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Title: Comprehensive Analysis of $PM_{2.5}$ Pollution from Construction Activities

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The Construction industry is one of the most hazardous industries in the US. Construction workers, on a daily basis, are exposed to numerous risks while performing a range of activities involving construction, alteration, and/or repair. Dust and diesel exhaust emissions from construction equipment are considered harmful to the workers in the long run. Several studies have highlighted the ill-effects of constant exposure to diesel fumes and dust, but without directly relating to the conditions at a construction site. This thesis evaluates the concentration levels of $PM_{2.5}$ on a construction site in Central Western Oregon and their relation with weather conditions. The paper also analyses the different $PM_{2.5}$ concentrations the equipment operators are exposed to in the presence and absence of closed operator cabins. The concentration levels of $PM_{2.5}$ were measured using an aerosol monitor, TSI DustTrak II 8530. The measuring device was placed inside the operator cabin while collecting data from an excavator and inside the DustTrak II 8535 enclosure while collecting data from an open, cabinless dozer. The conclusions from this study presented the impact of weather on the concertation levels of $PM_{2.5}$. The study revealed that temperature had minimal impact on particle matter pollution while precipitation had a significant negative correlation with the same. The research also found that the operators inside an enclosed cabin were exposed to higher levels of $PM_{2.5}$ than those working in an open cabin. This thesis also presents several strategies that can be used by construction professionals to mitigate emissions from construction equipment.

Comprehensive Analysis of $PM_{2.5}$ Pollution from Construction Activities

by

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Nahush Prabhakar Montadka, Author

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TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF FIGURES

LIST OF TABLES

1.0 Introduction

The construction industry is a high-risk sector in the US market, with the industry contributing to one in every five occupational fatalities (BLS 2016). Construction of residential, commercial and other infrastructural projects has significant impact on the environment. The impact could be during the construction phase or after its completion. The construction phase requires massive amounts of energy (in various forms) and subsequently resulting in production of huge amounts of waste and deteriorating the quality of air. According to the UK Green Building Council (UKGBC), the construction sector uses more than 400 million tons of material a year, many of which has an adverse impact on the environment (Willmott-Dixon Report 2010). Most construction activities involve the use of heavy nonroad equipment that are known to generate dust and emissions such as carbon monoxide, carbon dioxide, nitrogen dioxide, particulate matter and so on. These emissions impact worker health and reduce the quality of the surrounding as well as the working environment (CEQA 2012). Based on a report by the National Toxicology Program of the Department of Health and Human Services, continuous exposure to diesel exhaust is believed to be cancerous to humans and animals (NTP 2000, NIOSH 2016). In addition, according to a report prepared by the Willmott Dixon Group, construction activities are responsible for nearly 23% of air pollution. The report also states that almost half of the gases responsible for climate change are a result of construction activities (Willmott-Dixon Report 2010).

Despite producing higher emissions, diesel is a more efficient fuel than gasoline. Hence, most heavy-duty and nonroad equipment operators choose diesel over gasoline (NEDC 2016). However, higher emissions have an adverse impact on the environment as well as the workers at the construction site. According to the Northeast Diesel Collaborative (NEDC), construction equipment such as backhoes, cranes, and bulldozers are responsible for over 30 percent of all nitrogen oxide and fine particle emissions from mobile sources (NEDC 2016).

A study conducted by The Nevada Division of Environmental Protection of the Bureau of Air Quality Planning reports that, fugitive dust generated from on-road and nonroad engines account for more than 48,000 tons per year, while construction activities, irrespective of their size and type, account for a little over 143 tons per year (BAQP 2001).

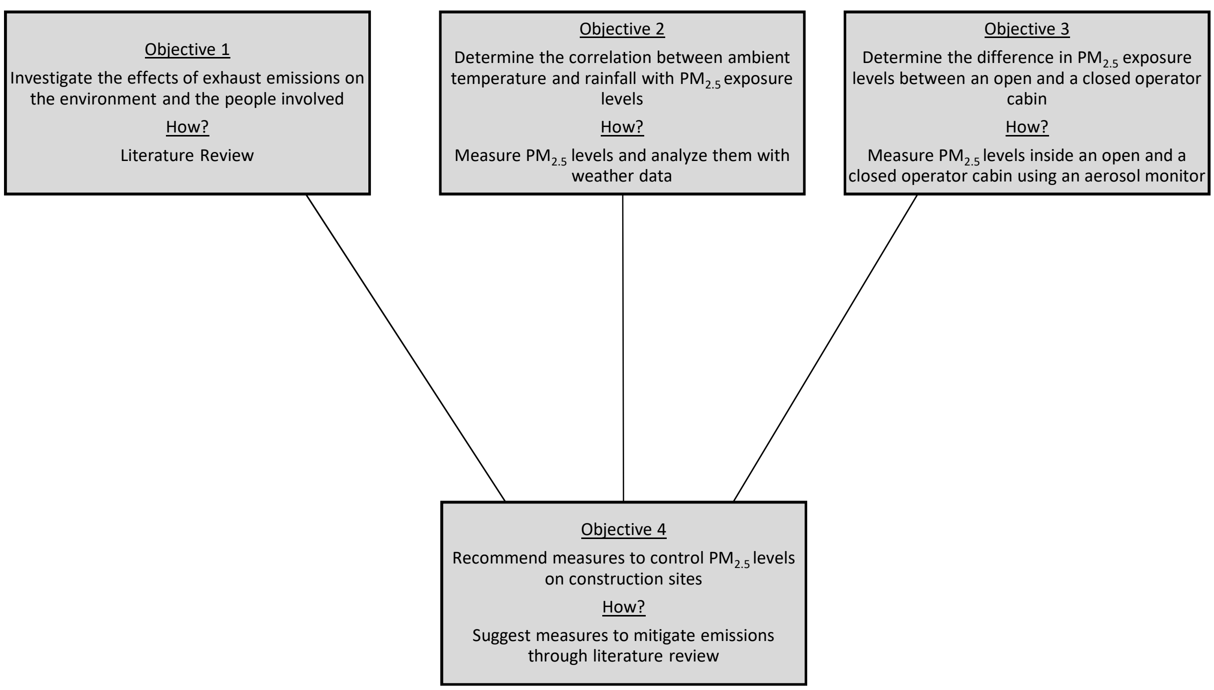
This shows the kind of impact the construction industry has on individuals directly involved in it as well as the environment and the public. As a result, this study was conducted to evaluate the impact of pollutants emitted from construction equipment on the environment and the workers alike and the correlation of one particular pollutants ($PM_{2.5}$) with weather conditions such as rainfall and temperature. The study also suggests strategies that would mitigate emissions from nonroad construction equipment while improving their performances, thereby making the construction industry more profitable for those involved and safer for the environment and the public.

1.1 Objectives

The objectives of this research can be summarized as follows:

- Review the numerous health effects associated with constant exposure to diesel exhaust emissions.
- Investigate the effects of temperature and rainfall on the amount of particulate matter equipment operators are exposed to.
- Determine the difference in particulate matter exposure levels between an open and an enclosed operator cabin.
- Recommend measures to mitigate emissions from construction equipment.

The following flow chart provides a brief overview of the outline of the study.



2.0 Literature Review

The construction industry is a major source of diesel pollution, using more diesel engines than any other sector in the US (NEDC 2016). Of the 2 million diesel engines currently used in construction equipment across the US, nearly 31 percent were manufactured before the introduction of emissions regulations. Backhoes, cranes, and bulldozers are known to be responsible for 32 percent of nitrogen oxide and 37 percent of fine particulate matter emissions from mobile sources, thereby exposing the workers and the public to poor quality of air (NEDC 2016, Diesel Engines 2016). These equipment contribute to particulate and ozone pollution that can cause severe cardiovascular and respiratory illnesses, asthma attacks, acute bronchitis, and even premature death. Lenient emission standards along with the use of old equipment have made the construction industry one of the major sources of diesel particulate matter pollution (USC 2006).

2.1 Diesel Exhaust

Diesel exhaust is a mixture of gases and fine particles, called diesel particulate matter (DPM). The exhaust of diesel engines contain numerous chemicals such as (OSHA 2016, Martin et al. 1955):

- Carbon monoxide
- Carbon dioxide
- Oxygen
- Sulphur dioxide

- Nitrogen dioxide
- Nitric oxide
- Particulate Matter
- Hydrocarbons
- Lead
- Hydrogen
- Volatile Organic Compounds
- Water Vapor
- Organic Acids
- Aldehydes
- Alcohols

According to the EPA, these pollutants are injurious to health and harmful to the environment. Pollutants such as carbon monoxide, carbon dioxide, sulfur dioxide, nitrogen dioxide, nitric oxide, and particulate matter are present in large concentrations and hence, are more dangerous than other diesel exhaust components that are present in smaller numbers. These pollutants that are present in higher concentrations, are termed as criteria air pollutants.

2.2 Criteria Air Pollutants

As directed by the Clean Air Act, the US Environmental Protection Agency (EPA) has set National Ambient Air Quality Standards (EPA 2016b) for six common air pollutants. The EPA calls these pollutants "criteria" air pollutants because of their negative effects on human health and the environment. Hence, the EPA has setup guidelines highlighting the permissible levels for these pollutants based on their level of impact on the environment and human health. The EPA has setup primary and secondary standards/levels for the pollutants, with the former focusing on the permissible levels with respect to human health, while the latter focuses on the threshold levels for the environment (EPA 2016b).

2.2.1 Ozone

Volatile organic compounds (VOC) emitted from onroad vehicles and nonroad equipment react with oxides of nitrogen in the presence of sunlight to form ozone, which is an ingredient of smog. Ozone is not directly released into the environment but emissions in the form of NOx and VOCs from vehicles, nonroad equipment, and industrial facilities are responsible for its formation (EPA 2016b). This is known as ground-level ozone. Ground level ozone is different from stratospheric ozone. Stratospheric ozone is a layer of ozone present in the stratosphere that primarily protects the earth from the harmful ultraviolet rays emitted by the sun. Ground-level ozone, although less concentrated than stratospheric ozone, is associated with several health issues such as airway inflammation, coughing, and throat irritation while worsening asthma and bronchitis. It is also known to affect sensitive vegetation and ecosystems (EPA 2016c).

2.2.2 Lead

Lead (Pb) is a metal found naturally in the environment as well as in manufactured products. Emission from the exhaust of on-road vehicles and nonroad equipment as well industrial sources are the major contributors of lead in the atmosphere. As a result, various regulations resulted in the removal of lead from onroad motor vehicle gasoline, thereby dramatically reducing lead emissions from the transportation sector and lead concentrations in the air by 95% and 94% respectively, between 1980 and 1999. Currently, the major sources of lead emissions are the ore and metal processing sectors, and piston-engine aircraft operating on leaded aviation gasoline (EPA 2016b). Long-term exposure to lead is known to cause health problems such as mental retardation and behavioral disorders in children as well as causing seizures and damage to the brain and kidney (DEQ 2017).

2.2.3 Carbon Monoxide

Carbon monoxide (CO) is a colorless, odorless gas, primarily emitted by the process of combustion. Mobile sources are the major sources of carbon monoxide pollution in urban areas. Carbon monoxide, like most criteria pollutants, causes respiratory problems in humans by cutting down the amount of oxygen delivered to the vital organs and tissues. The EPA has reported that exposure to high concentrations of CO is fatal (EPA 2016b).

2.2.4 Nitrogen Oxides

Nitrogen dioxide (NO_2), nitrous acid (HNO_2) and nitric acid (HNO_3) are, together, classified as nitrogen oxides (NO_x). Nitrogen dioxide is a highly reactive gas, emitted by several mobile sources such as cars, buses and nonroad equipment as well as industrial sources and power plants. In addition to contributing to the formation of ozone, and particulate matter pollution, NO_2 is also a precursor for the formation of HNO_2 and HNO_3. Like most other criteria pollutants, is associated with several respiratory diseases (EPA 2016b).

2.2.5 Sulfur Dioxide

Sulfur dioxide emissions are primarily produced by the combustion of fossil fuels at power plants and other industrial facilities. Emissions from diesel exhaust are comparatively lesser than the above mentioned sources. The amount of sulfur present in diesel fuel result in the concentration of SO_2 produced. Diesel fuels with higher sulfur content result in higher levels of SO_2 emissions. Like most pollutants, SO_2 is reported to cause and worsen existing respiratory health problems, while also being a major cause of acid rains (EPA 2016b).

2.2.6 Particulate Matter

Particulate matter is a complex mixture of extremely tiny dust particles and liquid droplets. They are generally made up of a number of components, including but not limited to acids (nitrates and sulfates), organic chemicals, metals, and soil. The sizes of these particles are directly linked to the health problems associated with them. Fine particles ($PM_{2.5}$) pose the greatest health risk, since they can get settled and accumulated in the respiratory tract as well as the lungs and the bloodstream resulting in health issues pertaining to lungs and heart. Coarse particles (PM_{10}), though less harmful, are known to irritate a person's eyes, nose, and throat. According to the EPA, particle pollution exposure leads to a variety of problems, including premature death in people with heart or lung disease, nonfatal heart attacks, irregular heartbeat, aggravated asthma, decreased lung function, increased respiratory symptoms, such as irritation of the airways, and coughing or difficulty breathing (EPA 2016b).

2.3 Pollution through Construction

Construction activities generate fugitive dust and particulate matter in many ways. Equipment exhaust, equipment travel and working on unpaved surfaces result in the presence of particulate dust in the environment. Earthmoving represents a large portion of the activities performed by the heavy civil construction sector. Most construction projects involve demolition and earthmoving with the use of heavy construction equipment, resulting in high levels of pollution. A literature review was done to analyze the different factors that affect these equipment and their emissions.

According to a study conducted by Clark et al. (2002), emission rates for equipment are dependent on several factors including vehicle class and weight, driving cycle, vehicle vocation, fuel type, engine exhaust after treatment, vehicle age, and the terrain they travel on. The study found that higher emissions were produced when the equipment was operating at a site with unequal gradient and required continuous acceleration and frequent braking. The research also stated that heavier equipment use more fuel resulting in higher emission rates. Additionally, the study also highlighted that older, lower tier equipment tend to have higher emission rates than newer, higher tier equipment. The study concluded that drive cycles, age, and terrain have the biggest impacts on the rate of PM and NO_x emitted in-operation.

These results were well supported by another study conducted by Frey et al. (2010). This study was based on data collected from nine different construction equipment: backhoes, bulldozers, excavators, generators, motor graders, nonroad trucks, skid steer loaders, track and wheel loaders. Two different types of fuels were used; petroleum diesel fuels and B20 biodiesel fuels. The data was collected using a portable emission monitoring system (PEMS) called the Montana System. These sensors were attached to the engine of the equipment to collect information such as engine speed, intake air temperature, and engine load and the exhaust concentrations of NO_x, HC, CO, CO_2, and PM were measured from tailpipe exhaust samples. Most of the 39 equipment used in this study were tier 1, 2 or 3 with model year ranging between 1988 and 2007. The study was conducted on time-based and fuel-based rates. The study results revealed that engine size had the greatest impact on time-based petroleum diesel fuel use and emission rates of NO_x, HC, CO, and CO_2. It was also shown that the engine load had the most significant impact on B20 biodiesel fuel use and emission rates of NO_x, HC, and CO_2. Finally, the model year had the most significant impact on CO emission rates. This research concluded that, irrespective of the type and quantity of fuel used, emission rates decrease with higher tier and model year.

The study results of Lewis et al. (2012a) stated that older engines emit a higher amount of CO_2. The study analyzed 47 nonroad equipment (backhoes, bulldozers, excavators, motor graders, skid-steer loaders, tractors and wheel loaders). This study assessed equipment features such as equipment type, engine size, engine age, equipment (operational and annual) usage, fuel use, and carbon dioxide emissions. The majority of the equipment used in this study were old (Tier 0-3), barring one equipment, and as a result, the emission rates were higher as expected. The rate of exhaust emissions and pollutants were reported to be higher as the engine size and equipment usage increased. It was also assessed that backhoes produced a higher rate of pollutants than any other equipment type even when all the above-mentioned factors are the same.

This conclusion was backed by Lewis et al. (2009), who, in their study found that backhoes are the highest source of pollutants among the general nonroad equipment. After backhoes, loaders and bulldozers are the highest emitters of NO_x, while skid-steer loaders are the highest emitters of CO and PM_{10}. Dump trucks and excavators have low operational efficiencies, thereby increasing idle time and also increasing emissions and cost (Lewis et al. 2012b). The type of work to be executed affects the emissions produced by the equipment. Based on the results of the research done by Forsythe et al. (2014) and Kim et al. (2012), earthwork produces the largest percentage of emissions, with rocky earth having a higher cumulative emission than other soil types. Forsythe, in his study, concluded that the slope at a construction site has a linear effect on the amount of greenhouse gas produced by an equipment in operation (Forsythe et al. 2014). While a study conducted by Kim et al. indicated that earthwork produced 90% of the total greenhouse gas emissions collected during the study process. The study also reported that the dump truck, bulldozer and loaders were major contributors for these emissions (Kim et al. 2012).

Earthwork is not the only activity that has an impact on an equipment's emission rates. A study conducted by Muleski et al. (2005) analyzed the particulate matter emissions for a set of activities. The study findings indicated that loading and unloading operations produce only 10% of PM_{10} emissions when compared to the emissions generated by a scraper to haul dirt over a distance of 1000-2000 feet. It was also noted that loading produced nearly 100 times more emissions than dumping. This study result is backed by Forsythe et al. (2014) who found that cut operations produced higher emissions than fill.

The nonroad equipment also emit a higher amount of gases when in operation than when idle. Multiple researches, Lewis et al. (2009) & Rasdorf et al. (2010), have shown that during idling fewer amounts of NO_x, HC, and PM are produced when the equipment is in motion and operating. The studies compared idle and non-idle data collected from 39 different nonroad equipment and found that CO and CO_2 emissions remained the same irrespective of their activity mode. Meanwhile, emission of other pollutants such as NO, HC and PM were found to be higher while the equipment were in operation than when idle.

Despite producing smaller amounts of emissions, idling does have an impact on the environment and the quality of air. This is supported by two studies conducted by Lewis et al. (2012c) and Lewis et al. (2012b). These studies concluded that emissions of pollutants such as NO_x, HC, CO_2, CO, and PM are lower when the equipment is not in operation, but an increase in idle time reduces productivity thereby increasing the overall duration of the activity, and subsequently increasing the amount of emissions generated during the entire span of that particular activity. As mentioned earlier, these emissions have a considerable effect on the workers' health and safety.

2.4 Health Effects Associated with Diesel Exhaust

A recent report published in the Portland Business Journal conducted by Oregon Environmental Council showed that approximately 460 individuals die prematurely each year due to continuous exposure to diesel exhaust resulting in health issues related to brain, heart and lungs (Portland Business Journal 2016). Different pollutants emitted by the diesel engines affect the health of workers in more ways than one. For instance, according to the Office of Environmental Health Hazard Assessment (OEHHA), long-term exposure to diesel exhaust is one of the most common causes of cancer. The report estimates that constant inhalation of diesel exhaust is the cause for about 70% of cancer risk that an average Californian faces (OEHHA 2016). Another study by Fang et al. (2013) found that constant exposure and inhalation of particulate matter is globally responsible for nearly 3% of cardiopulmonary and almost 5% of lung cancer fatalities. This is backed by a study conducted by Jarvholm et al. (2003) on heavy equipment operators and truck drivers in Sweden. The study involved several craftsmen such as carpenters and electricians along with the general population and truck drivers. The study reported that the rate of lung cancer was higher among truck drivers and heavy equipment operators than all the other participants of the study. The findings also suggested that between the two, truck drivers had a higher risk of lung cancer than the heavy equipment operators and authors attribute it to the continuous exposure of diesel exhaust the truck drivers are exposed to. Another study conducted by Pronk et al. (2009) on diesel exhaust exposure in underground and tunneling construction stated that the exposure levels were higher compared to construction above ground since the operation was in an enclosed space.

Sudden short-term exposure to diesel exhaust can cause irritation of the eyes, throat and lungs; lightheadedness; headaches; fatigue; nausea; and respiratory symptoms like coughing and mucus, along with neurophysiological symptoms. The USEPA conducted several studies in multiple U.S. cities and the state of California to create a better understanding of the relationship between air pollution and premature deaths. The studies reported that particulate pollution is responsible for nearly 60,000 deaths each year in addition to other non-fatal health issues such as asthma, bronchitis, and emphysema, with constant exposure to $PM_{2.5}$ leading to a 26% increase in premature deaths (Dockery et al. 1993, NYT 1993). A study by Krewski looked at the difference in the average life expectancy when constantly exposed to $PM_{2.5.}$ The study concluded that exposure to $PM_{2.5}$ reduced life expectancy by 8.6 months. (Krewski 2009). These findings were supported by a study conducted by Correia et al. (2013) to explore the possibility of an increase in life expectancy with a reduction in exposure to fine particulate matter. The study was based on data collected from over 500 counties in the US for a period of 7 years and the results revealed that a decrease of 10 $\mu g/m^3$ of $PM_{2.5}$ would result in an increase in the mean life expectancy by 0.35 years.

Long-term exposure to diesel exhaust emissions can cause chronic cough and mucus, chest tightness and wheezing, and hamper lung functioning while aggravating pre-existing conditions such as asthma, chronic bronchitis, emphysema, heart diseases and lung cancer (Ali 2013). A study conducted by Pandya et al. (2002) investigated the possibility of long-term exposure to diesel exhaust causing asthma in individuals with no history of the illness. The study concluded that this was possible, thereby making diesel exhaust a catalyst and a cause for asthma while increasing the intensity of an asthma attack among those suffering from it.

In addition, the International Agency for Research on Cancer (IARC) considers diesel exhaust to be a probable human carcinogen (IARC 2012). This was confirmed by a study conducted by Mauderly et al. (1992), which concluded that exposure to diesel exhaust led to cancer due to possible cell mutation and DNA damage. In addition to this, the California EPA estimates that constant inhalation of diesel exhaust is accountable for about 70% of all cancer risk from air pollution in California (OEHHA 2003b). Findings from multiple studies have attributed long term PM exposure to cardiopulmonary mortality (Krewski 2009, Laden et al., 2006 and Pope et al., 2004). Laden et al. concluded that ambient $PM_{2.5}$ levels are surely linked with cardiovascular and lung cancer mortality. In addition to the respiratory and carcinogenic problems, diesel exhaust pollution also aggravates heart conditions. Studies conducted by Krewski (2009) and Pope (2004) found that PM exposure is one of the driving factors in causing cardiovascular diseases and subsequent mortality. However, the studies indicated that PM exposure is not the primary or sole cause of cardiovascular fatalities. Several factors like the use of tobacco, personal lifestyle, dietary and exercise patterns, and access to health services can be seen as other influencing factors that eventually lead to cardiovascular diseases.

A report by OEHHA on the health effects of diesel exhaust studied more than 30 individuals who either worked with or in the vicinity of diesel equipment such as equipment operators, miners, railroad workers and truck drivers. The study results revealed that operators and drivers, such as the study subjects, have a higher risk of lung cancer than those who are less frequently exposed to diesel exhaust (OEHHA 2003b).

The effects of diesel exhaust are more serious on the old and the young. The OEHHA states that young children and the elderly (especially those already suffering from chronic respiratory and pulmonary health irregularities) are more vulnerable to the ill effects of long-term exposure of diesel exhaust than an average middle-aged individual (OEHHA, 2003a). Long-term exposure to $PM_{2.5}$ is also known to have a serious effect on the health of women. Miller et al., in their research studied medical records of more than 1800 women and concluded that long-term exposure to fine particulate pollution has a positive link on the occurrence of cardiovascular disease and death in postmenopausal women (Miller et al. 2007).

2.5 Regulations and Control Measures

This section of the document sheds light on the different regulations imposed by various Governments to improve the quality of air by curbing diesel exhaust emissions. The second half of the section talks about the different control measures that were suggested in various literature to reduce diesel exhaust emissions.

2.5.1. Regulations

The Clean Air Act of 1990 developed standards in the US, known as the National Ambient Air Quality Standards (NAAQS), to evaluate and regulate the threshold levels of various pollutants from industrial and vehicular sources. These criteria pollutants are broken down into two categories based on their effect on the environment and human health, with the primary standards aimed at protecting human health while the secondary standards focus on protecting the environment from being exposed to unsafe levels of pollutants. States and counties submit reports and recommendations to the EPA regarding the air quality standards. These reports are based on data collected from sensors and monitors in various urban and rural stations. The standards of the criteria pollutants in the US are listed on table 1 (EPA 2016a).

Table 1: NAAQS Criteria Pollutants (EPA 2016a)

Pollutant	Primary/Secondary	Averaging Time	Level	Form
Carbon Monoxide (CO)	Primary	8 Hours	9 ppm	Not to be exceeded more than once per year
		1 Hour	35 ppm	
Lead (Pb)	Primary and Secondary	Rolling 3 month period	0.15 $\mu g/m^3$	Not to be exceeded
Nitrogen Dioxide (NO_2)	Primary	1 Hour	100 ppb	98th percentile of 1-hour daily maximum concentrations, averaged over 3 years
	Primary and Secondary	1 Year	53 ppb	Annual Mean
Ozone (O_3)	Primary and Secondary	8 Hours	0.07 ppm	Annual fourth highest daily maximum 8-hour concentration, averaged over 3 years
Sulfur Dioxide (SO_2)	Primary	1 Hour	75 ppb	99th percentile of 1-hour daily maximum concentrations, averaged over 3 years
	Secondary	3 Hours	0.5 ppm	Not to be exceeded more than once per year
Particle Pollution				
$PM_{2.5}$	Primary	1 Year	12.0 $\mu g/m^3$	Annual mean, averaged over 3 years
	Secondary	1 Year	15.0 $\mu g/m^3$	Annual mean, averaged over 3 years
	Primary and Secondary	24 Hours	35 $\mu g/m^3$	98th percentile, averaged over 3 years
PM_{10}	Primary and Secondary	24 Hours	150 $\mu g/m^3$	Not to be exceeded more than once per year on average over 3 years

In order to reduce pollution from diesel equipment, the EPA has set up a funding program under the Diesel Emissions Reduction Act (DERA). This program aims at providing grants to contractors to retrofit or reconfigure their older diesel engines. According to reports from 2009 to 2013, the EPA provided grants of around $520 million to retrofit or replace 58,800 engines in vehicles, vessels, locomotives or other pieces of equipment (AGC 2016). These grants would help contractors and owners to reestablish and update their fleet and also help them save more money while contributing to the betterment of the environment and their employees' health. According to the EPA, this program would reduce 312,500 tons of nitrogen oxides (NO_X), 18,900 tons of hydrocarbons (HC), 58,700 tons of carbon monoxide (CO) and 12,000 tons of particulate matter ($PM_{2.5}$) emissions over the lifetime of the older affected engines. This, in turn, would also reduce the number of premature deaths due to continuous exposure to these pollutants with a saving of $11 billion in monetary health benefits to workers over the lifetime of the affected engines (AGC 2016).

US is not the only country to set threshold limits for harmful pollutants. Several countries around the world have set regulations for particulate matter. However, different countries have different regulation guidelines since there is no solid evidence to support a safe level of exposure. These differences in varying emission standards can be attributed to the difference in weather conditions, the population, and the economic progress of the countries. Table 2 shows the list of threshold levels set by various governments from around the world (Kim et al. 2015).

Table 2: PM Regulations around the World (Kim et al. 2015)

Country	Averaging Time	PM_{10} (µg/m^3)	$PM_{2.5}$(µg/m^3)
United States of America	Yearly Average	None	12
	Daily Average	150	32
European Union	Yearly Average	40	25
	Daily Average	50	None
China	Yearly Average	70	35
	Daily Average	150	75
Hong Kong	Yearly Average	50	35
	Daily Average	100	75
Japan	Yearly Average	None	15
	Daily Average	100	35
South Korea	Yearly Average	50	25
	Daily Average	100	25
Australia	Yearly Average	None	8
	Daily Average	50	25
WHO	Yearly Average	20	10
	Daily Average	50	25

The study by Kim et al. (2015) reveals that the average annual exposure levels of particulate matter is higher in developing countries than in developed countries. This difference in particulate matter levels can be attributed to the technical and financial risks involved in setting and meeting stringent emission standards on a regular basis. These stringent standards could have a financial impact on automakers (in the form of research and manufacture) and governments (in the form of research and implementation) in developing countries, failure to which would result in higher particulate matter levels (World Bank, 2016). Table 3 shows the particulate matter levels in developing and developed countries. It is evident from Table 3 that most Asian countries have significantly higher levels of PM pollution. As a result, these countries have introduced various laws and techniques to suppress particulate pollution. The government of China introduced “The Airborne Pollution Prevention and Control Action Plan (2013-2017)” to reduce PM pollution by introducing measures to control PM pollution by using emission-cutting exhaust filters and introducing stringent pollution-control standards and reducing the use of coal. Due to the westerly winds, China’s neighboring countries, Japan and Korea, have also been affected by their air pollution scenario and have resorted to their own set of regulations on on-road vehicles (Kim et al. 2015).

However, all these regulations are set for urban traffic i.e. mainly onroad vehicles. It is a well-known fact that nonroad vehicles produce air pollutants at a higher rate than onroad vehicles. This is because onroad engines have much more advanced emission control features than nonroad engines (DEE 2016).

Table 3: Average yearly Exposure Levels in Developed and Developing Countries (Kim et al. 2015)

Country	Year/ $PM_{2.5}$ in µg/m^3		
	2009	**2010**	**2011**
Developed Countries			
Australia	15	14	14
Canada	15	14	14
Finland	16	16	16
New Zealand	18	17	16
Ireland	18	17	18
United States	20	19	18
Japan	20	19	19
United Kingdom	20	19	20
France	25	24	24
Germany	25	24	24
Norway	25	23	24
Russia	30	28	27
Italy	36	34	34
South Korea	50	48	46
Developing Countries			
Argentina	39	36	36
Brazil	41	38	36
South America	42	40	40
Philippines	44	42	43
Thailand	45	44	45
Indonesia	50	49	47
Malaysia	49	49	47
Sri Lanka	67	66	62
Afghanistan	68	65	63
Turkey	70	66	65
Kenya	70	71	66
China	86	85	82
India	108	105	100
Egypt	129	125	120
Pakistan	207	184	171

2.5.2 Control Measures

The key to control pollution from diesel engines involves the implementation of rules for the use and operation of equipment along with the usage of new diesel engines. Improvements to diesel fuel and to the attributes of diesel engines are known to reduce emissions of some of the pollutants associated with diesel exhaust. California is one of the leading states in the US that is making an effort to reduce the amount of toxic substances present in these emissions, thereby controlling their ill effects. It is stated that when the California Air Resources Board's "Diesel Risk Reduction Plan" is implemented, the state will see a reduction of 85% in particle emissions from diesel equipment by the year 2020. The plan is based on the use of cleaner fuels, retrofitting existing older engines with filters, and replacing older equipment with newer and more efficient equipment (CARB 2016b).The use of other power sources, such as natural gas, propane, and electricity offer alternatives to diesel fuel. The use of such fuels result in lower generation of polluting emissions even from older engines. Ultra-low sulfur diesel fuel (ULSD) is another alternative that is mandated in the US (CARB 2016a). It greatly reduces the sulfur dioxide, which is a key component in the formation of smog.

Retrofitting the existing older equipment is another way of controlling emissions. Installation of pollution controls such as filter and diesel oxidation catalysts greatly reduces the emissions from older equipment. These filters are known to reduce carbon pollution by up to 90% in existing equipment (NEDC 2016). The research conducted by Rasdorf et al. (2010) recommends several strategies that might help reduce pollution caused by diesel equipment. Some of the recommendations were to conduct regular equipment maintenance programs, alter operations, timely evaluation of emissions, and to utilize newer energy efficient equipment. Another aspect that helps in mitigating diesel exhaust emissions is the reduction in idle time. Excessive idling results in wastage of fuel and adds unnecessary nonproductive hours to the engine, thereby shortening its life and wasting the machine's warranty. Workers can be protected from being exposed to these emissions by enclosing them in a safer environment. Based on a study conducted by Jarvholm et al. (2003), it was found that the use of enclosed cabins lowered the risk of health complications among equipment operators. These cabins protected the workers from being exposed to the exhaust fumes. Replacing an old construction equipment with a newer one is another way of mitigating emissions. Newer models are equipped with advanced emission control technologies that control the amount of emissions generated. However, it is not certain that the equipment owners will be ready to replace their existent fleet with newer equipment. According to reports, the purchase price of a new equipment is 8-20% higher than the older ones. This difference in price is to cover R&D costs and the cost of additional control devices that are absent in the older models. However, this increase in cost can be offset by the improvement in fuel economy of these new equipment. The new fleet would also help the owners and contractors to submit competitive bids on certain government projects or jobs that require work to be done in EPA non-attainment designated zones (BLS 2016).

The implementation of the above-mentioned strategies will help improve the performance of the equipment fleet while reducing air pollution and the risk of health complications among construction personnel. The literature review, however, did not clearly define the influence of ambient weather conditions such as temperature and rainfall on the pollution levels, specifically $PM_{2.5}$ levels. There is also no evidence about the difference in pollution levels in an open and an enclosed cabin. As a result, the study was conducted to provide possible answers for these uncertainties.

3.0 Methodology

The methodology section provides a brief overview of the different entities involved in the data collection process. The methodology section sheds light on the location and scope of the construction project in question, the sensor used to measure the particulate matter produced by the activities and the equipment at the project, the different construction equipment involved in the construction project, and the method used to collect data.

3.1 Selection of Construction Project

Construction projects can be primarily categorized into buildings, infrastructure and industrial (Chitkara 1998). Each of the above-mentioned categories uses a varied set of nonroad construction equipment to perform activities ranging from demolition of existing structures to finishing newly constructed structures. The present study was conducted in Corvallis, a city with a population of 55,298 in Central Western Oregon. This region of Oregon has a subtropical climate with an average temperature of 52.65° F, and experiencing an average annual rainfall of 42.76 inches (U.S. Climate Data 2017). The construction project is located on the Western fringe of the city, within the campus limits of Oregon State University.

The construction project involved the demolition and the reconstruction of Peavy Hall, College of Forestry at Oregon State University. Oregon State University, the owner, contracted with other entities to ensure that the end product would be of high quality while promoting safety during the construction, both on and off the site. Swift Company and KPFF were contracted as the landscape architects and civil engineers respectively, to study and deem the location and design fit for reconstruction and to make the area around the structure aesthetically pleasing to attract new students to the facility. Michael Green Architect Inc. was contracted to design the new Peavy Hall. Equilibrium Consulting, a structural engineering firm, was hired to ensure that the design of the project was structurally sound and would promote safety and create innovative working spaces for students and faculty. Oregon State University hired Andersen Construction, as the general contractor, to build the new Peavy Hall and make the working environment safe for the workers and the students. They are contractually responsible for the construction phase of the project and coordinating the subcontractors needed for the building phase of the project so that the project can stay on schedule and within budget. The overall square footage for the project is 114,000, with 80,000 square feet being designated to the building that will replace the existing Peavy Hall and 18,000 square feet for the Advanced Wood Products Laboratory. The study presented here was conducted during the demolition and excavation phases. In the first half of the study, excavators were used to tear down the existing slabs and the retaining walls along the perimeter of the site, while in the latter phase, excavators were used for structural excavation and backfilling while a dozer was used to push the soil post-excavation.

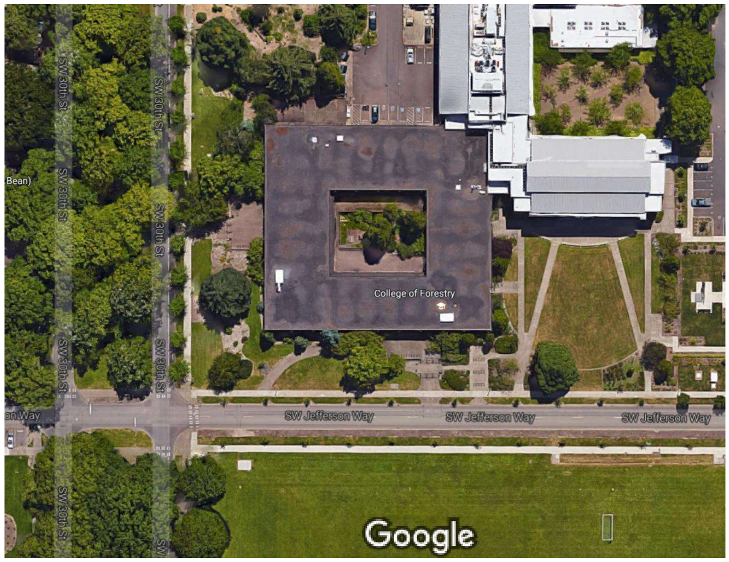


Figure 1: Peavy Hall (Google 2017)

Figure 2: Site Plan (OSU Webcams 2017)

3.2 Construction Equipment Studied

Data was collected during the demolition and excavation phases. During these phases, there were three different equipment present on the project site. Excavator 1 was an Isuzu Link-Belt 370LX excavator and it was assigned to the demolition phase, while Excavator 2, a Komatsu PC228USLC excavator, was solely involved in the excavation phase, with cutting and backfilling forming the majority of its scope of work. Excavator 1 and 2, as seen in Figure 3 and 4 respectively, have an enclosed operator cabin. These enclosed operator cabins are designed and engineered to provide operators with a comfortable, healthy and safe working environment. Meanwhile, the dozer, a Komatsu D41P is a crawler tractor with a blade on the front does not have an enclosed operator cabin, as shown in Figure 5.

Figure 3: Excavator 1

Figure 4: Excavator 2

Figure 5: Dozer

With the help of the aerosol monitor, the concentration of $PM_{2.5}$ was measured inside the enclosed operator cabins of the excavators and in the open operator cabin of the dozer. The equipment specifications can be found below in Table 4.

Table 4: Equipment Specifications

***Table* Type**	**Make**	**Model Year**	**Horsepower (HP)**	**Tier**	**Displacement (Litres)**	**Fuel**	**Average Engine Speed (rpm)**
Excavator 1	Isuzu Link-Belt 370LX	2004	247	2	7.8	ULSD	2000
Excavator 2	Komatsu PC228USLC	2000	148	1	6.69	ULSD	2000
Dozer	Komatsu D41P	1998	106	1	5.9	ULSD	2400

3.3 Measuring Device

The concentrations of $PM_{2.5}$ were collected and measured using TSI DustTrak II 8530, an aerosol monitor. This monitor is a battery-operated, light-scattering laser photometer that reads aerosol or dust mass and it is shown in Figure 6. It contains a pump that draws the dust through an optics chamber within which the PM particles are collected and measured (Dusttrak 8530 2017). The aerosol monitor is set to the "Ambient Cal" calibration setting, which is deemed appropriate for outdoor ambient dust or fugitive dust monitoring. The monitor is zero calibrated prior to every use in order to eliminate the possibility of zero drift, which might affect the readings. The flow rate of the monitor is set at 3L/min. At the end of each test, the device measures and records the time-weighted average (TWA) of $PM_{2.5}$ present during the test period. The time-weighted average is calculated using the formula

$$\mathbf{(C \times T)/480\ mins}$$

where **C** = average $PM_{2.5}$ concentration during 8 hours of testing in $\mu g/m^3$, **T** = time elapsed in minutes, and **480 mins** = number of minutes in an 8 hour workday.

The measuring device was placed a) inside the enclosed operator cabins while collecting data from excavators, and b) inside the Dusttrak II 8535 enclosure while collecting data from the dozer. The DustTrak II 8535 enclosure is used to protect the monitor from being exposed to the wet Oregon weather. The monitor was setup to collect test data for a duration of 8 hours each day at a log interval of 1 minute. The tests were conducted during the typical work hours at the jobsite, which roughly spanned from 7:00 AM until 3:00 PM, 5 days a week.

Figure 6: Dusttrak II Aerosol Monitor 8530 (DUSTTRAK 2017b)

3.4 Data Collection

Data collection was conducted in several phases. The first phase aimed at determining the relationship between the particulate matter present at the jobsite and the local weather conditions. For this purpose, local weather data including mean temperature, rainfall and wind speeds were collected from multiple sources. The mean temperatures and wind speeds were collected from the Weather Underground website (WU 2017) while the average daily rainfall was collected from the Hyslop Weather Station at Oregon State University (Hyslop 2017).

The second phase of data collection aimed at measuring the concentration levels of $PM_{2.5}$ at the construction site and comparing them with the environment. For this purpose the daily hour-by-hour $PM_{2.5}$ concentrations in the City of Corvallis were obtained from the State of Oregon: Department of Environmental Quality website (ODEQ 2017a). Data from the construction site were collected on non-working days to establish a baseline for $PM_{2.5}$ levels at the site in the absence of construction activities.

The third phase of data collection aimed at evaluating the difference in $PM_{2.5}$ levels the operators are exposed to in the presence and absence of an enclosed operator cabin. To evaluate these differences, the aerosol monitors were placed a) inside the operator cabins while collecting data from the excavators, and b) inside the Dusttrak II 8535 enclosure while collecting data from the dozer. In the former scenario, the monitor was placed in the storage compartment as shown in Figure 7. This gives a real-time value of the $PM_{2.5}$ concentrations the operators are exposed to when operating the equipment from inside the cabin.

Figure 7: Aerosol Monitor setup inside the Excavator Cabin

Figure 8: Enclosure setup inside the Dozer Cabin

In the dozer, the aerosol monitor was placed inside Dusttrak II 8535 enclosure to protect the monitor from rain. The enclosure was placed on a wooden platform setup behind the operator's seat in the open operator cabin. In order to prevent the enclosure from sliding off the cabin, multiple rubber tarp straps were used to fasten the enclosure to the body of the dozer. A graphical representation of the setup can be seen in Figure 8.

In addition to this, video footages of the day-to-day activities were collected. The construction activities were streamed live on the Oregon State University website. These video evidences were used to monitor and study the activities performed by the excavators and dozer.

4.0 Results and Analysis

As mentioned in previous sections, the data were collected and analyzed based on the following three criteria:

- The correlation between particulate matter present at the jobsite and the ambient temperature and rainfall
- Comparing the concentration levels of $PM_{2.5}$ in Corvallis and inside the equipment cabins at the construction site
- The difference in $PM_{2.5}$ levels the operators are exposed to in the presence and absence of an enclosed operator cabin

4.1 Results

Data was collected 5 days a week for a period of 28 days spanning from the 8th of March, 2017 till the 17th April 2017. Out of the 28 days, the aerosol monitor was placed in the excavators for 10 days. The monitor was placed in Excavator 1 for 6 days, out of which the equipment was in operation for 5 days. No activities were performed on the 6th day and it was used as a baseline to determine the $PM_{2.5}$ levels in the excavator cabin in the absence of construction activities. The monitor was placed in Excavator 2 for a total of 4 days. Similarly, the aerosol monitor was placed in the Dozer for 18 days, including the 4 non-working days used to establish the baseline.

The collected data were tabulated along with the daily 8-hour $PM_{2.5}$ averages in Corvallis, as obtained from the Oregon Department of Environmental Quality website (ODEQ 2017).

Once the daily PM2.5 levels were collected, their respective Air Quality Index (AQI) were calculated using the AQI Calculator to determine the severity of the particulate pollution present at the site and in the city of Corvallis (AQI 2017). The AQI Calculator is a calculator developed by the EPA to convert the air pollutant concentration to an Air Quality Index (AQI). The AQI Calculator converts different concentrations of pollutants such as ozone, $PM_{2.5}$, PM_{10}, carbon monoxide, sulfur dioxide and nitrogen dioxide to a simpler scale that is more comprehensible to the public. The daily mean temperatures and average rainfall were also noted and accordingly tabulated. Table 5 shows all the data collected during the month-long study. Meanwhile, Table 6 shows the scale used by the US EPA to convert PM2.5 concentrations to their respective AQI ratings along with the issues associated with them.

Table 5: Collected Data

Date	PM 2.5 Level (in µg/m³)				Temperature (in °F)[3]	Rain [4]	Comments
	Corvallis		Construction Site				
	8-Hour TWA [1]	AQI [2]	8-Hour TWA	AQI [2]	Mean	(inches)	
Excavator 1							
3/8/2017	2.5	9	107	177	48	0.39	Working Days
3/9/2017	1.3	6	71	158	55	0.34	
4/11/2017	3.3	9	160	210	44	0.03	
4/12/2017	2.1	8	72	159	52	0.38	
4/13/2017	1.5	7	145	197	48	0.15	
4/14/2017	1.7	3	5	21	46	0.06	Non-Working Day
Excavator 2							
3/10/2017	1.9	8	70	158	55	0.47	Working Days
3/13/2017	2.7	8	54	146	52	0	
3/27/2017	1.6	9	15	56	48	0.26	
3/28/2017	3.4	12	37	104	53	0.02	
Dozer							
3/14/2017	2.3	8	14	54	56	0.24	Working Days
3/16/2017	2.6	10	19	65	47	0.31	
3/17/2017	7.1	33	32	93	44	0	
3/20/2017	3.8	20	16	59	44	0	
3/21/2017	4.1	10	32	93	56	0.34	
3/22/2017	1.7	8	13	52	48	0.09	
3/23/2017	3.2	8	16	59	44	0.09	
3/24/2017	1.8	8	6	25	50	0.98	
3/29/2017	1.9	7	6	25	50	0.33	
3/30/2017	1.7	7	14	54	48	0.26	
4/3/2017	3.1	14	13	52	44	0.02	
4/4/2017	5.9	40	25	78	50	0	
4/5/2017	4.5	16	22	71	52	0.01	
4/6/2017	3.9	12	19	65	56	0.09	
3/15/2017	2.4	8	5	21	50	0.96	Non-Working Days
3/31/2017	3.9	17	15	56	48	0.01	
4/7/2017	1.3	2	2	8	48	0.19	
4/17/2017	2.5	9	4	17	52	0.31	

Table 6: US EPA Scale for PM2.5 Concentrations (AQI 2017)

Concentration	**0-12**	**12-35.5**	**35.5-55.5**	**55.5-150.5**	**150.5-250.5**	**250.5 +**
AQI	**0-50**	**50-100**	**100-150**	**150-200**	**200-300**	**300 +**
Rating	Good	Moderate	Unhealthy for Sensitive Groups	Unhealthy	Very Unhealthy	Hazardous
Sensitive Groups	People with respiratory/heart diseases, elderly and children at risk	People with respiratory /heart diseases, elderly and children at risk	People with respiratory/heart diseases, elderly and children at risk	People with respiratory/heart diseases, elderly and children at risk	People with respiratory/heart diseases, elderly and children at risk	People with respiratory/heart diseases, elderly and children at risk
Health Effects		Unusually sensitive people should consider reducing prolonged or heavy exertion.	Increasing likelihood of respiratory symptoms in sensitive individuals, aggravation of heart or lung disease and premature mortality in persons with cardiopulmonary disease and the elderly.	Increased aggravation of heart or lung disease and premature mortality in persons with cardiopulmonary disease and the elderly; increased respiratory effects in general population.	Significant aggravation of heart or lung disease and premature mortality in persons with cardiopulmonary disease and the elderly; significant increase in respiratory effects in general population.	Serious aggravation of heart or lung disease and premature mortality in persons with cardiopulmonary disease and the elderly; serious risk of respiratory effects in general population.
Caution		Unusually sensitive people should consider reducing prolonged or heavy exertion.	People with respiratory or heart disease, the elderly and children should limit prolonged exertion.	People with respiratory or heart disease, the elderly and children should avoid prolonged exertion; everyone else should limit prolonged exertion.	People with respiratory or heart disease, the elderly and children should avoid prolonged exertion; everyone else should limit prolonged exertion.	Everyone should avoid any outdoor exertion; people with respiratory or heart disease, the elderly and children should remain indoors.

4.2 Analysis

The data collected from the jobsite were analyzed empirically rather than the use of a statistical model. The main reason behind this method of analysis is the fact that the equipment for the study were not randomly selected but were picked as per the day-to-day plan and convenience of the contractor at the jobsite. As a result, the collected data lacked statistical independence and was thus deemed inappropriate to fit a statistical model. The analysis are based on observations and graphical displays with the results being backed by previous researches.

For the first criterion, data collected from the Hyslop Weather Station and the jobsite were analyzed to determine a correlation between the $PM_{2.5}$ levels and the two variables (daily mean temperature and rainfall). To determine the correlation between the observed PM at the site and daily mean temperatures, a scatter plot of the collected data was produced. The plot, shown in Figure 9, suggested that there was a weak negative correlation between the daily mean temperatures and the PM concentration, thereby indicating that higher temperatures might induce lower PM concentrations. This is in agreement with a study conducted by Csavina et al. (2014), which reported that ambient temperature did not have a significant effect on the amount of PM_{10} produced. However, other studies have produced different results. A study conducted by Nam et al. (2010) found that as temperatures decreased, the particulate matter emissions increased exponentially. However, another study by Tai et al. (2012) revealed that $PM_{2.5}$ components had a strong positive correlation with temperature. Hence, it is evident that there is no definite correlation between temperature and levels of particulate matter.

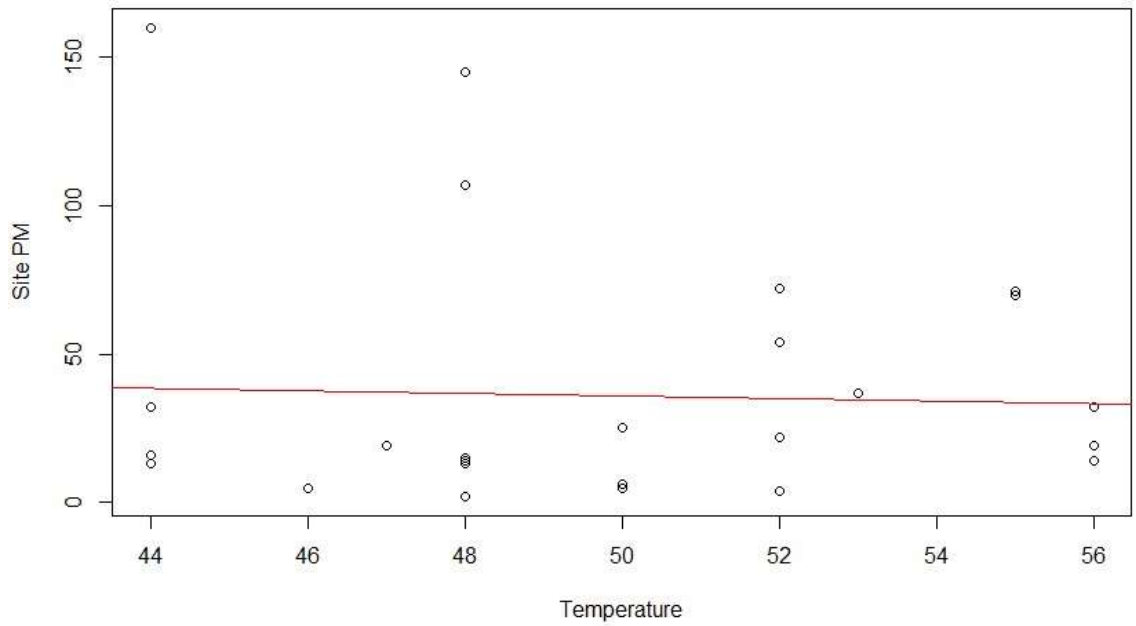


Figure 9: Correlation between PM levels and Mean Temperature

Another scatter plot was used to test the correlation between the daily precipitation levels and the PM levels at the site. The trendline on the scatterplot, as shown in Figure 10, suggested that the two variables have a moderate negative correlation, therefore indicating that an increase in precipitation levels results in a decrease in the PM concentrations in the environment. Several studies have indicated that rainfall and particulate matter pollution have a negative correlation. Studies by Owoade et al. (2012), and Wang et al. (2015) have concluded that an increase in rainfall results in lower levels of particulate matter pollution, irrespective of their size. The studies attributed this trend to wet deposition, also known as scavenging. Seasonal variations also have an impact on the concentrations of particulate matter. The present study was conducted during the seasonal transition from winter to spring and according to a research conducted by Sokhi (1996), there exists a seasonal correlation between rainfall and particulate matter levels. The author states that the two variables have a negative correlation during winter and a positive correlation during summer, holding scavenging and dust resuspension, respectively, accountable for the seasonal dependence (Sokhi 1996).

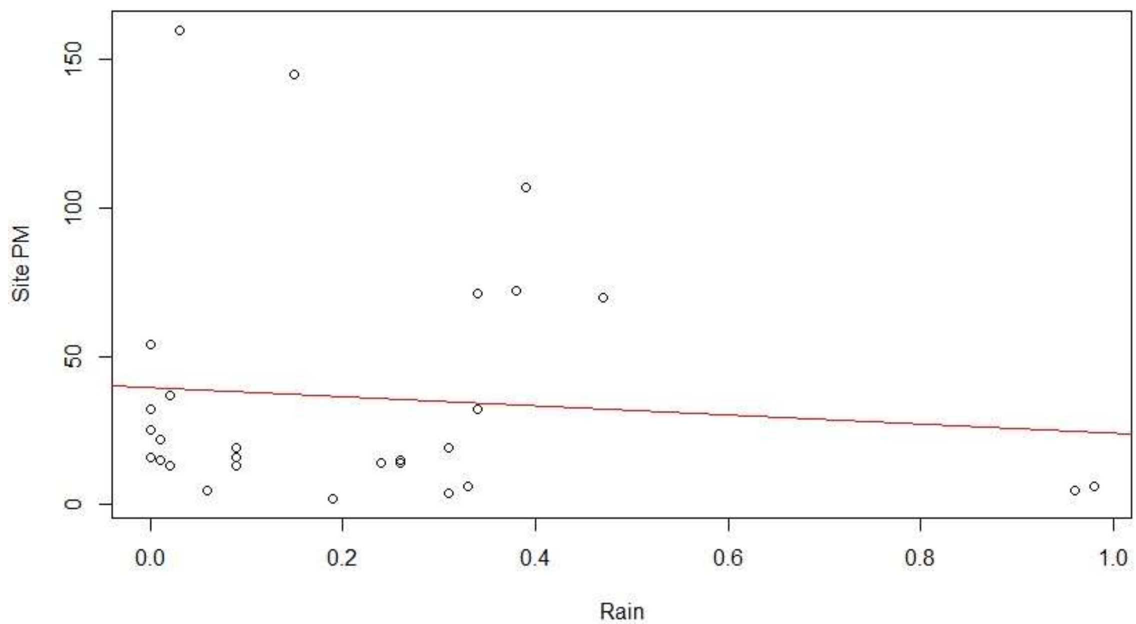


Figure 10: Correlation between PM levels and Avg. Rainfall

For the second criterion, the concentration levels of $PM_{2.5}$ in the operator cabin at the construction site were compared with the $PM_{2.5}$ levels in the city of Corvallis as a whole. The $PM_{2.5}$ readings for the city of Corvallis were found to be considerably lower than that in the operator cabin, as seen in Table 5 and Figure 11. This difference in the particle concentration levels can be attributed to the dust produced by the construction activities on the site. The excavators and dozer were present at a lower elevation than their surroundings, thereby replicating a confined, partially enclosed space, which reduced the chances of particle matter being dispersed by the wind.

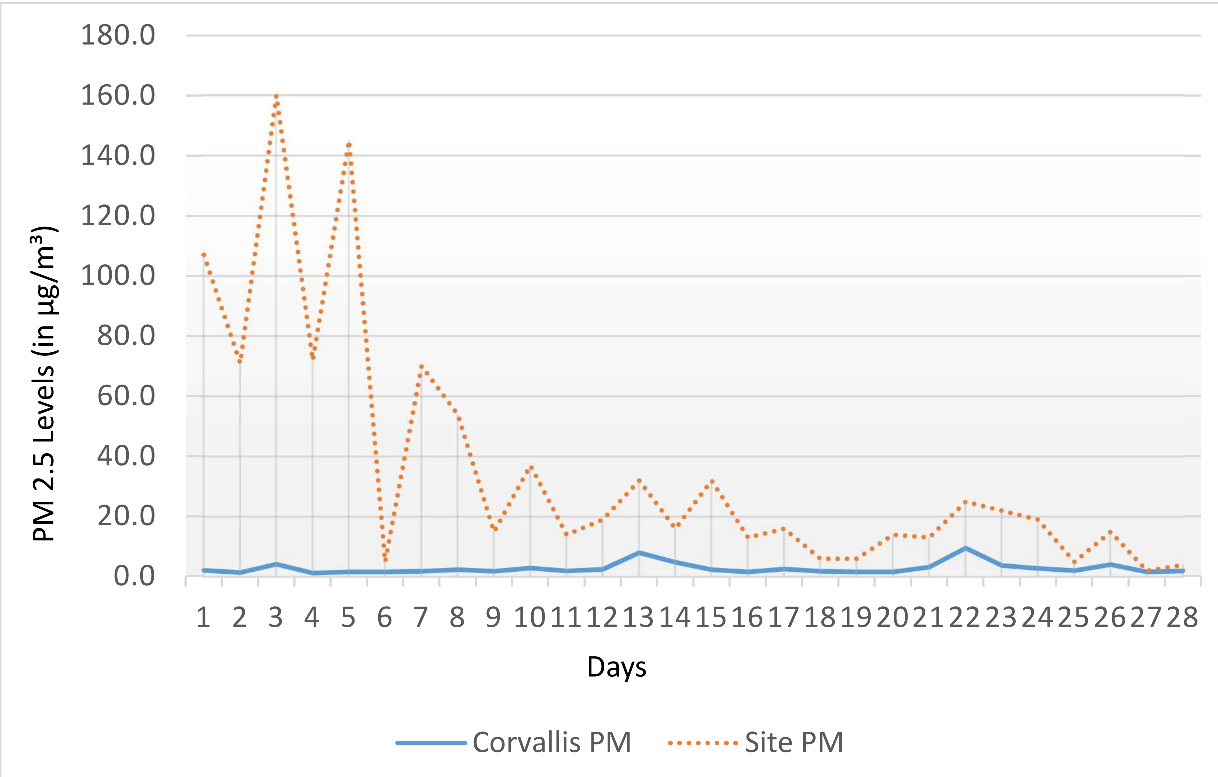


Figure 11: $PM_{2.5}$ concentration levels in Corvallis and the Operator Cabin

Another criterion that was looked into during this study was the difference in $PM_{2.5}$ exposure levels in the presence and absence of an enclosed operator cabin are compared. Enclosed cabins were introduced to house the operators in a safer environment, protecting them from falling objects during operation and from dust and exhaust emissions. However, when the cabins are not fitted with any form of filter, the cabins are effective in cutting down a small fraction of dust and particulate matter. A study conducted by Noll et al. (2011) showed the difference in diesel particulate matter levels in the presence and absence of an effective cabin filter. These air filters were 99% efficient in capturing diesel particulate matter. However, based on the data collected during the present study, $PM_{2.5}$ concentrations were higher inside the enclosed operator cabin of the two excavators, than the open operator cabin of the dozer, as shown in Table 5 and Figure 12 This difference in particle matter concentrations can be attributed to several reasons. One of the primary reasons for this vast difference is the cab cleanliness. The operator cabin in Excavator 1 was extremely dusty as shown in Figure 13. and the constant use of the heater stirred up the dust particles resulting in them being recirculated inside the cabin.

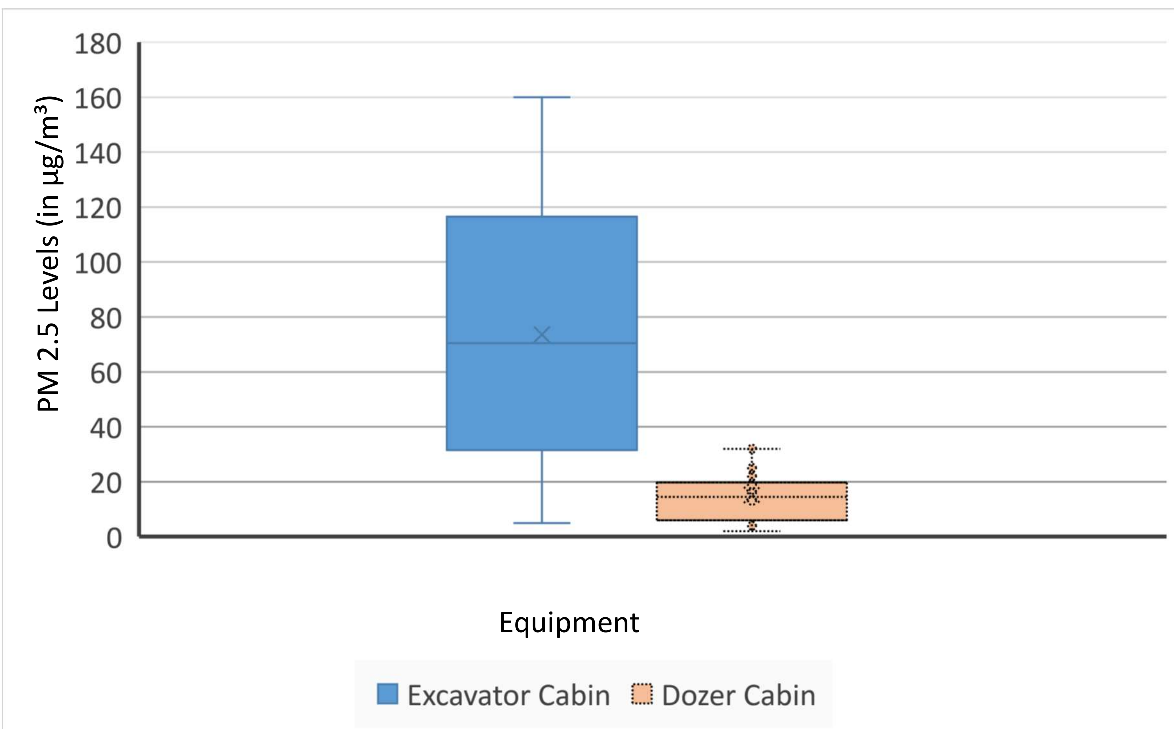


Figure 12: Comparison of PM2.5 between Excavator and Dozer Cabins

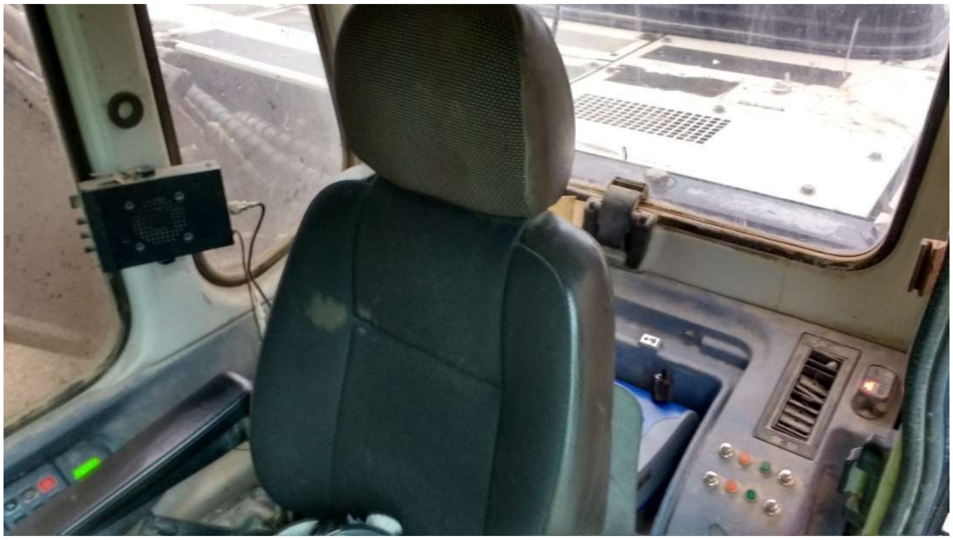


Figure 13: Operator cabin of Excavator 1

The excavators at the job site were not equipped with any kind of air filters. Hence, the dust generated by the heating system and the operators' clothing were recirculated within the cabin without the particles being expelled from the cabin. The third reason for this difference can be attributed to the way the operators operated the equipment without shutting the cabin door. The operators of Excavator 1 and Excavator 2 left the cabin door open while operating the equipment. As a result, the dust particles were accumulated inside the cabin. However, the dozer and excavator operators suggested that this difference in particulate matter readings were mainly due to the wind. Activities such as clearing and loading produced high concentrations dust but since the dozer did not have an enclosed operator cabin, the dust particles were dispersed by the wind. However, this was not the case with the excavators. Due to lack of proper ventilation, the particulate matter would get collected inside the enclosed operator cabin, thereby increasing their concentration levels. The observed $PM_{2.5}$ levels inside the equipment cabin were, however, well within the levels specified by OSHA (OSHA 2017). According to OSHA, the permissible exposure limit values during an 8-hour period in the construction industry is 15mg/m^3 (or 1500 μg/m^3). These levels are, however, higher than the 24-hour permissible exposure levels specified by the EPA, which is 35 μg/m^3.

Another finding from the study indicated that the $PM_{2.5}$ levels were seen to be relatively lower during periods of inactivity or when the equipment were idle. This can be verified when the daily minute-by-minute activity visuals are compared with the graphs produced by Dusttrak II 8530 (sample graph shown in Appendix A). It was observed that in case of excavator used during the excavation phase, the particulate matter concentration levels were higher while digging and scooping out soil from the excavation pit. During this phase, Excavator 2 was present at a lower elevation than the overall jobsite elevation and this replicated a confined space, thereby reducing the possibilities of dispersion caused by the winds. Loading and unloading the dump truck were observed to be the other activities that produced high volumes of particulate matter. During the demolition phase, Excavator 1 was used to tear down the pre-existing slabs and retaining walls, and much of the peaks in the concentration of particulate matter were observed while tearing down and moving the rubble. Meanwhile, the dozer was in operation during the excavation and the demolition phases. Video evidences suggested that the majority of the peaks in the particulate matter concentrations were graphed when the dozer operated in the vicinity of the excavators, either Excavator 1 or Excavator 2.

5.0 Conclusions

A study was conducted to analyze and evaluate the $PM_{2.5}$ levels at a construction site in Central Wester Oregon, US. The study was purely observational and the ensuing results were empirically analyzed. The study was conducted for a period of 28 days stretching from March 8, 2017 to April 17, 2017. Dusttrak II 8530, an aerosol monitor, was used to measure the amount of $PM_{2.5}$ equipment operators are exposed to during their hours of work. The scope of the construction project involved demolition of the existing building and excavation of a sump. A dozer and 2 excavators were used to complete these activities and the aerosol monitor was placed in them at various points of the study. A total of 10 readings were obtained from inside the enclosed operator cabins of the excavators, while 18 readings were taken from the open operator cabin in the dozer. The study was conducted for 8 hours each day. Local weather data (daily average rainfall and mean temperature) and local $PM_{2.5}$ data were collected from various resources to help shape the study.

The main findings of this research are:

- The on-site $PM_{2.5}$ readings and daily mean temperatures were taken into consideration to investigate if there was a correlation between the two variables. The study revealed that there was a weak negative correlation between them.
- The correlation between rainfall and the $PM_{2.5}$ levels were investigated and the study found that there was a significant negative correlation. This correlation can be attributed to wet deposition of the particles, also known as the scavenging effect.

- The study also found that the particulate matter levels were higher in the operator cabin at the construction site than the entire city where the study was conducted. This can be attributed to the two activities that produce most amount of dust at a construction site viz. demolition and excavation.
- Another important finding of this research was the difference in the $PM_{2.5}$ concentration levels between an open and an enclosed operator cabin. The dozer had an open operator cabin and the $PM_{2.5}$ readings were considerably lower than the $PM_{2.5}$ readings in the enclosed operator cabins of the excavators. Several factors were responsible for this vast difference in particle matter readings. Cabin cleanliness, lack of air filters, operating style of the operators, and the lack of dispersion of dust were seen as the major reasons for this difference.

The final section of the document mentions several measures to reduce the particulate matter pollution produced by construction equipment. These control measures help improve the quality of air as well as prove beneficial to the equipment owners, operators and nearby workers alike. Some of the control measures that were recommended in the paper are equipment operation strategies (reduce idling), the use of alternate fuels (such as biodiesel and ULSD), and equipment modifications (such as equipment retrofits, equipment repowering and equipment electrification).

This research is intended to provide information on the effects of diesel engine exhaust emissions with focus on $PM_{2.5}$, while providing strategies to reduce these exhaust emissions. As with most studies, this research has constraints. Since this was an observational study and the equipment were not randomly chosen, it is difficult to generalize the output of this study to a larger population. Since the collected data had a lack of statistical independence, the data was analyzed empirically and not statistically. In addition, the size of the data was too small and a larger data size would have provided stronger support to the argument. The study also does not indicate the source of $PM_{2.5}$ levels. The particulate pollution could be caused by construction activities, such as demolition and excavation, or could be produced by the diesel engine of the equipment present on site.

6.0 Recommendations

This section of the document helps identify and suggest low cost measures to reduce emissions from construction equipment. This section highlights the benefits of these emission reduction strategies and their potential cost to the construction companies and the equipment owners. The recommendations are based on observations made on the site during the study. These strategies can be further divided based on equipment operations, alternate fuel usage, equipment modifications and changes at the site:

6.1 Equipment Operation Strategies

An effective way of reducing emissions from construction nonroad equipment and their operating cost is by changing their mode of operation. Reducing equipment idling, regular maintenance and equipment operator training are seen as effective economic measures of reducing equipment emissions.

According to an article from the Construction Business Owner website, each year nearly 5,000 tons of particulate matter are emitted due to truck and locomotive idling (CBO 2017a). Unnecessary idling results in fuel wastage, reduces engine life and increases emissions. An effective way of mitigating these losses is by providing appropriate training to the operators and by better equipment maintenance and management. Reducing idling will result in cleaner air and provide better working environment for the workers. A simple yet effective strategy to reduce equipment idling is by raising awareness among the operators and workers about the cost incurred by the company due to unnecessary idling. In regions of extreme weather conditions, the equipment is kept turned on in order to run cab accessories such as air-conditioners and heaters. However, this can be prevented by using an alternate power source such as the Auxiliary Power Unit (APU) to run these cab accessories. The APUs are commonly found in trucks and other heavy-duty vehicles. This, however, requires an upfront investment that could be proven cost-effective in the long run. Reducing engine idling reduces particulate matter, NOx, CO and HC emissions, while significantly reducing fuel and maintenance costs and prolonging engine life.

Along with reduction in idling, another strategy that might prove beneficial to the contractors is through better and regular maintenance of the engine. This helps in reducing repair and maintenance costs while improving the performance of the engine. This strategy requires low administrative expenses and thus, result in lower emissions, reduced fuel consumption, lower expenditures through maintenance and longer equipment life (EPA 2007).

6.2 Alternate Fuels

The amount of emissions produced by an equipment can also be reduced by using alternate fuels to run the equipment. Previously, several alternate fuels such as propane and compressed natural gas were used in order to reduce missions and prolong the life of the engines. However, according to a report prepared by the ICF International for the American Association of State Highway and Transportation Officials (AASTO), the amount of CO_2 emitted per horsepower-hour by propane and compressed natural gas-fired equipment is more than diesel-fired equipment (Gallivan et al. 2010). However, two forms of fuel, ultra-low sulfur diesel (ULSD) and biodiesel, are known to reduce exhaust emissions while improving the life and performance of the engine.

6.2.1 Ultra-Low Sulfur Diesel

Ultra-low sulfur diesel (ULSD) is a refined, cleaner form of diesel fuel that can be used to fire any diesel engine equipment. The regular diesel fuel used by nonroad equipment contains 3000-5000 ppm of sulfur, while ULSD contains a maximum of 15 ppm. The EPA has set standards directing nonroad equipment operators to start using ULSD since June 2010(EPA 2007, CDFA 2016). This change in fuel has little to no financial impact on the equipment owners. According to data collected from the U.S. Energy Information Administration, the cost of one gallon of No. 2-Diesel fuel is the same as ULSD (EIA 2017).

The use of ULSD also reduces the smoke produced by up to 60% while decreasing the sulfur dioxide emissions by 90% (ULSD 2017). The use of ULSD, as mentioned earlier, has a positive influence on the quality of air as well as the engine of the equipment. Along with reduction in sulfur dioxide emissions, the use of ULSD reduces PM emissions by 5-9%. The particulate emissions can be cut down up to 90% by retrofitting the diesel engine with diesel particulate filters (CDTI 2017). In addition to reduction in exhaust emissions, ULSD also reduces engine maintenance costs. Based on a cost-benefit analysis run by the EPA, the use of ULSD results in maintenance savings of more than three cent per gallon when compared to the regular nonroad diesel fuels (EPA 2004). The use of ULSD also increases the oil change interval, making them last 35% longer than those nonraod engines using regular diesel fuel (EPA 2007).

6.2.2 Biodiesel

Another form of fuel recommended by the EPA is biodiesel. Biodiesel is a fuel produced from domestic products such as vegetable oils (peanuts, cottonseed, and canola), animal fats and even biotic wastes like recycled cooking grease. Biodiesel is generally blended with petroleum diesel in various concentrations to fuel diesel engines. B5, B20 and B100 are the three common blends of biodiesel.

B5 contains 5% biodiesel and 95% petroleum diesel, while B20 contains 20% biodiesel and 80% petroleum diesel (EPA 2007). Lower blends of biodiesel (B5 and B20) can be used in regular diesel engines without any modifications; however, biodiesels in their purest form (B100) can be used in diesel engines albeit with certain modifications in order to avoid maintenance and performance issues (EPA 2017a). The cost of biodiesel varies depending on the blend and production process, with higher grades costing more than regular diesel and lower grades of biodiesel. According to data reported by the U.S. Department of Energy, the national average cost of biodiesel B20 is $2.57/gallon, $0.01 less than the cost of a gallon of diesel. However, the cost of a gallon of B100 is almost 50 cents higher than a gallon of B20 (DOE 2017). In addition to lower prices, the use of biodiesel also helps improve air quality by reducing emissions produced from nonroad equipment. Biodiesel reduces CO, HC and PM emissions from nonroad equipment exhausts. Additionally, biodiesel also has a positive impact on the equipment engine. Biodiesel reduces fuel-related failures, thereby reducing maintenance costs while producing lesser smoke and noise (EPA 2007). It also reduces the amount of PM emitted from the exhaust by up to 40% (EPA 2007, EPA 2017a). Using biodiesels also proves beneficial to equipment owners by reducing maintenance and repair costs while increasing the longevity of the engine.

However, use of biodiesel has few limitations. Despite reducing CO, HC and PM emissions, the use of biodiesel increases NO_x emissions by 2%. Biodiesel also produces less energy than the conventional diesel thereby producing negligibly lower power, torque and fuel economy (EPA 2007). Pure blends of biodiesel are also not suitable for winter use since they are prone to solidifying or waxing and gelling, a condition common in most diesel fuels, resulting in clogging the fuel filters and injectors. This can be fixed by altering the temperature of the fuel with the help of additives (CBO 2017b).

6.3 Equipment Modifications

Another strategy to reduce emissions from nonroad construction equipment is by altering various aspects of the equipment. These modifications require an initial investment but they turn out to be cost-effective in the long run while improving air quality. Retrofit technologies, engine upgrades and electrification are some of the most effective techniques to curb nonroad equipment emissions while being profitable for the equipment owners.

6.3.1 Retrofits

Retrofits are devices, attached to the engine to reduce exhaust emissions. Based on a report prepared by the California Air Resources Board, in terms of cost per ton of pollutant reduced retrofitting engines is the most cost-effective approach (CARB 2004). An estimate from 2000-2004 shows that retrofitting engines resulted in a fall in 36 tons/year of CO, 12 tons/year of HC and 3 tons/year of PM (EPA 2007).

Devices such as Diesel Oxidation Catalyst (DOC), Closed Crankcase Ventilation Systems (CCV), Selective catalytic Reduction (SCR), Diesel Particulate Filter (DPF), Urea Injection, Exhaust Gas Recirculation (EGR), Fuel Borne Catalysts (FBC) and NOx adsorbers are commonly used to reduce the engine exhaust emissions.. Diesel Oxidation Catalysts are devices that oxidize CO emissions while reducing other pollutants such as PM, HC, and VOC. DOCs reduce PM emissions by approximately 40%, HC by 50%, and CO by 40% (ODEQ 2017b). The DPF retrofit kits are slightly more expensive than DOCs but are slightly more effective in reducing emissions. It reduces PM, CO and HC emissions by up to 90% (ODEQ 2017b, FCP 2016). DPFs are devices, coated with metals like platinum and palladium, prevent diesel particulate discharge from the tailpipe. Another retrofit for reducing emissions is the use of CCVs. The use of CCV systems reduces PM, CO and HC emissions by 90% and sometimes even 100% (ODEQ 2017b, CDTI 2017). Retrofit technologies like SCR, EGR, Urea Injections and NOx adsorbers are uncommon in the nonroad engine sector. However, these technologies are effective in reducing exhaust emissions. These technologies, though less effective than DPFs and DOCs, reduce varying percentages of NOx, CO, VOC and PM emissions (ODEQ 2017b, CDTI 2017).

In addition to reducing pollutants and bettering air quality, equipment retrofitting helps fleet owners and contractors in acquiring projects that follow strict air quality regulations. Investing in retrofitted equipment also benefits the fleet owner and the construction company. Several public agencies and projects have mandated the use of low emission equipment on the projects and retrofitting the equipment would benefit the construction companies in acquiring such projects. The availability of several public and state grants and subsidies help minimize the burden of retrofit costs on construction companies. Several state and federal programs such as the California Carl Moyer program, National Clean Diesel Campaign, and Congestion Mitigation and Air Quality are some of the grants that fund engine retrofits (Pacific Institute 2005).

6.3.2 Engine Upgrades

This section highlights another strategy to reduce emissions while improving the performance of the engines. Engine upgrades refers to adding emission-reducing parts to an engine or repowering old engines by replacing some or all of the parts to enhance their performances. Completely replacing an old engine with a new one might be expensive but with the availability of public grants and subsidies and maintenance and fuel cost savings in the long run might prove to be beneficial for equipment owners.

Repowering or replacing an engine depends on the model and type of the equipment, with smaller engines costing lesser than larger ones. Repowering a smaller equipment generally tends to be less expensive than repowering a larger one. However, grants from state agencies tend to reduce these expenses, sometimes as high as 60% of the total repowering cost. A practical approach of improving life and performance of the engine is by refurbishing it by replacing some of the vital components. This helps reduce PM, NOx, CO and HC emissions, with reductions varying from 25% to 75%. In addition to reduction in emissions, engine upgrades also lower fuel consumption thereby reducing fuel costs around $3000 per year in some cases. The engine upgrades also lower the maintenance costs while increasing the resale value of the equipment. Most manufacturers offer emission upgrade kits that help reduce PM emissions by 15%, CO by 3%, HC by 61% and NOx by 27% (EPA 2007).

6.3.3 Electrification

This section provides a brief analysis of the use of electric or hybrid equipment in the construction industry. It also discusses the possibility of generating clean electric power at a construction site rather than conventional on-site diesel generators.

The use of electric power in lieu of diesel power results in lower emissions, quieter construction sites, and lower costs. According to a report submitted to the EPA, the emissions produced by an electric powered generator is lesser than the emissions generated by on-site diesel generators, with the reduction being 91% of CO emissions, 75% of NOx emissions and 98% of PM emissions per kilowatt-hour (EPA 2017b). Electric power is also seen to be substantially less expensive than using a diesel generator. A report submitted by the US EPA suggests that the use of electric generators would save organizations nearly $12,000 each year. (EPA 2007). However, hybridization of larger equipment with higher horsepower and load requirements may not be a viable option. Since diesel engines equipment have a long operating life, the equipment owners would not be willing to meet the higher cost of hybrid engines which may or may not be able to meet the operational qualities of the diesel engines (Gullivan et al. 2010, ODEQ 2017b).

6.4 Non-equipment Strategies

The amount of particulate matter produced by construction equipment and their activities can be mitigated by various measures other than modifying the engine of the equipment. As mentioned in previous sections, particulate matter can be produced during construction activities such as excavation, demolition, soil loading, unloading and hauling. Some projects in the construction industry has implemented several dust control measures such as water spray systems and dust barriers. These measures are the most common and most cost effective measures in suppressing dust produced on construction sites. In the former system, water tanks are driven around the construction site 2-3 times a day spraying water over the areas in question, thereby preventing the suspension of dust due to vehicular traffic and the wind. However, care should be taken to prevent excess water from being sprayed, as this would lead to erosion problems. Another common strategy to dust suspension is the use of screens or barriers. These plastic screens are generally laid over excavated soil in order to prevent dispersion due to wind. Some of the more uncommon strategies implemented on construction sites include the use of surfactants, polymers, and chlorides. The use of Respiratory Protective Equipment (RPE) also helps in reducing exhaust gas and dust inhalation among workers present on the construction site.

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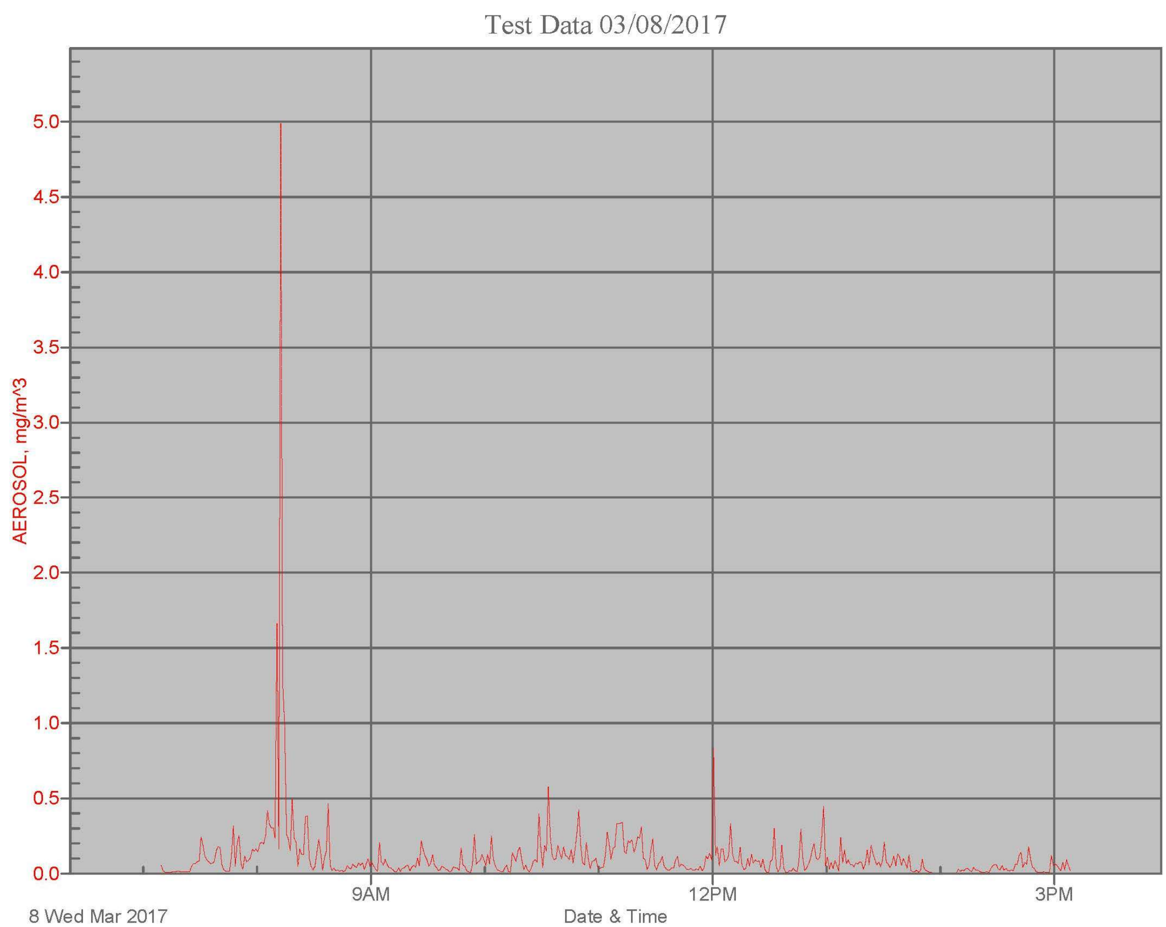
APPENDIX

(Sample Graph and Table)


Test Data 03/08/2017
AEROSOL, mg/m^3
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
9AM
12PM
3PM
8 Wed Mar 2017
Date & Time

Sample Test Data

Instrument		Data Properties	
Model	DustTrak II	Start Date	03/08/2017
Instrument S/N	8530164115	Start Time	07:08:26
Total Time	0:08:00:00	Stop Date	03/08/2017
Logging Interval	60 seconds	Stop Time	15:08:26

Statistics	
	AEROSOL
Avg	0.107 mg/m^3
Max	4.990 mg/m^3
Max Date	03/08/2017
Max Time	08:12:26
Min	0.006 mg/m^3
Min Date	03/08/2017
Min Time	13:57:26
TWA (8 hr)	0.107
TWA Start Date	03/08/2017
TWA Start Time	07:08:26
TWA End Time	15:08:26

Test Data			
Data Point	Date	Time	AEROSOL mg/m^3
1	03/08/2017	07:09:26	0.054
2	03/08/2017	07:10:26	0.019
3	03/08/2017	07:11:26	0.010
4	03/08/2017	07:12:26	0.009
5	03/08/2017	07:13:26	0.009
6	03/08/2017	07:14:26	0.008
7	03/08/2017	07:15:26	0.011
8	03/08/2017	07:16:26	0.012
9	03/08/2017	07:17:26	0.014
10	03/08/2017	07:18:26	0.016
11	03/08/2017	07:19:26	0.014
12	03/08/2017	07:20:26	0.011
13	03/08/2017	07:21:26	0.012
14	03/08/2017	07:22:26	0.011
15	03/08/2017	07:23:26	0.011
16	03/08/2017	07:24:26	0.011
17	03/08/2017	07:25:26	0.049
18	03/08/2017	07:26:26	0.067
19	03/08/2017	07:27:26	0.067
20	03/08/2017	07:28:26	0.078

Test Data (Continued)			
Data Point	Date	Time	AEROSOL mg/m^3
21	03/08/2017	07:29:26	0.084
22	03/08/2017	07:30:26	0.244
23	03/08/2017	07:31:26	0.189
24	03/08/2017	07:32:26	0.117
25	03/08/2017	07:33:26	0.093
26	03/08/2017	07:34:26	0.079
27	03/08/2017	07:35:26	0.067
28	03/08/2017	07:36:26	0.070
29	03/08/2017	07:37:26	0.078
30	03/08/2017	07:38:26	0.153
31	03/08/2017	07:39:26	0.177
32	03/08/2017	07:40:26	0.174
33	03/08/2017	07:41:26	0.059
34	03/08/2017	07:42:26	0.025
35	03/08/2017	07:43:26	0.016
36	03/08/2017	07:44:26	0.015
37	03/08/2017	07:45:26	0.016
38	03/08/2017	07:46:26	0.115
39	03/08/2017	07:47:26	0.317
40	03/08/2017	07:48:26	0.050
41	03/08/2017	07:49:26	0.202
42	03/08/2017	07:50:26	0.255
43	03/08/2017	07:51:26	0.066
44	03/08/2017	07:52:26	0.031
45	03/08/2017	07:53:26	0.116
46	03/08/2017	07:54:26	0.079
47	03/08/2017	07:55:26	0.087
48	03/08/2017	07:56:26	0.105
49	03/08/2017	07:57:26	0.161
50	03/08/2017	07:58:26	0.149
51	03/08/2017	07:59:26	0.162
52	03/08/2017	08:00:26	0.146
53	03/08/2017	08:01:26	0.200
54	03/08/2017	08:02:26	0.207
55	03/08/2017	08:03:26	0.197
56	03/08/2017	08:04:26	0.256
57	03/08/2017	08:05:26	0.418
58	03/08/2017	08:06:26	0.327
59	03/08/2017	08:07:26	0.303
60	03/08/2017	08:08:26	0.305
61	03/08/2017	08:09:26	0.235
62	03/08/2017	08:10:26	1.660

Test Data (Continued)			
Data Point	Date	Time	AEROSOL mg/m^3
63	03/08/2017	08:11:26	0.163
64	03/08/2017	08:12:26	4.990
65	03/08/2017	08:13:26	1.280
66	03/08/2017	08:14:26	1.000
67	03/08/2017	08:15:26	0.258
68	03/08/2017	08:16:26	0.228
69	03/08/2017	08:17:26	0.153
70	03/08/2017	08:18:26	0.493
71	03/08/2017	08:19:26	0.238
72	03/08/2017	08:20:26	0.209
73	03/08/2017	08:21:26	0.048
74	03/08/2017	08:22:26	0.163
75	03/08/2017	08:23:26	0.127
76	03/08/2017	08:24:26	0.127
77	03/08/2017	08:25:26	0.377
78	03/08/2017	08:26:26	0.384
79	03/08/2017	08:27:26	0.101
80	03/08/2017	08:28:26	0.047
81	03/08/2017	08:29:26	0.024
82	03/08/2017	08:30:26	0.047
83	03/08/2017	08:31:26	0.140
84	03/08/2017	08:32:26	0.227
85	03/08/2017	08:33:26	0.146
86	03/08/2017	08:34:26	0.022
87	03/08/2017	08:35:26	0.102
88	03/08/2017	08:36:26	0.150
89	03/08/2017	08:37:26	0.466
90	03/08/2017	08:38:26	0.057
91	03/08/2017	08:39:26	0.021
92	03/08/2017	08:40:26	0.037
93	03/08/2017	08:41:26	0.018
94	03/08/2017	08:42:26	0.023
95	03/08/2017	08:43:26	0.015
96	03/08/2017	08:44:26	0.021
97	03/08/2017	08:45:26	0.014
98	03/08/2017	08:46:26	0.018
99	03/08/2017	08:47:26	0.053
100	03/08/2017	08:48:26	0.037
101	03/08/2017	08:49:26	0.032
102	03/08/2017	08:50:26	0.064
103	03/08/2017	08:51:26	0.047
104	03/08/2017	08:52:26	0.040

Test Data (Continued)			
Data Point	Date	Time	AEROSOL mg/m^3
105	03/08/2017	08:53:26	0.071
106	03/08/2017	08:54:26	0.055
107	03/08/2017	08:55:26	0.071
108	03/08/2017	08:56:26	0.027
109	03/08/2017	08:57:26	0.064
110	03/08/2017	08:58:26	0.100
111	03/08/2017	08:59:26	0.047
112	03/08/2017	09:00:26	0.074
113	03/08/2017	09:01:26	0.050
114	03/08/2017	09:02:26	0.027
115	03/08/2017	09:03:26	0.017
116	03/08/2017	09:04:26	0.205
117	03/08/2017	09:05:26	0.078
118	03/08/2017	09:06:26	0.054
119	03/08/2017	09:07:26	0.094
120	03/08/2017	09:08:26	0.061
121	03/08/2017	09:09:26	0.041
122	03/08/2017	09:10:26	0.036
123	03/08/2017	09:11:26	0.024
124	03/08/2017	09:12:26	0.013
125	03/08/2017	09:13:26	0.014
126	03/08/2017	09:14:26	0.039
127	03/08/2017	09:15:26	0.014
128	03/08/2017	09:16:26	0.034
129	03/08/2017	09:17:26	0.037
130	03/08/2017	09:18:26	0.052
131	03/08/2017	09:19:26	0.055
132	03/08/2017	09:20:26	0.018
133	03/08/2017	09:21:26	0.044
134	03/08/2017	09:22:26	0.055
135	03/08/2017	09:23:26	0.042
136	03/08/2017	09:24:26	0.101
137	03/08/2017	09:25:26	0.051
138	03/08/2017	09:26:26	0.219
139	03/08/2017	09:27:26	0.161
140	03/08/2017	09:28:26	0.116
141	03/08/2017	09:29:26	0.090
142	03/08/2017	09:30:26	0.050
143	03/08/2017	09:31:26	0.071
144	03/08/2017	09:32:26	0.123
145	03/08/2017	09:33:26	0.057
146	03/08/2017	09:34:26	0.040

Test Data (Continued)			
Data Point	Date	Time	AEROSOL mg/m^3
147	03/08/2017	09:35:26	0.021
148	03/08/2017	09:36:26	0.024
149	03/08/2017	09:37:26	0.049
150	03/08/2017	09:38:26	0.040
151	03/08/2017	09:39:26	0.028
152	03/08/2017	09:40:26	0.023
153	03/08/2017	09:41:26	0.011
154	03/08/2017	09:42:26	0.019
155	03/08/2017	09:43:26	0.046
156	03/08/2017	09:44:26	0.037
157	03/08/2017	09:45:26	0.036
158	03/08/2017	09:46:26	0.022
159	03/08/2017	09:47:26	0.170
160	03/08/2017	09:48:26	0.058
161	03/08/2017	09:49:26	0.048
162	03/08/2017	09:50:26	0.019
163	03/08/2017	09:51:26	0.011
164	03/08/2017	09:52:26	0.009
165	03/08/2017	09:53:26	0.063
166	03/08/2017	09:54:26	0.259
167	03/08/2017	09:55:26	0.063
168	03/08/2017	09:56:26	0.080
169	03/08/2017	09:57:26	0.085
170	03/08/2017	09:58:26	0.126
171	03/08/2017	09:59:26	0.094
172	03/08/2017	10:00:26	0.053
173	03/08/2017	10:01:26	0.127
174	03/08/2017	10:02:26	0.063
175	03/08/2017	10:03:26	0.251
176	03/08/2017	10:04:26	0.096
177	03/08/2017	10:05:26	0.054
178	03/08/2017	10:06:26	0.025
179	03/08/2017	10:07:26	0.020
180	03/08/2017	10:08:26	0.014
181	03/08/2017	10:09:26	0.011
182	03/08/2017	10:10:26	0.037
183	03/08/2017	10:11:26	0.054
184	03/08/2017	10:12:26	0.012
185	03/08/2017	10:13:26	0.010
186	03/08/2017	10:14:26	0.137
187	03/08/2017	10:15:26	0.108
188	03/08/2017	10:16:26	0.082

Test Data (Continued)			
Data Point	Date	Time	AEROSOL mg/m^3
189	03/08/2017	10:17:26	0.150
190	03/08/2017	10:18:26	0.174
191	03/08/2017	10:19:26	0.089
192	03/08/2017	10:20:26	0.028
193	03/08/2017	10:21:26	0.054
194	03/08/2017	10:22:26	0.024
195	03/08/2017	10:23:26	0.013
196	03/08/2017	10:24:26	0.036
197	03/08/2017	10:25:26	0.079
198	03/08/2017	10:26:26	0.092
199	03/08/2017	10:27:26	0.077
200	03/08/2017	10:28:26	0.398
201	03/08/2017	10:29:26	0.179
202	03/08/2017	10:30:26	0.041
203	03/08/2017	10:31:26	0.185
204	03/08/2017	10:32:26	0.150
205	03/08/2017	10:33:26	0.576
206	03/08/2017	10:34:26	0.248
207	03/08/2017	10:35:26	0.114
208	03/08/2017	10:36:26	0.093
209	03/08/2017	10:37:26	0.099
210	03/08/2017	10:38:26	0.187
211	03/08/2017	10:39:26	0.135
212	03/08/2017	10:40:26	0.100
213	03/08/2017	10:41:26	0.178
214	03/08/2017	10:42:26	0.119
215	03/08/2017	10:43:26	0.113
216	03/08/2017	10:44:26	0.092
217	03/08/2017	10:45:26	0.160
218	03/08/2017	10:46:26	0.070
219	03/08/2017	10:47:26	0.156
220	03/08/2017	10:48:26	0.274
221	03/08/2017	10:49:26	0.423
222	03/08/2017	10:50:26	0.185
223	03/08/2017	10:51:26	0.070
224	03/08/2017	10:52:26	0.059
225	03/08/2017	10:53:26	0.206
226	03/08/2017	10:54:26	0.099
227	03/08/2017	10:55:26	0.033
228	03/08/2017	10:56:26	0.080
229	03/08/2017	10:57:26	0.086
230	03/08/2017	10:58:26	0.101

Test Data (Continued)			
Data Point	Date	Time	AEROSOL mg/m^3
231	03/08/2017	10:59:26	0.042
232	03/08/2017	11:00:26	0.034
233	03/08/2017	11:01:26	0.041
234	03/08/2017	11:02:26	0.042
235	03/08/2017	11:03:26	0.124
236	03/08/2017	11:04:26	0.276
237	03/08/2017	11:05:26	0.196
238	03/08/2017	11:06:26	0.097
239	03/08/2017	11:07:26	0.168
240	03/08/2017	11:08:26	0.177
241	03/08/2017	11:09:26	0.330
242	03/08/2017	11:10:26	0.331
243	03/08/2017	11:11:26	0.335
244	03/08/2017	11:12:26	0.338
245	03/08/2017	11:13:26	0.144
246	03/08/2017	11:14:26	0.133
247	03/08/2017	11:15:26	0.218
248	03/08/2017	11:16:26	0.207
249	03/08/2017	11:17:26	0.223
250	03/08/2017	11:18:26	0.143
251	03/08/2017	11:19:26	0.177
252	03/08/2017	11:20:26	0.245
253	03/08/2017	11:21:26	0.235
254	03/08/2017	11:22:26	0.311
255	03/08/2017	11:23:26	0.101
256	03/08/2017	11:24:26	0.092
257	03/08/2017	11:25:26	0.027
258	03/08/2017	11:26:26	0.055
259	03/08/2017	11:27:26	0.154
260	03/08/2017	11:28:26	0.230
261	03/08/2017	11:29:26	0.055
262	03/08/2017	11:30:26	0.025
263	03/08/2017	11:31:26	0.067
264	03/08/2017	11:32:26	0.080
265	03/08/2017	11:33:26	0.114
266	03/08/2017	11:34:26	0.048
267	03/08/2017	11:35:26	0.030
268	03/08/2017	11:36:26	0.022
269	03/08/2017	11:37:26	0.025
270	03/08/2017	11:38:26	0.038
271	03/08/2017	11:39:26	0.038
272	03/08/2017	11:40:26	0.088

Test Data (Continued)			
Data Point	Date	Time	AEROSOL mg/m^3
273	03/08/2017	11:41:26	0.114
274	03/08/2017	11:42:26	0.044
275	03/08/2017	11:43:26	0.063
276	03/08/2017	11:44:26	0.055
277	03/08/2017	11:45:26	0.044
278	03/08/2017	11:46:26	0.026
279	03/08/2017	11:47:26	0.026
280	03/08/2017	11:48:26	0.035
281	03/08/2017	11:49:26	0.022
282	03/08/2017	11:50:26	0.023
283	03/08/2017	11:51:26	0.032
284	03/08/2017	11:52:26	0.022
285	03/08/2017	11:53:26	0.049
286	03/08/2017	11:54:26	0.019
287	03/08/2017	11:55:26	0.035
288	03/08/2017	11:56:26	0.116
289	03/08/2017	11:57:26	0.098
290	03/08/2017	11:58:26	0.136
291	03/08/2017	11:59:26	0.091
292	03/08/2017	12:00:26	0.837
293	03/08/2017	12:01:26	0.121
294	03/08/2017	12:02:26	0.179
295	03/08/2017	12:03:26	0.052
296	03/08/2017	12:04:26	0.164
297	03/08/2017	12:05:26	0.163
298	03/08/2017	12:06:26	0.077
299	03/08/2017	12:07:26	0.092
300	03/08/2017	12:08:26	0.122
301	03/08/2017	12:09:26	0.332
302	03/08/2017	12:10:26	0.135
303	03/08/2017	12:11:26	0.082
304	03/08/2017	12:12:26	0.081
305	03/08/2017	12:13:26	0.067
306	03/08/2017	12:14:26	0.173
307	03/08/2017	12:15:26	0.053
308	03/08/2017	12:16:26	0.027
309	03/08/2017	12:17:26	0.033
310	03/08/2017	12:18:26	0.099
311	03/08/2017	12:19:26	0.050
312	03/08/2017	12:20:26	0.126
313	03/08/2017	12:21:26	0.069
314	03/08/2017	12:22:26	0.090

Test Data (Continued)			
Data Point	Date	Time	AEROSOL mg/m^3
315	03/08/2017	12:23:26	0.080
316	03/08/2017	12:24:26	0.083
317	03/08/2017	12:25:26	0.041
318	03/08/2017	12:26:26	0.095
319	03/08/2017	12:27:26	0.028
320	03/08/2017	12:28:26	0.009
321	03/08/2017	12:29:26	0.007
322	03/08/2017	12:30:26	0.080
323	03/08/2017	12:31:26	0.095
324	03/08/2017	12:32:26	0.301
325	03/08/2017	12:33:26	0.050
326	03/08/2017	12:34:26	0.012
327	03/08/2017	12:35:26	0.032
328	03/08/2017	12:36:26	0.187
329	03/08/2017	12:37:26	0.037
330	03/08/2017	12:38:26	0.009
331	03/08/2017	12:39:26	0.008
332	03/08/2017	12:40:26	0.019
333	03/08/2017	12:41:26	0.016
334	03/08/2017	12:42:26	0.036
335	03/08/2017	12:43:26	0.018
336	03/08/2017	12:44:26	0.013
337	03/08/2017	12:45:26	0.083
338	03/08/2017	12:46:26	0.295
339	03/08/2017	12:47:26	0.111
340	03/08/2017	12:48:26	0.019
341	03/08/2017	12:49:26	0.035
342	03/08/2017	12:50:26	0.063
343	03/08/2017	12:51:26	0.093
344	03/08/2017	12:52:26	0.157
345	03/08/2017	12:53:26	0.200
346	03/08/2017	12:54:26	0.106
347	03/08/2017	12:55:26	0.093
348	03/08/2017	12:56:26	0.109
349	03/08/2017	12:57:26	0.245
350	03/08/2017	12:58:26	0.446
351	03/08/2017	12:59:26	0.052
352	03/08/2017	13:00:26	0.111
353	03/08/2017	13:01:26	0.030
354	03/08/2017	13:02:26	0.074
355	03/08/2017	13:03:26	0.034
356	03/08/2017	13:04:26	0.087

Test Data (Continued)			
Data Point	Date	Time	AEROSOL mg/m^3
357	03/08/2017	13:05:26	0.053
358	03/08/2017	13:06:26	0.016
359	03/08/2017	13:07:26	0.240
360	03/08/2017	13:08:26	0.073
361	03/08/2017	13:09:26	0.158
362	03/08/2017	13:10:26	0.065
363	03/08/2017	13:11:26	0.091
364	03/08/2017	13:12:26	0.058
365	03/08/2017	13:13:26	0.061
366	03/08/2017	13:14:26	0.045
367	03/08/2017	13:15:26	0.071
368	03/08/2017	13:16:26	0.063
369	03/08/2017	13:17:26	0.079
370	03/08/2017	13:18:26	0.072
371	03/08/2017	13:19:26	0.029
372	03/08/2017	13:20:26	0.067
373	03/08/2017	13:21:26	0.155
374	03/08/2017	13:22:26	0.061
375	03/08/2017	13:23:26	0.190
376	03/08/2017	13:24:26	0.132
377	03/08/2017	13:25:26	0.091
378	03/08/2017	13:26:26	0.058
379	03/08/2017	13:27:26	0.078
380	03/08/2017	13:28:26	0.046
381	03/08/2017	13:29:26	0.087
382	03/08/2017	13:30:26	0.209
383	03/08/2017	13:31:26	0.077
384	03/08/2017	13:32:26	0.065
385	03/08/2017	13:33:26	0.040
386	03/08/2017	13:34:26	0.065
387	03/08/2017	13:35:26	0.115
388	03/08/2017	13:36:26	0.051
389	03/08/2017	13:37:26	0.132
390	03/08/2017	13:38:26	0.111
391	03/08/2017	13:39:26	0.056
392	03/08/2017	13:40:26	0.100
393	03/08/2017	13:41:26	0.071
394	03/08/2017	13:42:26	0.035
395	03/08/2017	13:43:26	0.123
396	03/08/2017	13:44:26	0.020
397	03/08/2017	13:45:26	0.012
398	03/08/2017	13:46:26	0.011

Test Data (Continued)			
Data Point	Date	Time	AEROSOL mg/m^3
399	03/08/2017	13:47:26	0.023
400	03/08/2017	13:48:26	0.009
401	03/08/2017	13:49:26	0.018
402	03/08/2017	13:50:26	0.096
403	03/08/2017	13:51:26	0.030
404	03/08/2017	13:52:26	0.021
405	03/08/2017	13:53:26	0.014
406	03/08/2017	13:54:26	0.008
407	03/08/2017	13:55:26	0.007
408	03/08/2017	13:56:26	0.007
409	03/08/2017	13:57:26	0.006
410	03/08/2017	13:58:26	0.006
411	03/08/2017	13:59:26	0.006
412	03/08/2017	14:00:26	0.006
413	03/08/2017	14:01:26	0.006
414	03/08/2017	14:02:26	0.006
415	03/08/2017	14:03:26	0.006
416	03/08/2017	14:04:26	0.006
417	03/08/2017	14:05:26	0.006
418	03/08/2017	14:06:26	0.006
419	03/08/2017	14:07:26	0.006
420	03/08/2017	14:08:26	0.007
421	03/08/2017	14:09:26	0.029
422	03/08/2017	14:10:26	0.015
423	03/08/2017	14:11:26	0.024
424	03/08/2017	14:12:26	0.018
425	03/08/2017	14:13:26	0.032
426	03/08/2017	14:14:26	0.033
427	03/08/2017	14:15:26	0.020
428	03/08/2017	14:16:26	0.012
429	03/08/2017	14:17:26	0.041
430	03/08/2017	14:18:26	0.024
431	03/08/2017	14:19:26	0.025
432	03/08/2017	14:20:26	0.015
433	03/08/2017	14:21:26	0.009
434	03/08/2017	14:22:26	0.006
435	03/08/2017	14:23:26	0.008
436	03/08/2017	14:24:26	0.013
437	03/08/2017	14:25:26	0.008
438	03/08/2017	14:26:26	0.029
439	03/08/2017	14:27:26	0.051
440	03/08/2017	14:28:26	0.061

Test Data (Continued)			
Data Point	Date	Time	AEROSOL mg/m^3
441	03/08/2017	14:29:26	0.058
442	03/08/2017	14:30:26	0.031
443	03/08/2017	14:31:26	0.025
444	03/08/2017	14:32:26	0.053
445	03/08/2017	14:33:26	0.022
446	03/08/2017	14:34:26	0.034
447	03/08/2017	14:35:26	0.021
448	03/08/2017	14:36:26	0.017
449	03/08/2017	14:37:26	0.025
450	03/08/2017	14:38:26	0.019
451	03/08/2017	14:39:26	0.062
452	03/08/2017	14:40:26	0.061
453	03/08/2017	14:41:26	0.120
454	03/08/2017	14:42:26	0.142
455	03/08/2017	14:43:26	0.043
456	03/08/2017	14:44:26	0.074
457	03/08/2017	14:45:26	0.063
458	03/08/2017	14:46:26	0.178
459	03/08/2017	14:47:26	0.096
460	03/08/2017	14:48:26	0.042
461	03/08/2017	14:49:26	0.032
462	03/08/2017	14:50:26	0.014
463	03/08/2017	14:51:26	0.007
464	03/08/2017	14:52:26	0.009
465	03/08/2017	14:53:26	0.008
466	03/08/2017	14:54:26	0.011
467	03/08/2017	14:55:26	0.009
468	03/08/2017	14:56:26	0.007
469	03/08/2017	14:57:26	0.009
470	03/08/2017	14:58:26	0.119
471	03/08/2017	14:59:26	0.053
472	03/08/2017	15:00:26	0.062
473	03/08/2017	15:01:26	0.056
474	03/08/2017	15:02:26	0.033
475	03/08/2017	15:03:26	0.018
476	03/08/2017	15:04:26	0.073
477	03/08/2017	15:05:26	0.025
478	03/08/2017	15:06:26	0.090
479	03/08/2017	15:07:26	0.051
480	03/08/2017	15:08:26	0.019