was used to determine prices of equipment for different model years and tiers. The model year was used to determine tier for each item and an average price per tier was determined. Not all equipment models had calculated averages for every tier, depending on the availability of data. The average difference in price between tiers was around 75% (that is, a lower-tier item of equipment usually cost 75% of a higher-tier item) based on the information available. Prices for some newer equipment were not available online and the price was estimated to be 10% higher than the previous model. The resale value after five years was determined to be 50% of the purchase price. The difference between the purchase price and the resale price is the value to recover that contractors need to allocate to the use of the equipment. In the future, the values we used in the initial model development can be improved by using the actual cost and the estimated resale value for their particular area and time period.
In addition to the initial purchase price of the equipment, the operating cost is needed to determine the total cost of the equipment. In our model, operating cost includes fuel use, maintenance, tire replacement, undercarriage maintenance, and repairs. Each one of these costs varies depending on equipment type and model. The Caterpillar Performance Handbook [CAT 2013] offers approximations for some of these values including fuel use, tire replacement periods, and undercarriage deterioration. It was found that a good approximation of the maintenance and repair cost is the purchase price, spread evenly throughout the ownership period.

An ownership period of five years was selected after conversations with an equipment dealer and because it is a typical value used for depreciation calculations. The five-year ownership assumption is used to calculate equipment cost per hour. Ownership period can be changed to reflect the actual time that the contractor used the equipment. The EPA NONROAD model provides average annual usage (in hours) for different types of equipment. This annual usage was multiplied by the ownership period to determine total hours of use for each item of equipment. As mentioned before, these total hours of use can be improved in the future by adding actual annual hours of use for each item of equipment. Annual use depends on the equipment type, the type of work performed, the age of the equipment, and the owner’s pattern of use.

The value to recover was divided by the total time of use to determine hourly cost of each item of equipment. The cost of interest, taxes, and insurance was added to the value to recover. The resulting cost is the complete value of ownership for the contractor. The operating cost was also divided by the total time of use to determine hourly operating cost. The sum of the ownership cost and the operating cost represents the total cost of using each item of equipment. The total equipment cost can be used as one of the factors to minimize with the optimization model.
5.4.2.4 Emissions Calculations

Total emissions for the equipment were calculated using the emissions factors provided by the EPA NONROAD model for the six exhaust pollutants. The emissions factors were
adjusted to represent typical deterioration due to age and use. The adjusted formula is provided by EPA [EPA 2005] and is explained in detail in Rasdorf et al. [2015]. Figure 5.2 shows a flowchart of the methodology used to calculate emissions rates for each item of equipment.

The Caterpillar Performance Handbook was used to determine the equipment basic characteristics including engine horsepower and productivity for each item of equipment used for the calculations. The equipment models manufactured by Caterpillar are typical for construction equipment. However, the model can be updated to include information on actual items of equipment used by the contractor for each project and for the productivity expected from the equipment due to construction site conditions.

The project documents provided by the contractors were used to determine construction quantities for each activity. Some examples of these quantities are volume of earth movement or excavation, area for grading, and tons of pavement that needed to be placed. Construction quantities are divided by productivity to obtain activity durations in hours. These durations were used to calculate total emissions and to determine an estimated project schedule.

The emissions factors provided by the EPA NONROAD model are presented as grams of pollutant per horsepower hour. The adjusted emissions factors are multiplied by the engine horsepower of each item and by the duration in hours for each activity. The result is total emissions in grams for each item of equipment. Emissions per item are added to calculate total emissions per activity. Activity emissions are then added to calculate total emissions for the project. For this model, emissions per project were calculated using the four activities that produced the majority of emissions: earthmoving, excavation, grading, and paving. If desired, at any future point, additional activities could be included. For typical projects, this would not be necessary but it could be the case that specialty projects could have other high emissions activities and these would need to be accounted for.
5.4.2.5 Schedule Calculation

An accurate construction schedule is needed in order to determine emissions per day (in grams) for each construction activity. The maximum daily peak can also be determined. The
daily peak can be used in the future as an additional optimization factor where limits might be placed to prevent peaks from exceeding specified limits. Additional work can be performed in the future to select an equipment fleet composition to minimize daily total emissions based on peak reduction.

The results from the model include the number of items of each equipment model that can be used for each activity and the total hours of use (based on productivity) for each item. The Visual Basic Application (VBA) function included in Excel was used to develop a routine that creates a schedule based on the selected equipment fleet. The routine was developed assuming that the activities are completed without delays, that the items would be in normal used for an eight hour day, and that the activities have simple finish to start relationships. The paving activity required the use of a paver, two tandem rollers, and a pneumatic roller. The productivity of the paver was used to determine the duration of the paving activity. The hours of use for the rollers were distributed during the paving activity duration as a ratio of the paver use. An excavator or a backhoe was selected to complete the excavation activity and their productivity was directly related to the productivity of the equipment. The earthmoving activity included fine grading and they were performed by a bulldozer and a motor grader, respectively. As previously noted, in the future, the methodology can include a larger number of activities with more complex logical relationships depending on the unique needs of each project.

5.5 Results

The following sections present the results for the sensitivity analysis and the use of optimization model to study the construction projects described earlier in the paper.

5.5.1 Sensitivity Analysis

While the primary focus of this research was on optimizing equipment combinations the results from the analysis also verified that changes in equipment characteristics and project
schedule do have a noticeable effect on total emissions per activity. Figure 5.3 shows the emissions differences when two different equipment types, crawler loader and bulldozer, were used to perform the same activity, moving fill from a stockpile. The productivity information for this calculation was obtained from RS Means. The emissions differences of Figure 5.3 clearly demonstrate that changing equipment does change the activity emissions production rates. The difference in emissions is due to the different emissions factors for both types of equipment and to the difference in productivity between the two equipment types. CO₂ and PM are not shown here because their magnitude is far beyond the scale used to present the data for the other four pollutants, but they too show differences.

![Figure 5.3 Emissions Difference for Fill from Stockpile Activity](image.png)

Figure 5.4 shows that schedule changes can also affect the quantity of emissions produced each day, although not changing total project emissions. The figure shows emissions for CO₂.
The reduction in days 50 to 54 is due to both the imposition of a daily emissions cap and to a schedule change. The original peak was 29.8 million grams of CO$_2$ and the limit for the Figure 3 scenario was 22.4 million grams of CO$_2$. To achieve the reduction some activity durations were changed to reduce daily production. Some activities were delayed or accelerated to take advantage of days with fewer activities and fewer emissions. Some activities required the reduction of daily equipment use to less than eight hours.

Figure 5.4 CO$_2$ Emissions for Original and 25% Cap Schedule
5.5.2 Optimization Model

The optimization model was used to select a fleet that would minimize any of total emissions, total cost of equipment use, or total daily emissions - the best solution for the constraints selected. The fleet selected was then used to calculate total emissions, equipment cost, activity schedule, and emissions per day.

Figure 5.5 illustrates some of the results (for the six pollutants) that minimize equipment cost while imposing a cap on each of the pollutants. Each graph shows the solution for 20 different cap quantities for each pollutant. The upper limit for emissions (maximum quantity of emissions) was determined by solving the model for minimum cost. The lowest level for the emissions for each pollutant was determined by solving the model for minimum emissions. These limits were used to determine 20 values for a pollution cap at equal intervals for each pollutant. The intervals are different for each pollutant due to the different magnitudes of pollution produced. The graphs were generated by solving the model for minimum cost with the corresponding emissions cap. The values for total equipment cost and total emissions produced were used to generate each point on the graphs. Each graph shows the solution when one pollutant was capped without constraining the other five pollutants.

The graphs show that equipment cost decreases as emissions increase. The minimum emissions solutions require newer equipment that, as expected, results in the most expensive solution (highest equipment cost). This results in a large peak and a steep slope on the left side of the graphs for all the pollutants. When the model is solved with a higher cap for each pollutant (more emissions), the model can select a variety of equipment from different tiers resulting in a lower equipment cost.

The graphs show that equipment cost decreases as emissions increase. The minimum emissions solutions require newer equipment that, as expected, results in the most expensive solution (highest equipment cost). This results in a large peak and a steep slope on the left side of the graphs for all the pollutants. When the model is solved with a higher cap for each
pollutant (more emissions), the model can select a variety of equipment from different tiers resulting in a lower equipment cost.

Figure 5.5 Total Emissions vs. Equipment Cost for Each Pollutant and for the Apex Project
The second pollutant group includes CO\(_2\) and SO\(_2\) and is shown in the two lower graphs of Figure 5. For these pollutants there is a large emissions peak at the beginning after which the cost decreases when the pollutant limit increases, but the slope is not entirely uniform. Still, the trend is similar to the other pollutants. It should be noted that CO\(_2\) and SO\(_2\) are not directly regulated by EPA nonroad regulations, which results in a smaller decrease of emissions factors between tiers. Thus, total emissions for CO\(_2\) and SO\(_2\) stay nearly the same for many of the cases calculated. This results in the graph shapes presented above with some points representing more than one case. This behavior also demonstrates that the quantity of emissions produce could be different from the emissions cap selected. Selecting different tiers or equipment models results on emissions quantity changes that are steps and not continuous quantities.

Total emissions reduction for each pollutant was between 25% and 85% when the quantities for minimum cost are compared to the quantities for minimum emissions. Emissions for CO were reduced by 85% and emissions for CO\(_2\) and SO\(_2\) were reduced by approximately 25%. Interestingly, the results for each one of the pollutants show that minimizing emissions for one pollutant results on a reduction for all the other pollutants and a corresponding increase in cost. This is an encouraging result because even very specific regulations to reduce one environmental problem could result on an overall improvement in air quality.

In Figure 5.5, the initial cost peak for all the pollutants also decreases to an inflection point where the slope changes significantly. This result shows that there is a point when increasing total emissions by a small amount results on a large reduction in equipment cost. For example, increasing HC emissions by 16% results in a cost reduction of 30%. Our model is able to quantify these savings and to show these optimal points and rates. Finally, it was noted earlier that the graphs of Figure 4 show two relatively uniform slopes with an inflection point. Both slope rates can be quantified as can the inflection point. The first (steeper) slope, as previously discussed, clearly demonstrate the significant equipment cost reduction that can be obtained
by an initial smaller increase in total emissions. After the inflection point additional, but less, cost reduction can be obtained.

The Wake Forest project was also used to solve the optimization model and the Figure 4 equivalent results are very similar for the solution for the Apex project. The solution again show that total equipment cost decreases when the cap for total emissions increase and that CO₂ and SO₂ behave differently than the other four pollutants. HC, PM, NOₓ, and CO show a relatively constant downward slope.

Table 5.2 shows the equipment selected for the two extreme cases of minimum CO₂ emissions and minimum equipment cost for the Apex project. The case for minimum CO₂ resulted on a fleet where all but one item is Tier 4. The case for minimum equipment cost resulted on a fleet where all the items are Tier 1. These results show how an equipment fleet structured to minimize pollution is more expensive because newer equipment, with lower emissions factors, is needed. The results are similar for the other five pollutants. The intermediate cases result in a fleet that combines equipment of different tiers to comply with the emissions cap. The results for the model show that the equipment cost reduction is approximately 63% when the cost for the minimum emissions solution is compared to the minimum cost solution.

<table>
<thead>
<tr>
<th>Minimum CO₂ Total Emissions Equip. Model</th>
<th>Tier</th>
<th>Minimum Total Equipment Cost Equip. Model</th>
<th>Tier</th>
</tr>
</thead>
<tbody>
<tr>
<td>D4K2 LGP</td>
<td>4</td>
<td>D4K2 XL</td>
<td>1</td>
</tr>
<tr>
<td>120K</td>
<td>4</td>
<td>120K</td>
<td>1</td>
</tr>
<tr>
<td>320E LRR</td>
<td>1</td>
<td>320E LRR</td>
<td>1</td>
</tr>
<tr>
<td>CB14B XW</td>
<td>4</td>
<td>CB14B XW</td>
<td>1</td>
</tr>
<tr>
<td>PS360C</td>
<td>4</td>
<td>PS150C</td>
<td>1</td>
</tr>
<tr>
<td>AP255E</td>
<td>4</td>
<td>AP1000E</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure 5.6 shows the project schedule (for the four activities under consideration) developed for the solution of the model when total equipment cost and total CO₂ production were optimized, respectively, for the Apex project. The schedule for minimum total equipment cost has a shorter duration than the schedule for minimizing total CO₂ emissions. This difference is particularly visible for the paving activity. The difference in duration is due to the selection of equipment with smaller emissions factors that usually also have smaller engine sizes and productivity rates. Using this less productive equipment, results in longer activity durations. Figure 5.6 shows the different duration for the paving activity for both cases. The difference in duration for the pacing activity change the duration for the entire project from 35 days to 20 days resulting in a 43% reduction when the total equipment cost is minimize. The schedule can be affected in different ways by changing the constraints of the model, by changing the number of items that can be used for one activity, or by limiting the size (horsepower) of the equipment available, for example.

| Activity         | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 |
|------------------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Earth Movement   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Excavation       |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Grading          |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Paving Min Cost1 |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Paving Min CO₂  |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |

**Figure 5.6 Schedule for Minimum Total Equipment Cost and Minimum CO₂**

### 5.6 Conclusions

The results from this research can be used to select equipment fleets that could result in a smaller environmental impact from construction activities. However, only one other research study previously addressed it [Miller-Hooks et al. 2010]. Our study extended the work of the previous study by answering the research questions posed in the like named section. As a
result, especially in combination, significant new methodological knowledge has been learned leading to the conclusions noted below.

The sensitivity analysis showed that emissions from a construction project can be changed by changing the characteristics of the equipment fleet or the schedule of the construction activities. This knowledge was then used to develop an optimization model to determine a fleet composition capable of minimizing either cost or emissions.

The first research question presented was “can an effective model be created to select an equipment fleet that will produce the minimum amount of emissions?” We found that the optimization model was effective in selecting a fleet composition that can be used to reduce either emissions or cost. The solutions for the extreme cases of minimum cost and minimum emissions follow the expectation of having older equipment with lower cost and newer equipment with lower emissions levels, respectively. The more interesting solutions resulted from minimizing equipment cost while capping the quantity of emissions produced at a desired limiting level. Different emissions limits resulted in different equipment costs and fleet compositions. The differences in cost and emissions are due primarily to the selection of equipment of different tiers. Higher tier equipment produces lower quantities of emissions, but at a higher cost. Lower tier equipment is older, less expensive, and produces higher quantities of emissions.

The results show that emissions can be reduced 25% to 85% from the minimum cost solution depending on the pollutant. Emissions for CO generally have the larger percent reductions from the minimum cost solution while CO$_2$ has the lower percent reduction. The results also showed that there an inflection point where a small increase in emissions results in a larger reduction in cost.

The method presented in this paper can be used to select an equipment fleet after minimizing or capping one pollutant or any combination of the six pollutants. The model can also be used to develop a preliminary schedule of the project based on the equipment fleet selected and
estimate daily totals based on this schedule. These outputs can be added to the emissions estimation methodologies previously developed.

The model presented here was develop taking into consideration the data that is typically available to contractors. The information needed includes the model, engine size, and number of item available in the fleet as well as the cost information for each item of equipment. The cost information includes purchase price, fuel cost, productivity, and tire replacement information, among others. Contractors can also select the availability of rental equipment that will be presented as Tier 4 equipment, in accordance with the fleet configuration usually kept by rental companies. Contractors and fleet managers usually keep equipment and cost information for their own records and cost estimations. The user will also need to provide the quantities of production for each activity and the number of each item of equipment that would be needed to complete each activity. The project size, type, and construction site configuration would determine the amount of work needed and how many items of equipment the contractor can use. All of this information is normally readily available to contractors. The last piece of information needed is the maximum quantity of emissions that are allowed and that will by use to cap each pollutant.

The optimization model and the schedule calculation methodology presented here are functional and produce results that can be used by contractors to make decisions during the planning and construction phases of the project. The model was developed using Caterpillar equipment, four construction activities, and two transportation construction projects as study cases. However, the scope can be easily expanded by using actual equipment fleet information and construction project details.

The second research question presented was “what are the effects on fleet equipment selection when equipment cost is used as a selection factor?” The results demonstrated that total equipment cost can be used as a factor to select equipment fleet composition and to make predictable changes in fleet composition to adjust emissions levels. Equipment cost was
reduced by 63% when the minimum cost solution was compared with the minimum emissions solution. Equipment cost is one of the most important characteristics of a construction project. The ability to use this model to calculate not only emissions, but also cost and, to determine its impact on emissions, enables contractors to have a better understanding of a project and its trade-offs during the bidding process.

The third research question for this study was “what is the effect of selecting a minimum emissions fleet composition on a project schedule?” The methodology used here showed that changes in construction fleet can affect the duration of individual activities, and consequently, the total project duration. Total project duration for the Apex project changed from 20 to 35 days with a 43% reduction from the minimum emissions to the minimum cost solutions, for example. This result is due to the selection of smaller equipment that has lower emissions factors but that also has lower productivity. Delaying the project would affect other construction cost in addition to equipment cost, however, these cost are not included in the optimization model. Changing the schedule can help contractors to reduce daily peaks and to comply with capping requirements.

5.7 Recommendations

Additional time and effort can be invested in enabling the model to contain company-specific fleet data. It can thus be customized for a particular user. The values for the cost calculations can also be changed to represent those for the particular location and time of the forecast. Furthermore, dealers and rental companies can change their prices depending on their relationship with clients and updating this information would give contractors a better understanding of the equipment cost and how it affects total cost for a particular project. These improvements will make the model immediately useful for contractors who would then be able to use the results to select more efficient fleets and to estimate daily and total quantities of emissions for their projects.
Additional work should also be performed to include daily peaks of emissions as one of the optimization variables. Presently the total quantity of emissions can be capped but reduction of daily peaks can have a direct effect on particular environmental problems such as ozone production. Daily peaks can also be relevant at locations that need to reduce the quantity of pollutants in the environment to comply with EPA and local regulations. Finally, reducing daily peaks could reduce the exposure of construction workers and nearby residents to potentially dangerous emissions.

The results of this study show that contractors can directly affect emissions and cost by changing the composition of the construction fleet. Many larger construction companies have their own construction fleets and can select items and distribute them between the different projects being performed at the same time. Their ability to select an optimal project fleet composition would depend on the equipment available in the overall fleet at a particular time. Smaller companies can rent equipment to supplement their limited equipment fleets. Contractors should pay close attention to the equipment selected to be able to minimize emissions without an excessive increase in cost. This would be particularly important if new regulations are developed to limit in any way the quantity of emissions produced by construction projects.

Regulatory agencies can use the results of this study as input during the regulation creation process. Agencies such as state departments of transportation can add clauses to contracts to ensure that contractors are selecting an environmentally responsible fleet composition that reduces the environmental impact of construction activities and projects. One way to do so is to regulate the tier composition of the fleet as mentioned for the Maryland case. Another way to ensure that contractors work to reduce total emissions is to include emissions as a criterion for bidding in addition to total cost and project schedule. DOTs could also determine an upper limit of emissions allowed for each project and expect all contractors to update their fleet and construction method to comply with the limit. Cost allowances can be determined by DOT to help smaller contractors with older fleets that might not be competitive on this type of bidding.
environment. However, to take steps such as those recommended here requires the availability of models such as that presented herein.

Another realization of significance is that over time, contractors and rental companies will update their fleets to more efficient and less polluting equipment. Doing so will be affected, in part, by how quickly owners start to routinely ask for reduced pollutant emissions from their projects. This could be the result of an increased awareness by owners of the environmental effects of their construction projects. They may also seek to develop incentive programs similar to LEED certification whereby contractors are engaged to help owners be recognized or certified by a third party. Owners can offer the recognition to their clients while incentivizing contractors to reduce pollutant emissions production.
6.0 POLICY IMPLICATIONS OF CONSTRUCTION EQUIPMENT EMISSIONS ESTIMATIONS

6.1 Introduction

The Clean Air Act empowered the US Environmental Protection Agency to regulate pollutants emissions from different sources. Mobile sources, including onroad vehicles, nonroad vehicles, and equipment have separate regulations from the one for stationary sources such as factories, and processing plants. The nonroad regulations apply to vehicles and equipment that are not operated on the roads. Nonroad sources include aircraft, boats and ships, personal watercrafts, diesel equipment, generators, compressors, lawn and garden equipment, locomotives, and snowmobiles. Our interest focuses primarily on equipment used for construction, including diesel power equipment, generators, and compressors as noted previously.

The present study presents an assessment of the emissions reduction policies that are in place today at both the federal and state level. The policies presented here included regulations, governmental incentive programs, and voluntary certification programs. These policies directly affect companies that perform equipment intensive operations such as earthmoving, road construction, and utility installation. Owners and managers of construction equipment fleets are also affected. Manufacturers of construction equipment are also affected because some of these regulations would need the improvement of current technology or the development of completely new technology.

The second part of this study discusses how the research done on equipment emissions estimations and optimization is related to the current regulations. The results and lessons learned during the study of construction activities and the emissions produced can be used to update current regulations and to ensure that future policies are rooted on the current situation of the construction industry.
6.2 Current Regulations

The following sections present the pollutants emissions regulations that are created and currently enforce in the US. These regulations include both state and federal regulations that directly affect diesel-powered nonroad construction equipment.

6.2.1 Current Federal Regulations

An original Clean Air Act was passed on 1963 to establish funds to study and reduce air pollution. A more comprehensive Clean Air Act was implemented by Congress in 1970 and authorizes the US Environmental Protection Agency (EPA), also established in 1970, to develop National Ambient Air Quality Standard (NAAQS) to protect human health, ecosystems, and the built environment from hazardous pollutants. The Act also included deadlines for the states to comply with the standards. The Act was amended in 1990 to extend the goal dates for the standards because many areas were not able to meet the deadlines previously determined [EPA 2014b].

The EPA develops the NAAQS and each region and state needs to work to make sure that the air pollution in the area complies with the standards. Each region is responsible for developing a working plan to ensure compliance by the determined deadline. California has a unique capacity to set separate standards from the Clean Air Act regulation with approval from EPA. Some of the regulations already enforced in California were more stringent than the Federal regulations presented by the Clean Air Act. Other states can decide to use the California regulation or the federal regulation [Bryner 1995].

EPA developed NAAQS for six pollutants that are classified as criteria pollutants. The six criteria pollutants are: particulate matter (PM), ground-level ozone, carbon monoxide (CO), sulfur oxides (SO$_3$), nitrogen oxides (NO$_3$), and lead. Particulate matter and ground-level ozone are identified as the biggest threats to human health [EPA 2007].
EPA developed regulations for nonroad equipment that limit the quantity of HC, CO, NOx, and PM that can be produced by new engines. The nonroad emissions regulations were determined in 1994 to be implemented in 1996 for Tier 1 engines. More stringent regulations had been developed since then with Tier 4 regulations to be final in 2015. Each regulation includes different limits and deadlines depending on engine sizes in horsepower. Tier 1 engines were phased in between 1996 and 2005; Tier 2 between 2001 and 2010; Tier 3 between 2006 and 2011; and Tier 4 started in 2008 and will be in place for all engine sizes in 2015. Engines that were manufactured before emissions standards were in place are referred to as Tier 0 engines. These regulations apply to new equipment manufactured after each regulation was enforced. Manufacturers are responsible for the engines compliance with the corresponding emissions limits.

6.2.2 Current State regulations

The California Air Resource Board (CARB) of the California Environmental Protection Agency approved a standard to reduce PM and NOx emissions from the existing diesel nonroad fleet in July 2007 [CARB 2014a]. The regulation includes different requirements that were implemented in a progressive manner based on the size of the fleet. A fleet is considered small if has less than 2,500 horsepower total, medium fleet are up to 5,000 horsepower, and large fleet have more than 5,000 horsepower.

In 2008, the requirements for idling limit, written idling policy, and disclosure for selling vehicles were enforced. Fleet operators need to limit unnecessary idling to five minutes and medium and large fleets need a written idling policy. Sellers need to include information about the nonroad regulation on the invoice and keep record that the disclosure was provided. The seller also needs to report the vehicle sale to CARB. The requirement enforced in 2009 included reporting each item of equipment to CARB and labeling each item with the equipment identification number provided. Fleet owners need to report information about the
fleets annually that includes changes to the composition and hour meter readings for each item of equipment.

The regulation also restricts the equipment that can be added depending on the size of the fleet. Starting January 2014, Tier 0 engines cannot be added to any fleet. Tier 1 engines cannot be added to large and medium fleets since January 2014; and to small fleets since January 2016. Restrictions on Tier 2 engines will be enforced for large and medium fleets in January 2018 and for small fleet in January 2023.

The final part of the CARB regulation is a yearly compliance with fleet composition. Every year fleet managers need to demonstrate that the fleet has a lower NOx emissions rate than the target emissions rate for that particular fleet or they will need to comply with turning over or retrofitting of an indicated percent of the fleet. The percent for turnover is based on fleet size and are presented below.

<table>
<thead>
<tr>
<th>Large Fleets</th>
<th>2014: 4.8%</th>
<th>2015 to 2017: 8%</th>
<th>2018 to 2023: 10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium Fleets</td>
<td>2017: 8%</td>
<td>2018 to 2023: 10%</td>
<td></td>
</tr>
<tr>
<td>Small Fleets:</td>
<td>2019 to 2028: 10%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fleets smaller than 500 horsepower can follow the regulations for small fleets or they can comply with an optional fleet composition requirement. The objective is for all Tier 0 and Tier 1 engines to be eliminated by 2029. Table 6.1 presents the optional schedule for fleets smaller than 500 horsepower.
Table 6.1  Optional Compliance Schedule for Fleets with 500HP of Less [CARB 2014b]

<table>
<thead>
<tr>
<th>Compliance Date (January 1)</th>
<th>Percent of Fleet (by horsepower) which must have a Tier 2 or Higher Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>25</td>
</tr>
<tr>
<td>2022</td>
<td>50</td>
</tr>
<tr>
<td>2026</td>
<td>75</td>
</tr>
<tr>
<td>2029</td>
<td>100</td>
</tr>
</tbody>
</table>

The regulations explained above are different from the first regulation presented in 2007 by CARB. The changes were in part the result of efforts by the local and national chapters of The Associate General Contractors of America (AGC). There were two major issues that AGC wanted to fix before the regulation could be enforced. The first issue was the underestimation of the cost that contractors needed to incur to prepare their fleet for compliance. CARB estimated the cost in $3.4 billion while AGC estimated $13 billion. The second issue was that AGC stated that CARB overestimated the total quantity of pollution produced by construction equipment. AGC performed independent studies to estimate emissions and determine that actual production was below the levels imposed by the regulations. After the discussion time, CARB accepted that their emissions estimate was wrong and accepted to delay the enforcement of the regulations by four years, among other changes to the regulation [CARB 2014].

Other states and regions have developed policies and regulations that directly affect construction equipment fleets. One of these policies is the one approved by the Clean Diesel Construction Initiative in the City of Chicago in 2011. The initiative prohibits the use of Tier 0 equipment and on-road vehicles manufactures before 1998 to be used on City construction projects. The rule applies for projects $2 million or grater [CC 2014].
6.3 Current Incentive Programs

One of the best-known incentive programs for green construction is the Leadership in Energy and Environmental Design (LEED). As mentioned in the literature review section of this document, LEED certification does not include emissions from construction equipment as one of the categories to receive points toward certification. However, LEED is a good example of one green construction incentive program that was accepted by the community and now is required by a number of owners. The owners desire to have a certified property directly affect the contractor’s compliance with LEED provisions. Even when this particular program does not include equipment emissions, it is an example of successful green construction policies that are voluntarily introduced to the planning and construction phases of a project.

In January 2006, 19 federal agencies signed the “Memorandum of Understanding for Federal Leadership in High Performance and Sustainable Buildings” that charges the agencies with reducing the life cycle environmental impact by designing, constructing, and operating high-performance sustainable buildings. As part of this effort, the U.S. General Service Administration decided that new buildings and major renovations should comply with LEED Gold certification [GSA 2014]. This decision from the Federal Government shows a commitment to improve the sustainability of new infrastructure and a willingness to use common industry standards as measures of this improvement.

There are at least three existing green highway rating systems that are analogous to LEED certification for buildings: GreenLITES (New York), Greenroads (Washington and Oregon), and I-Last (Illinois).

GreenLITES [NYDOT 2014] is a transportation environmental sustainability rating system implemented by the New York DOT. The system is a self-certification program that is used to measure the performance and recognize the use of sustainable practices during transportation projects. The projects are assigned an appropriate certification level (certified, silver, gold, and evergreen.) based on the total credits received. The system includes 175
individual opportunities for credits divided into 13 sections. The construction process is mentioned in the Water Quality section to ensure that an environmental construction monitor is assigned to oversee sensitive environmental areas. Emissions are not addressed.

Greenroads [GF 2014] is a sustainability rating system that was developed particularly for roadway projects. The rating system provides project managers with an opportunity to obtain points for sustainable decisions in seven areas: project requirements, environment and water, access and equity, construction activities, materials and resources, pavement and resources, pavement technologies, and custom credit. The construction activities area includes points for fossil fuel use reduction and equipment emissions reduction. Projects receive one point for using 15% of biofuel and 2 points for using 25% of biofuels. The projects can also receive one point if 50% (two points if 75%) of the operating hours are completed using equipment that complies with EPA Tier 4 emissions standards.

The Illinois Livable and Sustainable Transportation Rating System (I-LAST) was developed to provide a list of sustainable practices, have a system to evaluate transportation projects performance, and to record the use of sustainable practices [IDOT, 2012]. A project team can use the rating system at the beginning of a project to identify the elements that are applicable to the specific project type and location. At the end of the project, the project team can compare the preliminary list with the sustainable practices actually used during the project. The system includes 16 categories, however, the only section related directly to environmental effects during the construction process is “Construction Practices to Protect Water Quality.” Again, emissions are not addressed.

Other rating systems have been created recently that are focused on other construction types. (For example, the Envision Sustainable Infrastructure Rating System [ISI 2014] was developed for infrastructure projects.) However, even when these rating systems address construction site management activities they usually focus only on erosion and runoff control.
The majority of the time they only require contractors to comply with the basic erosion control requirements of the EPA and local jurisdictions.

The Illinois Clean Diesel Grant Program is a state incentive program that offers financial help to buy new diesel vehicles and equipment or to retrofit older equipment. The objective of the program is to reduce pollution especially particulate matter. Contractors apply to the program and the Illinois EPA will approve the application based on the funds available and the type of work performed. If approved, the contractor will be reimbursed for the cost incurred during the projects to buy new or retrofit old equipment [IEPA 2014].

The Carl Moyer Memorial Air Quality Standards Attainment Program was developed by the CARB in 1998 to offer financial help to companies to buy equipment that is cleaner that the levels required by regulation. The Program is a complement to the CARB emissions regulation and the objective is to enable fleet owners to comply with the regulations in a timely manner and can be used for both on-road and nonroad vehicles and equipment. The benefits from the Program can be used to reduce fleet emissions by different strategies including repowering, retrofitting, new purchase, replacement of old equipment, or retirement of old equipment [CARB 2014b].

The Texas Emissions Reduction Program (TERP) is composed of eight different grants that can be used to reduce emissions from different sources. The Emissions Reduction Incentive Grants, the Rebate Grants, and the ARRA Rebate Grants Program are the three programs that offer funds for nonroad construction equipment. The other five grants offer support to reduce emissions form on-road heavy and light duty trucks, drayage trucks, and stationary sources. Each grant has its own requirements and eligibility [TCEQ 2014].

As part of the Energy Policy Act of 2005, the Diesel Emissions Reduction Act (DERA) offers two types of grants to help fleet owners reduce emissions from diesel vehicles and equipment [EPA 2014c]. These two grant programs are offered to agencies to develop programs that will help improve local fleets. The first program is the DERA National Funding Assistance
Program that offers grants to regional, state, local, or tribal agencies with transportation or air quality programs. The grant can also be offered to nonprofit organizations that promote air quality or transportation programs. The second grant program is the DERA State Program that offer help to states and territories that have clean diesel grants and loan programs. Each state or agency is responsible to develop the particular incentive that will help to improve equipment fleet in each region.

Another type of voluntary certification is the Green Fleet Certification developed by the Association of Equipment Management Professionals [AEMP 2014]. The goal of the program is to provide recognition to fleet managers that had worked on improving the fleet and to provide incentives for companies to reduce emissions. AEMP provides certifications for fleets comprised of both on and nonroad vehicles and for fleets comprised of only nonroad vehicles. Fleets can received one of four certifications levels as bronze, silver, gold, and platinum. The different levels correspond to the tier configuration of the fleet. For example, Bronze Status for nonroad fleets requires the fleet to be 50% Tier 2 or higher and to have a written idle policy. To achieve Platinum Status the fleet should have 75% Tier 2 or higher, 50% Tier 3 or higher, and 25% Tier 4 in addition to a written idle policy.

6.4 Potential Impact of Current Research

The regulations discussed on this study are an example of the policies that are developed and enforced by many different agencies in the US to reduce emissions from construction equipment. Each of these policies is addressing the problem from a different perspective with the objective that the combination of efforts would result in overall air pollution reduction. The process of updating current policies and the development of new policies could be improved by taking into consideration the results and the lessons learned from the different research projects that have contributed to the understanding, estimation, and forecasting of emissions from construction equipment. This section describes the relationship between the
work presented in this document and some of the regulations and incentive programs presented above.

The Clean Air Act and EPA regulations for nonroad equipment have reduced the emissions production from diesel engines to very low quantities. However, these regulations are only enforced based on the emissions produced by new engines. Previous research has shown that maintenance and use practices have a significant impact on the emissions actually produced by each item of equipment. Information collected from transportation construction projects and equipment rental companies showed that even when fleet managers acquire newer equipment that complies with the latest regulations, older equipment is kept in the fleet to supplement the use of the new equipment when needed.

CARB regulations address the problem of older equipment by requiring the registration of all equipment and by prescribing the configuration of fleets based on tier regulation. However, the CARB regulation had other problems. For example, the emissions estimation initially used to develop the regulation was not accurate. The controversies about the CARB emissions made evident the need for an accurate emissions estimation methodology. An accurate estimation methodology (similar to the one presented before) is necessary to determine a realistic and effective emissions limit. Regional estimates of construction emissions could be compared with current EPA regional pollution estimates to determine the overall effect of construction activities on the environment. Estimations of emissions from particular construction projects can be used to limit emissions on a time basis (e.g., emissions per day, emissions per week) or by total emissions per project.

Another aspect of the EPA nonroad regulation is that it regulates the quantity of HC, NOx, PM, and CO produced by the engines new equipment. The exhaust pollutants included in the forecasting and optimization methodologies presented before, included CO₂ and SO₂ in addition to the other four pollutants. CO₂ is one of the major contributors to the greenhouse effect and climate change. Future regulation should include provisions to reduce CO₂
emissions that would result on a reduced environmental footprint of construction activities. 
CO₂ and SO₂ emissions are directly linked to the combustion process and the fuel used and 
regulation aimed to minimize these two pollutants should be linked to changes in technology.

Future regulations could also include limits on daily emissions for one or a combination of 
pollutants. Reducing daily totals of emissions could reduce the exposure of workers and 
operators to dangerous emissions. This approach could also be useful for regions that exceed 
EPA limits for environmental quantities of pollutants such as ozone. Ozone production is 
caused by the combination of HC and NOx in the atmosphere and is accelerated by ultraviolet 
rays. Reducing the emissions of these two pollutants during sunny summer days could help 
the effected regions to reduce pollutions and stay below the EPA limits.

Voluntary rating systems including LEED, GreenLITES, Greenroads, and I-LAST are used 
during the planning and early construction phases of a project and currently do not include 
any provisions for construction equipment emissions. The optimization model presented 
above could be used to estimate the emissions production from a project. Future changes to 
rating system could include points for producing equal or less amount of emissions than those 
forecasted with the model. An incentive program of this type can offer the contractor the 
flexibility of selecting a fleet with a total cost based on the limitations of the project budget 
while taking into consideration the need to asses and reduce emissions production. In 
addition, incentive programs selected by the owner ensure that the project cost would take 
into consideration the additional cost for the contractor to improve their fleet and apply 
emissions reduction techniques.

Grant and incentive programs including the Illinois Diesel Grant Program, the Carl Moyer 
Program, TERP, and DERA offer financial help to companies and fleet manager that want to 
improve their fleet by retrofitting old equipment and buying new equipment that complies to 
EPA or CARB regulations. Research results showed that the emissions reduction between 
Tier 4 and older tiers is significant. These programs should also facilitate the removal of old
equipment from the fleets to ensure that older and more pollutant equipment are eliminated from the fleet.

Another way to incentivize emissions reduction is to include contractual clauses that require contractors to take actions to reduce emissions or to have a specific equipment fleet composition with more new equipment. These clauses could include the percent of equipment that should be Tier 4 for the contractor to be qualified to bid for the project. The benefit of this system is that the agency could select the larger projects that have a larger environmental impact to have the stricter provisions while being more lenient for smaller projects.
7.0 REFERENCES


APPENDIX A. LEED Certification Rating System

Sustainable Site

- Construction Activity Pollution Prevention: Required
  - Create and implement an erosion and sedimentation control plan.
    - Prevent loss of soil during construction by stormwater runoff or wind erosion
    - Prevent sedimentation of storm sewers or receiving streams
    - Prevent pollution of the air with dust and particulate matter

- Site Selection: 1 Point
  - Do not develop on land that meets any of these criteria:
    - Prime agricultural land
    - Elevation lower than 5 feet above the elevation of the 100-year flood
    - Land that provides habitat for threatened or endangered species
    - Land within a 100 feet of wetlands
    - Previously undeveloped land that is within 50 feet of a water body, defined as sea, lakes, rivers, streams, and tributaries that support or can support fish, recreation, or industrial use.
    - Land that was public parkland unless land of equal or greater value is accepted in trade by the public land owner.

- Development Density and Community Connectivity: 5 Point
  - Option 1: Construct or renovate a building on a previously developed site and in a community within a minimum density of 60,000 square feet per acre net.
  - Option 2: construct or renovate on a site that meets the following criteria:
    - Is located in a previously developed site
    - Is within ½ mile of a residential area or neighborhood with an average density of 10 units per acre net
    - Is within ½ mile of at least 10 basic services
    - Has pedestrian access between the building and the services

- Brownfield Redevelopment: 1 Point
  - Option 1: Develop on a site documented as contaminated.
  - Option 2: Develop on a site classified as a brownfield.

- Alternative Transportation – Public Transport Access: 6 Points
  - Option 1: Locate building within ½ mile walking distance of an existing or planned and funded commuter rail, light rail, or subway station
  - Option 2: Locate the project within ¼ mile walking distance of 1 or more stops for 2 or more bus lines.
Alternative Transportation – Bicycle Storage and Changing Rooms: 1 Points
  o Case 1: Commercial and Institutional Projects
    • Provide secure bicycles racks and or storage within 200 yards of a
      building entrance 5% or more of building users.
    • Provide showers and changing facilities in the building or within 200
      yards of a building entrance for 0.5% of full-time equivalent occupants.
  o Case 2: Residential Projects
    • Provide covered storage facilities for securing bicycles for 15% or more
      of building occupants.

Alternative Transportation – Low-Emitting and Fuel-Efficient Vehicles: 3 Points
  o Option 1: Provide preferred parking for low-emitting and fuel-efficient
    vehicles for 5% of the total vehicle parking capacity. Providing a discounted
    parking rate (20%) is an acceptable substitute for preferred parking.
  o Option 2: Install alternative-fuel refueling stations for 3% of the total vehicle
    parking capacity of the site.
  o Option 3: Provide low-emitting and fuel-efficient vehicles for 3% of full-time
    occupants and provide preferred parking for these vehicles.
  o Option 4: Provide building occupants access to a low emitting or fuel-efficient
    vehicle-sharing program.

Alternative Transportation – Parking Capacity: 2 Points
  o Case 1: Non-Residential Projects
    • Option 1: Size parking capacity not to exceed minimum local zoning
      requirements and provide preferred parking for carpool or van pools
      capable of serving 5% of the total parking space.
    • Option 2: For projects that provide parking for less than 5% of full time
      equivalent building occupants: Provide preferred parking for low-
      emitting and fuel-efficient vehicles for 5% of the total vehicle parking
      capacity. Providing a discounted parking rate (20%) is an acceptable
      substitute for preferred parking.
    • Option 3: Provide no new parking.
  o Case 2: Residential Projects
    • Option 1: Size parking capacity to meet but not to exceed minimal local
      zoning requirements. Provide infrastructure and support programs to
      facilitate shared vehicle use.
    • Option 2: Provide no new parking.
  o Case 3: Mixed Use Projects
    • Option 1: Projects with less than 10% commercial area must adhere to
      the residential requirements. Projects with more that 10% commercial
      area, the commercial space should follow the non-residential
requirements and residential area should follow the residential requirements.
- Option 2: provide no new parking.

- Site Development – Protect or Restore Habitat: 1 Point
  - Case 1: Greenfield sites
    - Limit site disturbance to 40 feet beyond the building perimeter; 10 feet beyond surface walkways, surface parking, and utilities; 15 feet beyond primary roadway curbs, and main utility branch trenches; and 25 feet beyond pervious paving areas.
  - Case 2: Previously Developed Areas or Graded Sites
    - Restore or protect a minimum of 50% of site (excluding building footprint) or 20% of the total site area (including building footprint), whichever is greater, with native or adapted vegetation.

- Site Development – Maximum Open Space: 1 Point
  - Case 1: Sites with Local Zoning Open Space Requirements
    - Reduce the development footprint and/or provide vegetated open space within the project boundary such that the amount of open space exceeds local zoning requirements by 25%.
  - Case 2: Sites with No Local Zoning Requirements
    - Provide a vegetated open space area adjusted to the building that is equal in area to the building footprint.
  - Case 3: Sites with Zoning Ordinance but No Open Space Requirements
    - Provide vegetated open space equal to 20% of the project site area.

- Storm Water Design – Quantity Control: 1 Points
  - Case 1: Sites with Existing Imperviousness 50% or Less
    - Option 1: implement a stormwater management plan that prevents the postdevelopment peak discharge rate and quantity from exceeding the predevelopment peak discharge rate and quantity for the 1- and 2-year 24-hour design storm.
    - Option 2: Implement a storm water management plan that protects receiving streams channels from excessive erosion.
  - Case 2: Sites with Existing Imperviousness Greater than 50%
    - Implement a stormwater management plan that protects receiving streams channels from excessive erosion.

- Storm Water Design – Quality Control: 1 Points
  - Implement a stormwater management plan that reduces impervious cover, promotes infiltration, and captures and treats the stormwater runoff from 90% of the average annual rainfall.
Treatment system designed to remove 80% of the average annual post development total suspended solids.

- **Heat Island Effect – Nonroof**: 1 Point
  - Option 1: Use any combination of the following strategies for 50% of the site hardscape.
    - Provide shade from the existent tree canopy or within 5 years from landscape installation.
    - Provide shade from structures covered by solar panels that produce energy used to offset some non-renewable sources use.
    - Provide shade from architectural devices or structures that have a solar reflectance index (SRI) of at least 29.
    - Use hardscape material with an SRI of at least 29.
    - Use an open-grid pavement system (at least 50% pervious).
  - Option 2: Place a minimum of 50% of parking space under-cover. Any roof used to shade or cover the parking must have an SRI of at least 29, be a vegetated green roof, or be covered by solar panels.

- **Heat Island Effect – Roof**: 1 Point
  - Option 1: Use roofing with SRI equal to or greater than 78 for low-sloped roof and 29 for steep-sloped roof for a minimum of 75% of the roof surface.
  - Option 2: Install a vegetated roof for at least 50% of the roof area.
  - Option 3: Install high-albedo and vegetable roof surface in combination.

- **Light Pollution Reduction**: 1 Point
  - For Interior Lighting
    - Option 1: Reduce the input power (by automatic device of) all nonemergency interior luminaires with a direct line of sight to any openings in the envelope (translucent or transparent) by at least 50% between 11 p.m. and 5 a.m. After-hours override may be provided by a manual or occupant-sensing device provided the override lasts no more than 30 minutes.
    - Option 2: All openings in the envelope (translucent or transparent) with a direct line of sight to any nonemergency luminaires must have shielding (controlled/closed by automatic device for a resultant transmittance of less than 10% between 11 p.m. and 5 a.m.).
  - For Exterior Lighting
    - Light areas only as required for safety and comfort.

**Water Efficiency**
- Water Use Reduction: Required
- Water Efficiency Landscaping: 2 – 4 Points
• Innovative Wastewater Technologies: 2 Point
• Water Use Reduction: 2 – 4 Points

Energy and Atmosphere
• Fundamental Commissioning of Building Energy Systems: Required
• Minimum Energy Performance: Required
• Fundamental Refrigerant Management: Required
• Optimize Energy Performance: 1 – 19 Points
• On-Site Renewable Energy: 1 – 7 Points
• Enhanced Commissioning: 2 Point
• Enhanced Refrigerant Management: 2 Point
• Measurement and Verification: 3 Point
• Green Power: 2 Point

Material and Resources
• Storage and Collection of Recyclables: Required
• Building Reuse – Maintain Existing Walls, Floors, and Roof: 1-3 Points
• Building Reuse – Maintain Existing Interior Nonstructural Elements: 1 Point
• Construction Waste Management: 1-2 Points
• Material Reuse: 1-2 Points
• Recycled Content: 1-2 Points
• Regional Materials: 1-2 Points
• Rapidly Renewable Materials: 1 Point
• Certifies Wood: 1 Point

Indoor Environmental Quality
• Minimum Indoor Air Quality Performance: Required
• Environmental Tobacco Smoke Control: Required
• Outdoor Air Delivery Monitoring: 1 Point
• Increased Ventilation: 1 Point
• Construction Indoor Air Quality Management Plan – During Construction: 1 Points
• Construction Indoor Air Quality Management Plan – Before Occupancy: 1 Points
• Low-Emitting Materials – Adhesives and Sealants: 1 Points
• Low-Emitting Materials – Paints and Coatings: 1 Points
• Low-Emitting Materials – Flooring Systems: 1 Points
• Low-Emitting Materials – Composite Wood and Agrifibers: 1 Points
• Indoor Chemical and Pollutant Source Control: 1 Point
• Controllability of Systems – Lighting: 1 Point
• Controllability of Systems – Thermal Control: 1 Point
• Thermal Comfort – Design: 1 Points
• Thermal Comfort – Verification: 1 Points
• Daylight and Views - Daylight: 1 Points
• Daylight and Views - Views: 1 Points

**Innovation Credits and Design/Build Process**
• Innovation in Design: 1 – 5 Points
• Accredited Professional: 1 Point

**Regional Priority**
• Regional Priority: 1 – 4 Points

**LEED Green Building Certification Levels**
- LEED Certified 40 – 49 Points
- LEED Certified Silver Level 50 – 59 Points
- LEED Certified Gold Level 60 – 79 Points
- LEED Certified Platinum Level 80 Points and Above
APPENDIX B. VBA Program to Develop the Project Schedule from Construction Quantities and Equipment Productivity

Option Explicit

Sub Schedule()

'Defining the variables used on the program
    Dim Col As Long
    Dim Row As Long
    Dim Hours As Single
    Dim StartCol As Long
    Dim StartColPav
    Dim PaverRow As Long
    Dim EndColPav As Long
    Dim Counter As Long

'Loop for grading with Bulldozer
    For Row = 4 To 163
        If Cells(Row, 56) <> Empty Then
            Hours = Cells(Row, 56)
            For Col = 57 To 106
                If Hours <= 0 Then
                    StartCol = Col
                    Exit For
                ElseIf Hours <= 8 Then
                    Cells(Row, Col) = Hours
                Else
                    Cells(Row, Col) = 8
                    End If
                    Hours = Hours - 8
            Next Col
        End If
    Next Row

'Loop for Excavating with excavator or Backhoe

    For Row = 235 To 375
        If Cells(Row, 56) <> Empty Then
            Hours = Cells(Row, 56)
            For Col = StartCol To 106
                If Hours <= 0 Then
                    StartCol = Col
                    Exit For
                ElseIf Hours <= 8 Then
                    Cells(Row, Col) = Hours
                Else
                    Cells(Row, Col) = 8
                    End If
                    Hours = Hours - 8
            Next Col
        End If
    Next Row
If Hours <= 0 Then
    StartCol = Col
    Exit For
ElseIf Hours <= 8 Then
    Cells(Row, Col) = Hours
Else
    Cells(Row, Col) = 8
End If
Hours = Hours - 8
Next Col
End If
Next Row

'Loop for Fine Grading with Motor Grader

For Row = 164 To 234
    If Cells(Row, 56) <> Empty Then
        Hours = Cells(Row, 56)
        For Col = StartCol To 106
            If Hours <= 0 Then
                StartColPav = Col
                Exit For
            ElseIf Hours <= 8 Then
                Cells(Row, Col) = Hours
            Else
                Cells(Row, Col) = 8
            End If
            Hours = Hours - 8
        Next Col
    End If
Next Row

'Loop for the Paving activity with Paver

For Row = 468 To 495
    If Cells(Row, 56) <> Empty Then
        Hours = Cells(Row, 56)
        For Col = StartColPav To 106
            If Hours <= 0 Then
                Exit For
            ElseIf Hours <= 8 Then
                Cells(Row, Col) = Hours
            Else
                Cells(Row, Col) = 8
            End If
            Hours = Hours - 8
        Next Col
    End If
Next Row
Cells(Row, Col) = Hours
EndColPav = Col
Else
    Cells(Row, Col) = 8
    EndColPav = Col
End If
Hours = Hours - 8
Next Col
PaverRow = Row
End If
Next Row

'Loop for the Paving activity with Tandem Roller

For Row = 376 To 451
    If Cells(Row, 56) <> Empty Then
        Hours = Cells(Row, 56)
        Counter = 0
        For Col = StartColPav To EndColPav
            If Hours <= 0 Then
                Exit For
            Else
                Cells(Row, Col) = Cells(Row, 56) * (Cells(PaverRow, StartColPav + Counter) / Cells(PaverRow, 56))
                Counter = Counter + 1
            End If
        Next Col
    End If
Next Row

'Loop for the Paving activity with Pneumatic Roller

For Row = 452 To 467
    If Cells(Row, 56) <> Empty Then
        Hours = Cells(Row, 56)
        Counter = 0
        For Col = StartColPav To EndColPav
            If Hours <= 0 Then
                Exit For
            Else
            End If
        Next Col
    End If
Next Row
Cells(Row, Col) = Cells(Row, 56) * (Cells(PaverRow, StartColPav + Counter) /
Cells(PaverRow, 56))
    Counter = Counter + 1
    End If
    Next Col
    End If
    Next Row
End Sub