AN ABSTRACT OF THE THESIS OF

Sai Akhila Boddi Reddy for the degree of Master of Science in Civil Engineering presented on December 1, 2017

Title: Estimating Air Pollutant Emissions for Nonroad Equipment using EPA MOVES – Case Study of a Building Project

Abstract approved: ____

Ingrid Arocho

Total emissions from the US contribute 15% to the global emissions. The construction industry is a major source of the exhaust emissions produced. Use of light duty vehicles and heavy-duty trucks for various construction activities contributes 83% to the total greenhouse gases produced. Construction equipment comprises of on-road and non-road equipment, and they produce significant amounts of pollutants. Non-road equipment is extensively used on buildings construction. Among the numerous pollutants identified on the construction site, this study will focus on CO, CO_2, NO_x, SO_x, and PM because of their ill effects on human health and because they are produced in large amounts compared to the other pollutants produced from diesel exhaust. This thesis summarizes the results of a research that used field data to estimate pollutant emissions from non-road equipment. The methodology for obtaining emissions using MOVES is presented. Basic information such as hours of operation per day, fuel used, and specifications of the engine are collected from a building construction site and are used for calculating total emissions. The output consists of emission rates for selected pollutants. The findings of this research are presented for excavators, mobile crane, loader, and a forklift. Results include total emission quantities per day and per equipment obtained from the data collected by direct observation and emission rates estimated using MOVES. Results indicate that CO_2 is produced in large quantities when compared to other selected pollutants. The total emissions of CO_2 are expected, but NO_x had surprisingly high total emissions for this project. The results from this study could be used by contractors and owners in the selection of the construction equipment in terms of reducing emissions.

Estimating Air Pollutant Emissions for Nonroad Equipment using EPA MOVES – Case Study of a Building Project

by
Sai Akhila Boddi Reddy

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APPROVED:

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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.

Sai Akhila Boddi Reddy, Author

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1.0 Introduction

Construction produces 7% of the U.S. greenhouse gas emissions, of which 76% originates from engines [Marshall et al. 2012]. The other 24% includes emissions from other activities in the construction. Figure 1.1 shows the emissions of eight pollutants for different industry sectors in Oregon for the year 2014. The industry sectors indicated in the figure and the categories that fall under each sector are explained in Appendix A. Some of the categories that falls under Mobile sector include construction dust, aircraft, non-road equipment-diesel, locomotives etc. According to Environmental Protection Agency (EPA), emissions from mobile sector (construction equipment emissions are considered mobile) is higher than other sectors (EPA 2017).

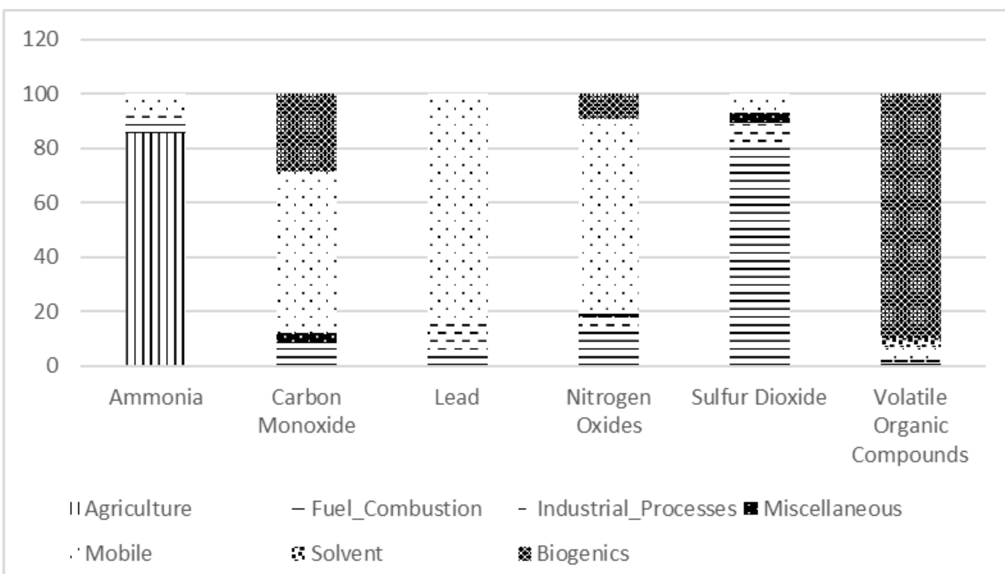


Figure 1.1: Multipollutant emissions comparison by source sector in Oregon in 2014 [EPA 2017]

Figure 1.1 shows that the mobile sector, which is indicated by dots, contributed to higher percentage of pollutants production, particularly for carbon monoxide, lead, and nitrogen oxides. Therefore, reducing air pollutant emissions from construction equipment during construction activities could have an important impact on the environmental effect of construction.

The construction industry has been showing interest on the percentage of its contribution to climate change. Different equipment such as excavators, backhoes, hauling units etc. are studied to evaluate and enhance their performance. The equipment is categorized as on-road and non-road equipment. All the equipment that can travel on highway is considered on-road equipment and the equipment which cannot travel on highways is considered non-road. Both on-road and non-road equipment produces diesel exhaust. Diesel exhaust contains pollutants such as carbon dioxide, nitrogen oxides, sulphur dioxide, particulate matter [DieselNet 2017]. Figure 1.2 shows the sources of diesel exhaust in Oregon. The pie chart shows that 29% of diesel exhaust produced is from construction equipment alone.

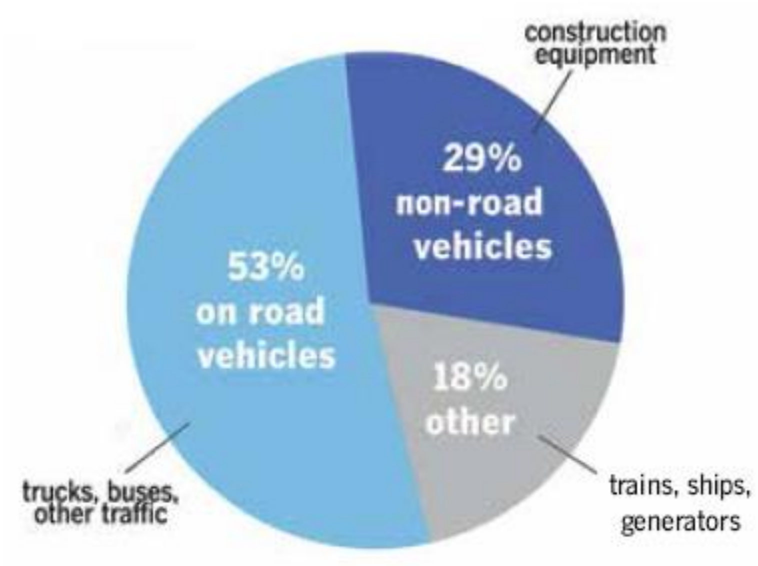


Figure 1.2: Sources of Diesel Exhaust in Oregon [DEQ 2017]

This study includes estimating emissions produced by construction equipment and shows the results for five types of pollutants produced by the exhaust system: carbon monoxide (CO), carbon dioxide (CO_2), particulate matter (PM10), nitrogen oxides (NO_x), and sulphur dioxide (SO_2). The mentioned pollutants are selected because they are harmful to the environment when present in large amounts and they are the most common exhaust pollutants as termed by EPA. The nonroad construction equipment selected for this study were two excavators, a forklift, and a mobile crane.

The main contribution of this research is to estimate emissions of the construction equipment using Motor Vehicle Emission Simulator (MOVES). MOVES 2014a is a newer version of MOVES 2014. The previous models to study non-road equipment are named as NONROAD Model and Mobile Model. All these programs are developed by Environmental Protection Agency (EPA) to estimate emissions rates of non-road equipment. This study presents results from a field study of 240 hours of nonroad diesel construction equipment. The number of hours the equipment was working per day on the site was noted by direct observation. Other data collected included engine model year, engine tier, and horsepower. Total quantity of emissions were calculated using the data collected and the emissions rates estimated from MOVES. Elements such as emissions per hour, emissions per day, emissions per equipment, and emissions per project were calculated.

This study has three objectives. The first objective of this research is to collect data from non-road construction equipment on the selected building project that includes project information and equipment details. The second objective is to introduce methodology to estimate emission rates of selected pollutants from non-road equipment using EPA MOVES. The third objective of this study is to calculate total emission quantities per day and total emission quantities per equipment using the information from the first and second objectives. Analysis is done to identify the most emitted pollutant and to identify the construction equipment that produces the highest emission pollutants. Recommendations from this study included measures to lower emissions from non-road construction equipment. In addition, measures are recommended to improve MOVES in terms of user-interface.

The results from this study could be used by contractors and owners to calculate emissions from construction equipment. Using MOVES reduces time and effort needed to measure emission from each item of equipment on the construction site. MOVES allow calculating emission rates for different scenarios including year, equipment type, and pollutant. The results could also be used for further research on emissions using MOVES and exploring various options provided in the MOVES program.

2.0 Literature Review

The following section explains the literature relevant to emissions from construction equipment. The construction industry, consisting of on-road and non-road equipment, is a major source of air pollutant emissions. Diesel is the performer of construction sector, powering more than three-fourths of all heavy construction equipment [Diesel Forum 2017]. There are two million diesel engines currently used across the United States out of which 31% were manufactured before the introduction of emissions regulations [NEDC 2017]. Diesel exhaust contains numerous chemicals that are harmful to human health which are discussed in the following section.

2.1 Diesel Exhaust Emissions

Diesel exhaust is a mixture of gases and particulates produced during the combustion of diesel fuel [USDL 2017, DieselNet 2017]. Short-term exposure to high concentrations of Diesel Exhaust (DE)/ Diesel Particulate Matter (DPM) can cause headache, dizziness, and irritation of the eye, nose and throat severe enough to distract or disable miners and other workers. Prolonged DE/DPM exposure can increase the risk of cardiovascular, cardiopulmonary and respiratory disease and lung cancer [OSHA 2017]. Diesel exhaust contains numerous chemicals including the ones listed below: [DEQ 2017]

- Carbon dioxide
- Carbon monoxide
- Sulphur dioxide
- Nitrogen oxides
- Particulate matter

- Hydrocarbons
- Lead
- Volatile organic compounds
- Water vapor
- Aldehydes
- Alcohols

EPA identified six common air pollutants among the above as criteria pollutants because of their negative effects on human health, the environment, and property. These criteria pollutants are carbon monoxide, lead, particulate matter, ground level ozone, nitrogen dioxide, and sulphur dioxide. The following sections will discuss each of the criteria pollutants and their effects.

2.1.1 Carbon Monoxide

Carbon monoxide (CO) is a colorless, odorless gas that can be harmful when inhaled in large amounts. At very high levels, CO can cause dizziness, unconsciousness and sometimes death. Short-term exposure to elevated CO may result in reduced oxygen to the heart accompanied by chest pain also known as angina [EPA 2016b].

2.1.2 Particulate Matter

Particulate matter (PM) also called particle pollution is a mixture of solid particles and liquid droplets found in the air. Particle pollution includes PM_{10}, and $PM_{2.5}$. PM_{10} are particles with diameters that are 10 micrometers and smaller. $PM_{2.5}$ are fine particles with diameters that are 2.5 micrometers and smaller. Figure 2.1 shows the size comparison of particulate matter with human hair. Exposure to these particles leads to premature death in people with heart or lung disease, aggravated asthma, and decreased lung function [EPA 2016b].

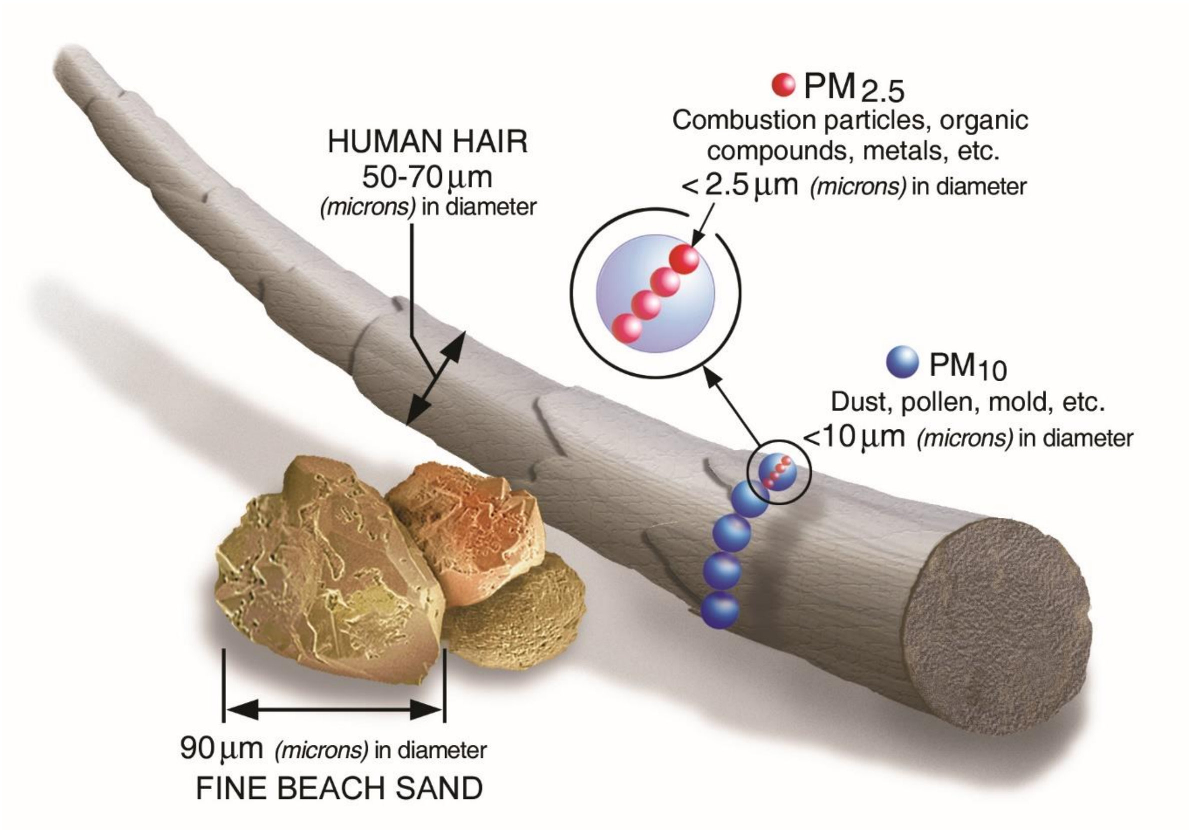


Figure 2.1: Size comparisons for PM particles [EPA 2016b]

2.1.3 Nitrogen Oxides

Nitrogen oxide (NO_2) primarily gets in the air from the burning of fuel. NO_2 forms from emissions from cars, trucks and buses, power plants, and off-road equipment. Breathing air with a high concentration of NO_2 can irritate airways in the human respiratory system. Such exposures over short periods can aggravate respiratory diseases, particularly asthma, leading to respiratory symptoms such as coughing, wheezing or difficulty breathing [EPA 2016b].

2.1.4 Sulphur Dioxide

EPA's national ambient air quality standards for sulphur dioxide (SO_2) are designed to protect against exposure to the entire group of sulfur oxides (SO_x). The largest source of SO_2 in the atmosphere is the burning of fossil fuels by power plants and other industrial facilities. Short-term exposures to SO_2 can harm the human respiratory system and make breathing difficult. Children, the elderly, and those who suffer from asthma are particularly sensitive to effects of SO_2 [EPA 2016b].

2.1.5 Lead

Lead can be found everywhere in our environment: air, soil, and water. Lead is emitted into the environment from industrial sources and contaminated sites. Lead is harmful for children, pregnant women, and adults too. Adults exposed to lead can suffer from decreased kidney function, cardiovascular effects, hypertension, and reproductive problems. In rare cases, ingestion of lead can cause seizures, coma and even death. Due to its adverse effects, various regulations resulted in removal of lead from onroad vehicle gasoline, which reduced lead concentrations in the air by 95% between 1980 and 1999 [EPA 2016b].

2.1.6 Ozone

Ozone can be good or bad depending on where it is found. Good ozone, also called stratospheric ozone, is found I the upper atmosphere which protects earth from harmful ultraviolet rays from the sun. Bad ozone, or ground level ozone, is not emitted directly in to the air. It is formed due to chemical reactions between nitrogen oxides and volatile organic compounds. Ozone can trigger a variety of health problems including chest pain, throat inflammation, and it reduces lung function. Outdoor workers are more at risk because they are exposed to bad ozone [EPA 2017]

Out of these six pollutants, lead and ozone will not be included in the present study because they are usually not produced in harmful amounts on a construction site. In addition to the above pollutants, carbon dioxide (CO_2) is produced in large amounts and is subject to interest for the study of emissions in the construction perspective [Marshall et al. 2012, Lewis et al. 2009].

2.1.7 Carbon Dioxide

CO_2 enters the atmosphere through burning fossil fuels (coal, natural gas, and oil), solid waste, trees and wood products, and because of certain chemical reactions. CO_2 is removed from the atmosphere when plants absorb it as part of the biological carbon cycle. Exposure to lower concentrations of CO_2 can cause hyperventilation, vision damage, lung congestion, central nervous system injury, abrupt muscle contractions, elevated blood pressure, and shortness of breath [EPA 2017a].

2.2 Emissions from Construction Equipment

Construction equipment is divided into two categories: on-road equipment and non-road equipment. Non-road equipment is defined as those equipment that cannot travel on highways, rest of the equipment is termed as on-road. Researchers developed several methodologies to study and analyze emissions from both types of construction equipment. However, limited field data are available for analyses of fuel use and emissions of nonroad diesel construction equipment [Frey et al. 2010]. The analysis of emissions could be done in several ways such as 1) estimating emissions from a project overall [Marshall et al. 2012], 2) estimating emissions from each equipment separately on a daily basis [Rasdorf et al. 2010], 3) a fuel based emission inventory [Kean et al. 2000], and 4) using wireless sensors to measure greenhouse gas emissions [Lee et al. 2009].

Lewis et al. [2009] developed a methodology for inventorying construction fleet emissions based on real-world measurements of construction vehicles using a portable emissions measurement system (PEMS). The research is limited to CO, $PM_{2.5}$ and NO_x; and the equipment included were backhoes, front-end loader and motor grader. The study showed that front-end loaders have the highest emissions rates for NO; backhoes have the highest emissions rates for PM and CO; and motor grades have the highest emissions rates for HC. The PEMS data reported here were collected in an uncontrollable observational mode. Based on the results, new emission factors can be developed for each construction vehicle. One of the drawbacks of using PEMS for field measurement is that different filters are required for the measurement of different types of pollutants.

Equipment characteristics such as age and engine size affects emission rates. A study by Guggemos et al. [2005] found that increasing the age of the equipment from 2 to 10 years increased CO, NO_2, and HC emissions between 30% and 68%. A study conducted by Frey et al. [2010] was based on emissions 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 study results revealed that engine size had the greatest impact on time-based petroleum diesel fuel use and emission rates of NOx, HC, CO, and CO2. It was also shown that the engine load had the most significant impact on B20 biodiesel fuel use and emission rates of NOx, HC, and CO2. Finally, the model year had the most significant impact on CO emission rates. This research concluded that, irrespective of the type of fuel used, fuel use and emission rates decrease with higher tier and model year.

The results of a study by Arocho et al. [2014] showed that the activities with the highest emissions during a road construction project are the initial demolition and excavation activities. Front-end loaders, closely followed by backhoes loaders and bulldozers, were the major contributors of HC, CO, and PM emission. Bulldozers were the major contributors of NO_x, CO_2, and SO_2.

PEMS was used by Lewis et al. [2012a] to gather engine and emissions data directly from the equipment while it was in use. A commonly accepted operational efficiency used in estimating productivity is 83%, which infers 50 minutes of nonidle time and 10 minutes of idle time per hour. Working at a reduced efficiency results in a reduced average hourly fuel use and emission rate but an increased total quantity of fuel used and emissions because of productivity reductions. The percentage increase in fuel use and carbon dioxide emissions decrease as idle time decreases. Nonidle fuel use and CO_2 emission rates are approximately three to five times higher than idle rates.

A study conducted by Frey et al. [2008] selected six motor graders that included two Tier 0, two Tier 1, one Tier 2, and one Tier 3 vehicles. Each vehicle was tested on one day using ultra-low sulfur diesel and on a separate day using soy-based B20 biodiesel. On average, the use of B20 instead of petroleum diesel leads to a negligible decrease of 1.6% in nitric oxide emission rate, and decreases of 19– 22% in emission rates of carbon monoxide, hydrocarbons, and particulate matter. Emission rates decrease significantly when comparing newer engine tier vehicles to older ones.

Significant reductions in tailpipe emissions accrue especially from the use of B20 and adoption of newer vehicles.

The findings from the study conducted on emissions from pollutants by Rasdorf et al. [2012] suggests that PM, NOx, and CO_2 emissions are largely independent of engine type and size. Alternatively, the remaining two pollutants, CO and total hydrocarbons (THC), have spikes in emissions and fuel use rates that vary from the first three. This suggests that certain engine types and/or sizes have varying effects on CO and THC. It was recommended that equipment emission factors be integrated into estimating and scheduling software so that they could be used as a project resource.

One way to reduce emissions, proposed by Lindgren et al. [2010] was to replace diesel used in the equipment with mixtures of biodiesel and diesel in different proportions. For example, (MK1) diesel fuel and three diesel substitutes Ecopar, Etamix D3, and Agrodiesel 15 were compared during steady state conditions, during transients, and during work operations commonly performed by tractors and construction equipment. This was carried out in order to determine how fuel, typical engine load/speed and transient effects influence emissions and engine efficiency during common work operations. They found out that differences between fuels in terms of fuel consumption, thermal efficiency and CO_2 emissions could be attributed to differences in their carbon fraction.

In a study conducted by Lewis et al. [2009], emissions from five backhoes, four front-end loaders (rubber tire loaders), and six motor graders were measured. Three emission reduction strategies were considered here: (a) increased use of B20 in lieu of petroleum diesel fuels, (b) replacement of older vehicles with newer ones, and (c) use of B20 exclusively in the newest vehicles available. If only B20 is used in vehicles with the highest available engine tier, NO would be reduced by approximately 7.5% to 39% for each vehicle type. PM, HC, and CO emissions would be reduced by approximately 21% to 82% for each vehicle type. The most effective strategy is the use of only B20 in the highest engine tier available for each vehicle. Fleet managers should consider using more B20 and less PD to reduce emissions. Average emission rates are lower for higher-tier engines than for lower-tier engines. Combining the benefits of both biodiesel and newer vehicles is a highly effective emissions reduction strategy.

2.3 Engine tiers

In the United States, emission standards are developed by the US EPA. EPA started regulating emissions from nonroad vehicles since 1994. Other regulations have been developed since then resulting on stricter restrictions to different pollutants. Engines are identified using the regulation that was enforced when the engine was manufactured from Tier 1 to Tier 4. Engines manufactured before the regulations were in place are called Tier 0. A more detailed explanation of each tier is presented below.

2.3.1 Tier 1

The first federal standards for new non-road diesel engines were adopted in 1994 to be phased-in from 1996 to 2000 depending on engine size. These standards are for engines over 37 kW (50 hp). The Tier 1 standards applied to vehicles up to 8,500 lbs. gross vehicle weight rating (GVWR). These standards specifically restrict emissions of carbon monoxide (CO), oxides of nitrogen (NOx), particulate matter (PM), formaldehyde (HCHO), and non-methane organic gases (NMOG) or non-methane hydrocarbons (NMHC) [DieselNet 2016].

2.3.2 Tier 2

The second set of standards were phased in from 2004 to 2009 depending on engine size. Within the Tier 2 ranking, there is a sub ranking ranging from BIN 1–10, with 1 being the cleanest (Zero Emission vehicle) and 10 being the dirtiest. These are applied to the vehicles up to 8500 lbs. gross vehicle weight rating. In this tier, sulphur content allowed in gasoline and diesel fuel are limited [DieselNet 2016].

2.3.3 Tier 3

The third round of regulations were enforced over the period of 2017-2025 depending on engine size. Tier 3 reduced sulphur content of gasoline and reduced an average of 80% of VOC and NOx emissions [UCAIR 2016].

2.3.4 Tier 4

The fourth set of standards were phased-in over the period of 2008-2015 depending on engine size. Tier 4 regulated the emissions of particulate matter (PM), oxides of nitrogen (NOx) and air toxics from new, non-road diesel engines [DieselNet 2016].

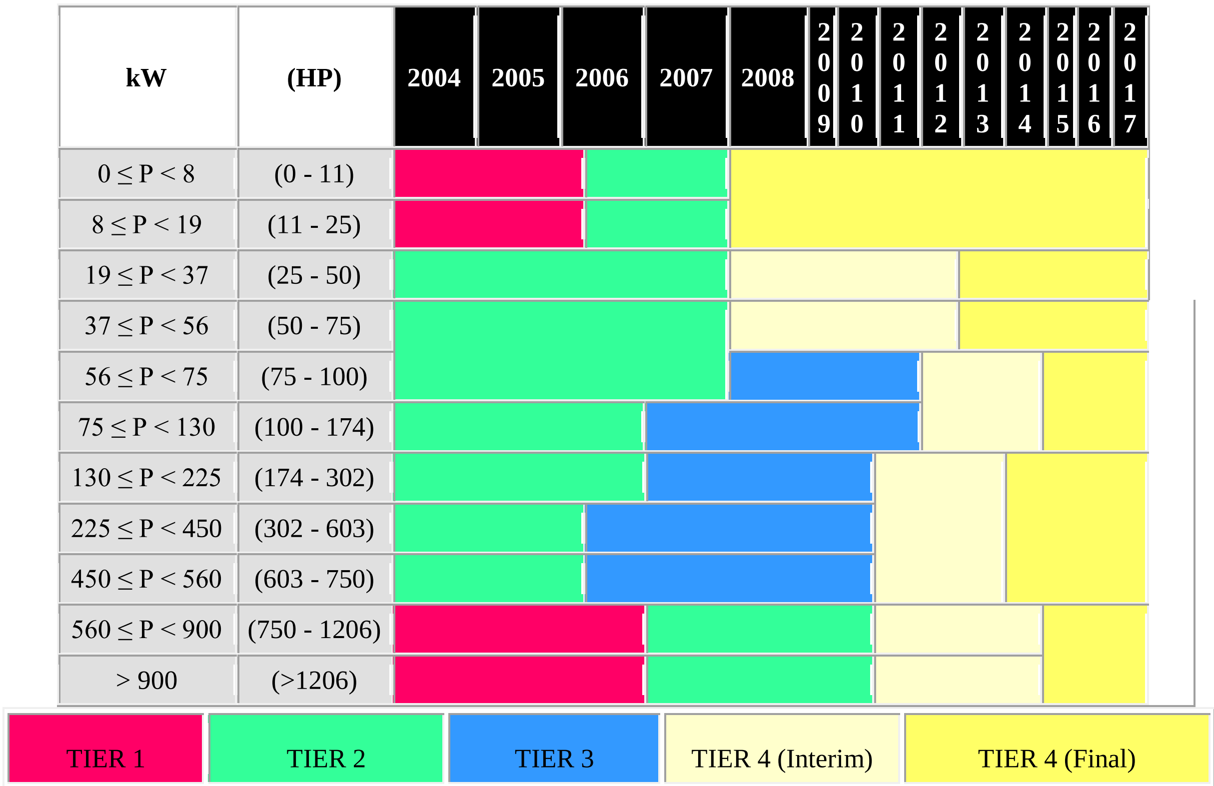
Table 2.1 shows the graphical representation of the division of tier system based on model year, horsepower, and power of the engine that is represented using kilowatts (kW) in the table. Each color represents a different tier. Table 2.1 shows the graphical representation of tiers 0, 1, and 2 with years and horsepower. Table 2.2 illustrates the graphical representation of tiers 2, 3, and 4 with years and horsepower. It can be observed from the following tables that engine tiers division is not based on year alone, it depends on horsepower too. For example in Table 2.1, for the year 1999, 0-11 HP falls under Tier 0, but 25-50 HP falls under Tier 1. Likewise, from Table

2.2, for the year 2007, 75-100 HP falls under Tier 2, but 174-302 HP falls under Tier 3. This information is important because of the fact that tiers are based on engine sizes.

Table 2.1: Classification of tiers based on engine size and model year for tiers 0, 1 and 2

kW	(HP)	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
0 ≤ P < 8	(0 - 11)	TIER 0									
8 ≤ P < 19	(11 - 25)	TIER 0									
19 ≤ P < 37	(25 - 50)	TIER 0									
37 ≤ P < 56	(50 - 75)	TIER 0									
56 ≤ P < 75	(75 - 100)	TIER 0									
75 ≤ P < 130	(100 - 174)	TIER 0									
130 ≤ P < 225	(174 - 302)	TIER 0									
225 ≤ P < 450	(302 - 603)	TIER 0									
450 ≤ P < 560	(603 - 750)	TIER 0									
560 ≤ P < 900	(750 - 1206)	TIER 0									
> 900	(>1206)	TIER 0									

Table 2.2: Classification of tiers based on engine size and model year for tiers 1, 2, 3 and 4



2.4 Regulations and Standards for Emissions

EPA regulates the quantity of pollutants from diesel engines by introducing tiers system. Each tier has its own set of regulations. Tier 1-3 emissions standards are listed in Table 2.3. Tier 4 emissions were phased in from 2008 through 2015 and are listed in Table 2.4. The blank spaces in both the tables indicate the pollutants that are not regulated for that horsepower.

Table 2.3: EPA Tier 1-3 Nonroad Diesel Engine Emission Standards, g/kWh (g/bhp·hr) [DieselNet 2016]

Engine Power	Tier	Year	CO	HC	NMHC+NOx	NOx	PM
kW < 8 (hp < 11)	Tier 1	2000	8.0 (6.0)	-	10.5 (7.8)	-	1.0 (0.75)
	Tier 2	2005	8.0 (6.0)	-	7.5 (5.6)	-	0.8 (0.6)
8 ≤ kW < 19 (11 ≤ hp < 25)	Tier 1	2000	6.6 (4.9)	-	9.5 (7.1)	-	0.8 (0.6)
	Tier 2	2005	6.6 (4.9)	-	7.5 (5.6)	-	0.8 (0.6)
19≤ kW < 37 (25 ≤ hp < 50)	Tier 1	1999	5.5 (4.1)	-	9.5 (7.1)	-	0.8 (0.6)
	Tier 2	2004	5.5 (4.1)	-	7.5 (5.6)	-	0.6 (0.45)
37 ≤ kW < 75 (50 ≤ hp < 100)	Tier 1	1998	-	-	-	9.2 (6.9)	-
	Tier 2	2004	5.0 (3.7)	-	7.5 (5.6)	-	0.4 (0.3)
	Tier 3	2008	5.0 (3.7)	-	4.7 (3.5)	-	-†
75 ≤ kW < 130 (100 ≤ hp < 175)	Tier 1	1997	-	-	-	9.2 (6.9)	-
	Tier 2	2003	5.0 (3.7)	-	6.6 (4.9)	-	0.3 (0.22)
	Tier 3	2007	5.0 (3.7)	-	4.0 (3.0)	-	-†
130 ≤ kW < 225 (175 ≤ hp < 300)	Tier 1	1996	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
	Tier 2	2003	3.5 (2.6)	-	6.6 (4.9)	-	0.2 (0.15)
	Tier 3	2006	3.5 (2.6)	-	4.0 (3.0)	-	-†
225 ≤ kW < 450 (300 ≤ hp < 600)	Tier 1	1996	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
	Tier 2	2001	3.5 (2.6)	-	6.4 (4.8)	-	0.2 (0.15)
	Tier 3	2006	3.5 (2.6)	-	4.0 (3.0)	-	-†
450 ≤ kW < 560 (600 ≤ hp < 750)	Tier 1	1996	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
	Tier 2	2002	3.5 (2.6)	-	6.4 (4.8)	-	0.2 (0.15)
	Tier 3	2006	3.5 (2.6)	-	4.0 (3.0)	-	-†
kW ≥ 560 (hp ≥ 750)	Tier 1	2000	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
	Tier 2	2006	3.5 (2.6)	-	6.4 (4.8)	-	0.2 (0.15)

† Not adopted, engines must meet Tier 2 PM standard.

Table 2.4: Tier 4 Emission Standards—Engines up to 560 kW, g/kWh (g/bhp-hr) [UCAIR 2016]

Engine Power	Year	CO	NMHC	NMHC+NO_x	NO_x	PM
kW < 8 (hp < 11)	2008	8.0 (6.0)	-	7.5 (5.6)	-	0.4[a] (0.3)
8 ≤ kW < 19 (11 ≤ hp < 25)	2008	6.6 (4.9)	-	7.5 (5.6)	-	0.4 (0.3)
19 ≤ kW < 37 (25 ≤ hp < 50)	2008	5.5 (4.1)	-	7.5 (5.6)	-	0.3 (0.22)
	2013	5.5 (4.1)	-	4.7 (3.5)	-	0.03 (0.022)
37 ≤ kW < 56 (50 ≤ hp < 75)	2008	5.0 (3.7)	-	4.7 (3.5)	-	0.3[b] (0.22)
	2013	5.0 (3.7)	-	4.7 (3.5)	-	0.03 (0.022)
56 ≤ kW < 130 (75 ≤ hp < 175)	2012-2014[c]	5.0 (3.7)	0.19 (0.14)	-	0.40 (0.30)	0.02 (0.015)
130 ≤ kW ≤ 560 (175 ≤ hp ≤ 750)	2011-2014[d]	3.5 (2.6)	0.19 (0.14)	-	0.40 (0.30)	0.02 (0.015)

The Clean Air Act 1990 was required to set National Ambient Air Quality Standards (NAAQS). NAAQS was set by EPA for pollutants that are considered harmful to human health and the environment, and to regulate the quantity of criteria pollutants present in the environment. In Table 2.5 showing the NAAQS standards, primary standards provide limits human health protection, whereas secondary standards provide limits for the environment, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings.

Table 2.5: NAAQS for 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	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

2.7 Control measures

The adverse effects of diesel exhaust on human health and the environment were discussed in this chapter. The best alternative to avoid diesel exhaust is to not use diesel engines and switch to electric engines. On the other hand, the fuel used could be modified to Ultra Low Sulphur Diesel (ULSD) fuel or biodiesel [USDL 2017]. The use of ULSD is mandated in the US [CARB 2016] which greatly reduced the emission of sulphur dioxide, which is one of the criteria pollutants.

EPA research shows that biodiesel reduces most emissions. Pure biodiesel (B100) offers the greatest emission reduction benefit, but 20% blend of biodiesel (B20) also improved air quality substantially. The percentage reduction in emissions is shown in Table 2.6 below. From the table, it is observed that all the listed pollutants emissions are considerably reduced by blending petroleum diesel fuels with biodiesel. Pure diesel reduced emissions as high as 100% in case of sulfates, a blend of 20% reduced emissions up to 20% for sulfates.

Table 2.6: Biodiesel-diesel Emissions Comparison

	% Change from Regular Diesel	
	B20	**B100**
Particles (also called particulates)	-12%	-47%
Total Unburned Hydrocarbons	-20%	-67%
Carbon Monoxide	-12%	-48%
Nitrogen Oxides	+2% to +4%	+10%
Greenhouse Gases	-	-~80%
Sulfates	-20%*	-100%
Polycyclic Aromatic Hydrocarbons	-13%**	-80%

*Estimated from B100 result;

**Average reduction across all compounds measured

EPA offered the following strategies to control diesel exhaust from diesel vehicles, vessels, locomotives, and equipment [USDL 2017].

- Install diesel retrofit devices with verified technologies
- Maintain, repair, rebuild, and repower engines
- Replace older vehicles and equipment
- Improve operational strategies
- Use cleaner fuels including natural gas and propane

To reduce diesel exhaust from construction equipment and to minimize the health and climate impacts from diesel engine emissions associated with construction activities, Department of Environmental Quality (DEQ) of Oregon State recommends consideration of the Clean Diesel Construction Pilot Credit issued by the US Green Building Council for all construction projects. Each state has its own DEQ to monitor air quality. Oregon State has its DEQ with a mission to be a leader in maintaining and enhancing the air quality of Oregon's air and water [DEQ 2017].

California Air Resources Board (CARB) came up with a Diesel Risk Reduction Plan. When this plan was first implemented, 75% reduction in particle emissions from diesel equipment were expected by 2010 when compared to 2000 levels, and 85% reduction by 2020. The plan included the use of cleaner-burning diesel fuel, retrofitting of existing engines with particle-trapping filters, as well as the use of alternative fuels. The use of other fuels, such as natural gas, propane and electricity offer alternatives to diesel fuel. All of them produce fewer polluting emissions than current formulations of diesel fuel [CARB 2017].

The literature review clearly suggests the importance of study of emissions from nonroad equipment used on construction sites. The study is important because of the effects emissions have on human health. The idea is to calculate emissions from the equipment without real world measurements, or without using any measuring sensors.

3.0 Methodology

The following sections explain the steps involved in this study starting from selection of a project to data collection. The methodology section describes the selected project details, different construction activities observed, the equipment selected for this study, and the means and methods used to collect data. MOVES is introduced and a flowchart is shown to explain the steps involved in it.

3.1 Construction Project and Activities

The construction industry is divided into two sectors: non-residential and residential. Non-residential has three sub-sectors: heavy industrial, institutional and commercial [Careers in Construction 2017]. Each sector uses a variety of on-road and non-road construction equipment. The current study was conducted on a building project, which is in Corvallis. Corvallis is a city in central western Oregon with a population of 57,110 [Census 2017].

The construction project, Peavy Hall, is in the Western part of the city on the Oregon State University campus. The project involves the demolition and reconstruction of existing Peavy Hall building, serving as College of Forestry at Oregon State University. The old building was rigid frame construction and contained 84,000 square feet. The overall available area for new construction is 114,000 square feet. At 80,000 square feet, the three-story structure is being constructed for new Peavy Hall, which is slightly lesser than the old building. The rest of the available area is being used for the construction of Advanced Wood Products Laboratory [Gazette Times 2017]. Figure 3.1 shows the google image of the construction site of new Peavy Hall.

The owner, Oregon State University, contracted several firms and companies to complete different phases of the construction. Swift company was contracted as the landscape architects and KPFF was contracted as civil engineers for the construction. Michael Green Architect Inc. was contracted to design the new Peavy Hall in a more sophisticated way. All the three companies made sure the design is elegant and the area around the structure is spacious enough. Equilibrium consulting was hired to check the structural and safety standards of the design. Andersen Construction was hired as general contractor for this project, and is responsible for the actual construction phase of the building. They are also responsible to complete the project within the allotted time and budget.

The construction activities studied for this research are as follows:

- Excavation
- Concrete pouring for footings
- Concrete reinforcement
- Wall closure forms

Figure 3.1: Peavy Hall [Google 2017]

3.2 Construction Equipment

Data was collected for the construction activities selected for this study. Most extensively used non-road equipment during these activities were two excavators, one mobile crane, and one forklift. Other equipment was also used for dumping the excavated dirt, sprinkling water to settle down dust, and to grade the earth. These are used rarely and are eliminated from this study. However, focus is laid on the selected equipment because of their extensive use on ongoing activities during the data collection.

Both the excavators shown in Figures 3.2 and 3.3 were used in the excavation operations of the construction. The forklift shown in Figure 3.4 with an extending boom is used to move construction materials around the site, majorly used to move pre-built wall forms and reinforced steel bars. Figure 3.5 shows the mobile crane used for lifting and moving heavy objects.

Figure 3.2: Excavator 1 [Hitachi 2014]

Figure 3.3: Excavator 2 [Komatsu 2011]

Figure 3.4: Forklift [JCB 2017]

Figure 3.5: Mobile crane [Crane Network 2017]

The specifications for the selected equipment is shown in Table 3.1 below. The table shows the manufacturer, model year, horsepower of the engine, and tier.

Table 3.1: Equipment Specifications

Equipment type	Manufacturer	Model Year	Horsepower (HP)	Tier
Excavator 1	Hitachi	2014	54	3
Excavator 2	Komatsu	2011	244	3
Mobile crane	Grove	2007	469.4	2
Forklift	JCB	2015	109	3

3.3 Pollutants Studied

Out of all the pollutants discussed in the literature review, this study focused on those pollutants that are harmful for both environment and human health. In addition, these pollutants are produced in large numbers especially from non-road equipment. The pollutants studied for this research are listed below and short forms of the pollutants are used hereafter.

- Carbon Monoxide (CO)
- Nitrogen Oxides (NOx)
- Sulphur Oxides (SOx)
- Carbon Dioxide (CO_2)
- Particulate Matter 10 (PM_{10})

3.4 Data Collection

The data collection process included two different methods. The first one are manual observations on the construction site. The second one includes using the MOVES model developed by EPA. This section explains the two different methods and the various steps involved.

3.4.2 Data collected

Data from field was required, which was obtained by direct observation in the field. Information like schedule of the project showing activities durations, cost estimates were provided by the project manager from Andersen Construction. Details of the selected equipment like engine characteristics, and number of actual working hours of the equipment per day and idle hours per day were noted for 30 days either by direct observation on site or observation through Oregon State University webcams. Safety training was given before allowing the researcher inside the site. A meeting with the operators was set up to discuss the reasons for engine idling, to understand the working of the equipment, and to know about the fuel usage and the fuel used. In addition to this, data was needed for MOVES input that included year, month, geographic location, equipment type and fuel. After inputting the required data into MOVES and simulating the data, output was generated as emission rates in grams per horsepower-hour.

3.4.1 Introduction to MOVES

EPA's MOtor Vehicle Emission Simulator (MOVES) is a state-of-the-science emission modeling system that estimates emissions for mobile sources at the national, county, and project level for criteria air pollutants, greenhouse gases, and air toxics [EPA 2017b]. There are many versions of MOVES, but the latest version is MOVES 2014a. MOVES 2014a incorporates significant improvements in calculating onroad and nonroad equipment emissions, but does not change the criteria pollutant emission results of MOVES 2014.

A user guide and a reference manual are available to understand the input and output system in MOVES [EPA 2014]. There is also an option in MOVES to import, export, or convert data into the current software compatible data. For this research, MOVES was used to calculate emission rates for the selected equipment.

3.4.1.1 Source Classification Codes (SCC)

The U.S. EPA uses Source Classification Codes (SCCs) to classify different types of activities that generate emissions. Each SCC represents a unique source category-specific process or function that emits air pollutants [EPA 2017c]. The focus of this research is on non-road equipment, so focus is laid on non-road sources in the SCC table.

SCCs can be searched in EPA database using keyword, industry, or actual SCC number. SCC is an 8 or 10-digit number that is constructed using codes. SCC represents either the equipment or the process involved in emitting pollutants. The classification of the emission process becomes more specific starting from the left of the code and moving towards right. For example, SCC number for mobile crane is 2270002045. The breakdown structure of this code is 22-70-002-045. Level 1 is represented by 22 and represents Mobile Source, 70 is level 2 and represents Off-highway Diesel Vehicle, 002 is level 3 and represents Construction and Mining Equipment, and 045 is level 4 and represents Cranes. Likewise, the SCC numbers for the equipment used for this study are: 2270002036 for excavators, and 2270002057 for forklifts.

The importance of using SCC numbers is to identify the type of equipment based on the number. Each equipment has a unique SCC, which makes it easier to decode it back to the equipment type. Moreover, while using MOVES, there is no option to select the non-road equipment type directly. SCC numbers must be used to estimate specific emission rates of each type of equipment.

3.4.1.2 Pollutant ID

The output generated from MOVES contains pollutants as numbers instead of their names. Using MySQL, the pollutant IDs are decoded back to the actual names of the pollutants. The pollutant IDs for the pollutants selected for this study are shown in Table 3 below.

Table 3.2: Pollutant IDs

Pollutant Name	Pollutant ID
Carbon Monoxide	2
Nitrogen Oxides	3
Carbon Dioxide	90
Particulate Matter 10	100
Sulphur Oxides	31

3.4.3 Working of MOVES

Elements such as fuel type, month, year, and equipment type were inputted into the MOVES software that gives out emission rates for the selected equipment type. The total number of hours the equipment was used on site could be directly measured or could be obtained from contractor's previous records. For this study, the project selected was currently active, so the hours were measured through observation.

The step by step procedure involved in simulating MOVES is explained below. There are 11 steps before simulating the results. Before starting any step, a runspec must be created. A runspec was needed to store the input before executing it. This allows the data manager to filter the default database for relevant information [MOVES User Guide 2014]. After creating runspec, a Navigation Panel with 11 steps appears on the left side of the screen. Pictorial representation of these steps is shown in Appendix A.

Step 1-Description: Briefly explain the purpose of the simulation.

Step 2-Scale: This step was to select the model, on-road or non-road. After selecting non-road, scale of the project was selected as National level by default. The calculation type was also selected as inventory by default. The other option for calculation type was emission rates, which is required for this study. But MOVES don't have an option to select emission rates calculation type for non-road. Instead, MySQL was used to generate bundle of tables in emission rates format.

Step 3-Time Span: There were five sections after clicking time spans: Time aggregation level, Years, Months, Days, and Hours. Time aggregation level was set to Day by default thus disabling the Hours section. Under Years section, 2017 was selected. As this study took place from July and August, these two were selected under Months section. And for Days section, only weekdays was selected because there wasn't any work going on for this project in weekends.

Step 4-Geographic Bounds: Under this step, after selecting the County button, Oregon was selected from States section, and then Benton County was selected from Counties section. Multiple counties can be selected at once. However, this was not recommended as it increases the output size.

<u>Step 5-Vehicles/Equipment</u>: Non-road equipment was selected as default because on-road was not selected from the beginning of the runspec. Under non-road equipment, fuel and sector combinations were selected. For this study, Non-road diesel fuel plus Construction was selected.

<u>Step 6-Road Type</u>: Click road type, and the selection of Non-road was already made.

<u>Step 7-Pollutants and Processes</u>: Large number of pollutants and processes were available for the selection. The pollutants selected were the five presented above as the focus of this research.

<u>Step 8-Manage Input Data Sets</u>: This step has to be skipped if there was no outside data to import.

<u>Step 9-Strategies</u>: The only strategy available was Rate of Progress. These calculations were not relevant to non-road equipment.

<u>Step 10-Output</u>: Click General output. There were two sections under General Output: Output Database and Units. Under Output Database, a database was to be created ending with "_out". Under Units, gram was selected for Mass units, Kilojoule was selected for Energy units, and Mile was selected for Distance units.

Click Output Emission Detail. A variety of options were available in this section for selection. 24-Hour day, County, SCC, Model year, and Fuel type were selected. Check Appendix B for a detailed understanding of this section. Snapshots from MOVES were attached to show each and every step.

<u>Step 11-Advanced Performance Features</u>: This was an optional step. This section was for advanced users and troubleshooting only. This step was not completed for this study.

After completing all the steps, green checks appeared on the left side of the navigation panel. Green indicates that the runspec was ready for the execution. Click Action on the top menu bar and click run. It takes several minutes for MOVES to run this. A bundle of tables was generated and were stored in the database created in Step 10. After executing the runspec, click Post Processing on the menu bar and click ‘Run MySQL Script on Nonroad Output Database’. The files can be opened in MySQL workbench and can be processed.

3.4.5 Structured Query Language (SQL)

SQL is used for post processing of obtained MOVES output. Output tables can be generated and accessed using SQL. The tables can then be exported to excel [MySQL 2017]. Graphs are generated using excel. The commands used in MySQL are shown in Appendix D.

4.0 Results and Analysis

This section presents the emissions for the entire project as well as for each equipment and each day for each pollutant. The data required for this study was collected from a building project for a period of 30 days. These 30 days includes only weekdays from July 15, 2017 to August 31, 2017. Weekends were not included because no work was done. Number of working hours of each equipment for all the 30 days were collected either by direct observation on site or from the webcams videos provided by Oregon State University. Figure 4.1 shows a snapshot of construction site from Oregon State University webcam. The data collected from the construction site including number of hours of each equipment is tabulated in Appendix C. Horsepower of the engine and the model year for all the equipment were obtained from their respective manuals.

Figure 4.1: Snapshot of Construction Site from OSU Webcam [Webcam OSU 2017]

The MOVES input consists of MOVES run ID, year ID representing the year the emission rates are estimated, month ID, state ID, geographic location in the selected state, fuel type ID, pollutant ID, and output consists of emission rates and SCC numbers. For this study, the year ID was 2017 and the month IDs were July and August because the project was active and data was collected in these months. State ID and County ID represents Oregon State and Benton County respectively. Fuel used was same for all the equipment, which is diesel. Pollutant IDs were demonstrated in the methodology section.

The input required for MOVES were entered and simulation was done as explained in the Methodology section. After the execution of the program, the output was stored in the selected database. Post processing of scripts was done using MySQL workbench. The commands used for MySQL to obtain emission rate tables are shown in Appendix D. The emission rates obtained from MySQL were in grams per horsepower-hour and are shown in Table 4.1.

Table 4.1: MOVES Output Showing Emission Rates of the Pollutants

Year ID	SCC	Emission Rate (g/hp-hr)				
		CO	NO_x	SO_X	PM_{10}	CO_2
2017	2270002045	0.563676947	2.116220978	0.003054117	0.099639936	532.7924112
2017	2270002036 (1)	0.543028167	1.363538079	0.002878664	0.092118641	541.4673757
2017	2270002036 (2)	0.543028167	1.363538079	0.002878664	0.092118641	541.4673757
2017	2270002057	1.536110474	2.34269461	0.003290069	0.226217933	569.0104064

Table 4.1 shows the output from MOVES that includes SCC numbers, pollutants and their emission rates. Both the excavators bear the same SCC number, hence the emission rates for excavator 1 and excavator 2 were same. Any immediate conclusions cannot be drawn using these

numbers regarding this project, as the emission rates were not adjusted to the characteristics of equipment and the project.

To understand the output generated from MOVES, a graph was plotted using Table 4.1 for emission rates per each equipment as shown in Figure 4.2. All the pollutants were plotted except for CO_2 because of its high magnitude in the values of emission rates when compared to other pollutants. SO_2 is hardly seen on the chart because of its low magnitudes for each equipment. From the graph, forklift has the highest emission rates among all the equipment with NO_x being the highest emission rate pollutant after CO_2.

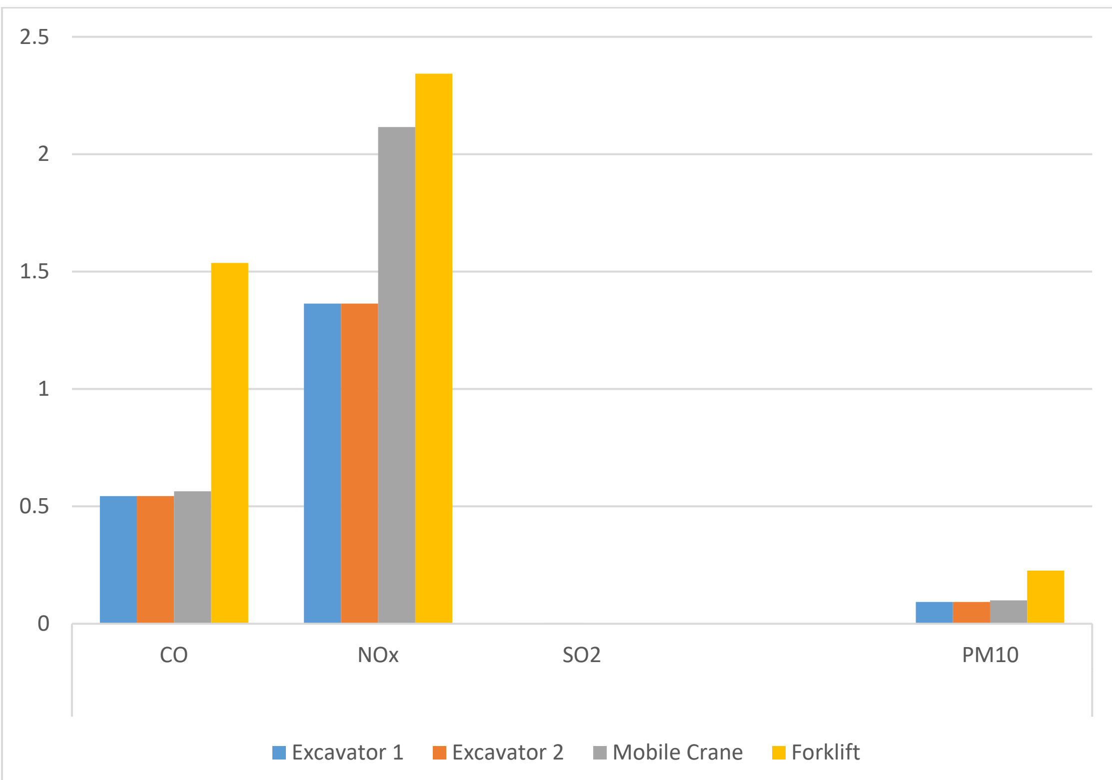


Figure 4.2: Emission Rates obtained from MOVES in grams/hp-hr

A graph was separately plotted to show CO_2 emission rates for all the equipment and was shown in Figure 4.3. Figure 4.3 shows that forklift had the highest CO_2 emission rate compared to other equipment.

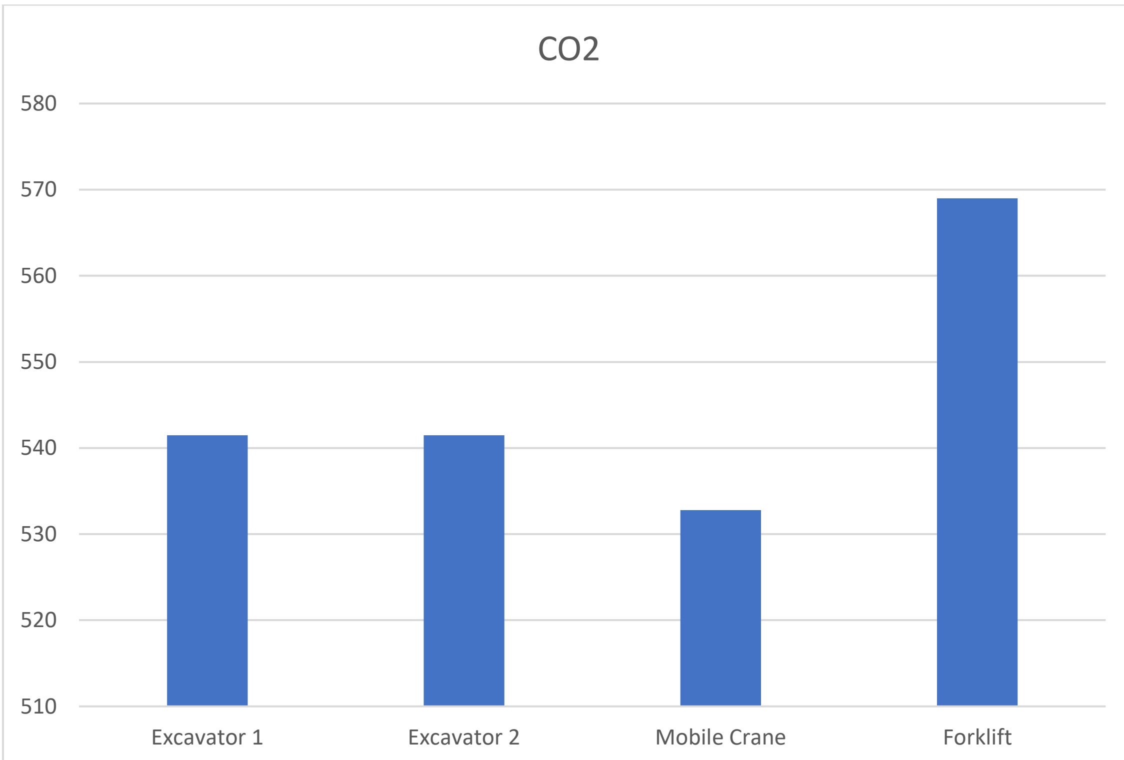


Figure 4.3: Emission Rates of CO_2

The numbers presented on Table 4.1 where adjusted using specific equipment characteristics for horsepower and using actual hours of use to determine the total quantity of emissions produced by each item of equipment.

4.1.1 Emissions per day

The data collected from the construction site and the emission rates obtained from MOVES are used together for the analysis. Horsepower (HP) of each equipment was used to calculate the emissions in grams per hour. These emissions were obtained by multiplying horsepower of each equipment by the emission rates presented in Table 4.1. Table 4.2 shows these calculated emissions with the respective horsepower.

Emission per day were calculated by multiplying number of working hours of each equipment per day with the emissions obtained from Table 4.2. Figure 4.4 shows a flowchart of the methodology used to calculate the total emissions per day. Table 4.3 presents the total emission quantities per day for all the pollutants separately. All the numbers were rounded to two significant digits for easy understanding. August 29, 2017 was selected to represent the total emissions per day because out of all the days, this day showed the highest total emissions of 2,818,439 grams. This number includes the emissions of each equipment and each pollutant. It represents the total emissions quantity from the project for that day.

Table 4.2: Emissions Shown in Grams per Hour

HP	Equipment	Emissions (g/hr)				
		CO	NO_x	SO_X	PM_{10}	CO_2
469.4	Mobile Crane	264.58	993.35	1.43	46.77	250,092.75
54	Excavator (1)	29.32	73.63	0.15	4.97	29,239.23
244	Excavator (2)	132.49	332.70	0.70	22.47	132,118.03
109	Forklift	167.43	255.35	0.35	24.65	62,022.13

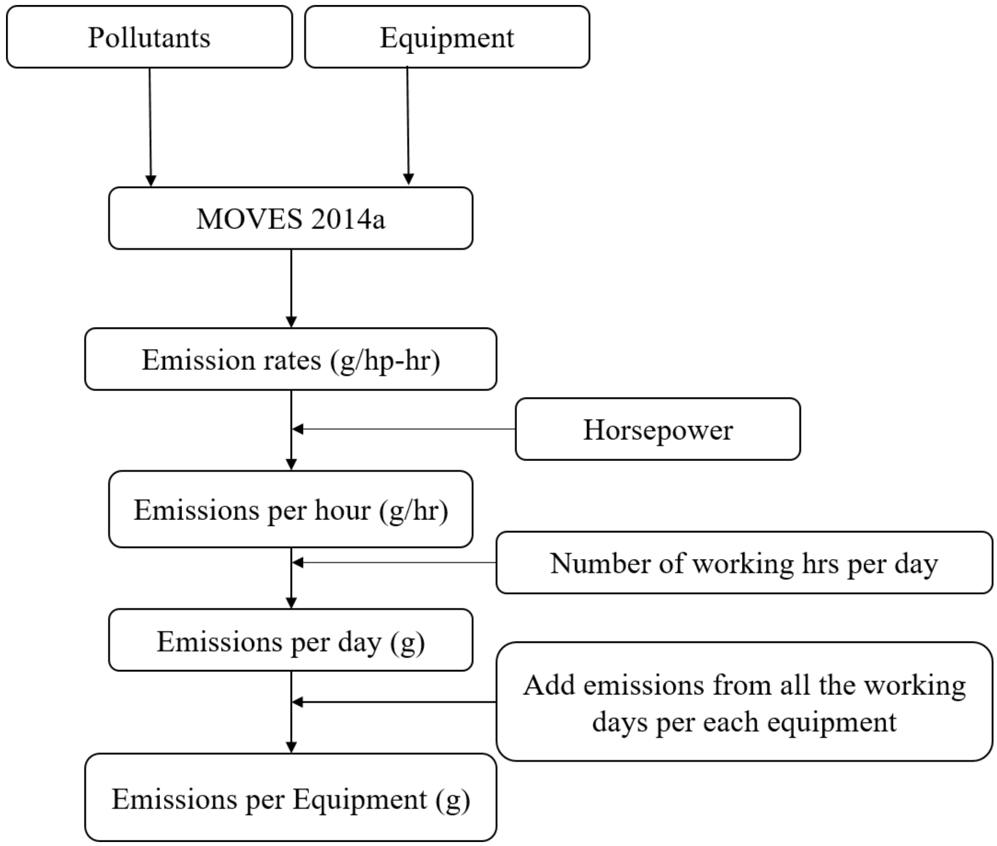


Figure 4.4: Flowchart showing the Methodology to Calculate Total Emission Quantities

Table 4.3: Total Emissions for August 29, 2017 in Grams

Hours	Equipment	Total Emissions (grams)				
		CO	NO_x	SO_X	PM_{10}	CO_2
7	Mobile Crane	**1,852.12**	**6,953.47**	**10.03**	**327.39**	**1,750,649.30**
3.5	Excavator (1)	102.63	257.70	0.54	17.41	102,337.33
4.5	Excavator (2)	596.24	1,497.16	3.16	101.14	594,531.17
5.75	Forklift	962.75	1,468.28	2.06	141.78	356,627.27

Multiplying horsepower to the emission rates changed the conclusions drawn from Figure 4.2 and Figure 4.3. Initially forklift had the highest emission rates among all the four equipment. From Table 4.3, the numbers highlighted in red indicates the highest total emission quantities of pollutants CO_2 and NO_x and are produced by mobile crane. In fact, mobile cranes produced highest total emissions in case of all the pollutants.

4.1.2 Emissions per Equipment

The total emissions per equipment were calculated by adding up the emissions for each equipment and for each pollutant for all the 30 days. Table 4.4 and Table 4.5 shows the total emissions per equipment for the months of July and August respectively. These tables were used for the analysis of emissions in the following section. Two separate tables were shown for July and August because data collection started mid-July and went on until the end of August which resulted in different number of working days for July and August. There were 10 working days in July and 20 working days in August.

Table 4.3 is an example of total emissions per day for August 29, 2017 for each equipment and each pollutant. The total emissions for all the 30 days is used to calculate total emissions per each equipment. Figure 4.5 and Figure 4.6 shows total emissions per equipment for the months of July and August respectively. These bar charts were plotted using the data presented in Table 4.4 for July and Table 4.5 for August. The reason behind plotting two separate graphs for both the months was they have different number of working days. The magnitudes of total emissions were different for both the months and it is difficult to represent emissions for two months on a single graph.

Table 4.4: Total Emissions per Equipment for July

Year ID	Equipment	Total Emissions (grams)				
		CO	NO_x	SO_X	PM_{10}	CO_2
2017	Mobile Crane	13,864.51	52,051.75	75.12	2,450.79	13,104,860.51
2017	Excavator (1)	1,052.71	2,643.35	5.58	178.58	1,049,688.65
2017	Excavator (2)	4,638.78	11,647.94	24.59	786.91	4,625,452.56
2017	Forklift	7,214.81	11,003.19	15.45	1,062.50	2,672,533.76

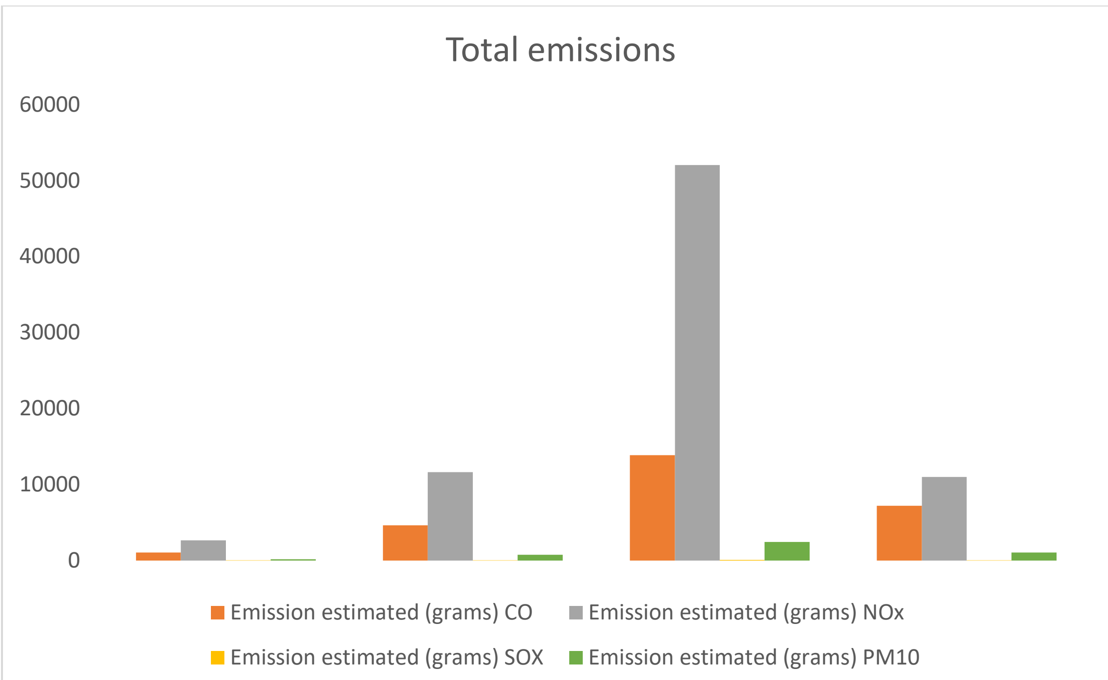


Figure 4.5: Total Emission Quantities per Equipment for July

From Table 4.4 and Figure 4.5, NO_x was produced in fairly large quantities in this project. Total emissions for all the pollutant were highest for mobile cranes followed by forklift. Initially forklift had the highest emission rates. The shift of mobile crane to the top indicates that the activities occurring during the data collection extensively used mobile cranes. In addition to that, it is important to lay focus on controlling other pollutants along with CO_2. Few strategies to control the second highest emitted pollutant NO_x are discussed in the following section.

Table 4.5: Total Emissions per Equipment for August

Year ID	Equipment	Total Emissions (grams)				
		CO	NO_x	SO_X	PM_{10}	CO_2
2017	Mobile Crane	34,462.84	129,384.37	186.72	6,091.92	32,574,581.71
2017	Excavator (1)	1,114.29	2,797.98	5.90	189.027	1,111,091.05
2017	Excavator (2)	4,206.83	10,563.32	22.30	713.64	4,194,747.76
2017	Forklift	13,227.44	20,172.94	28.33	1,947.96	4,899,748.61

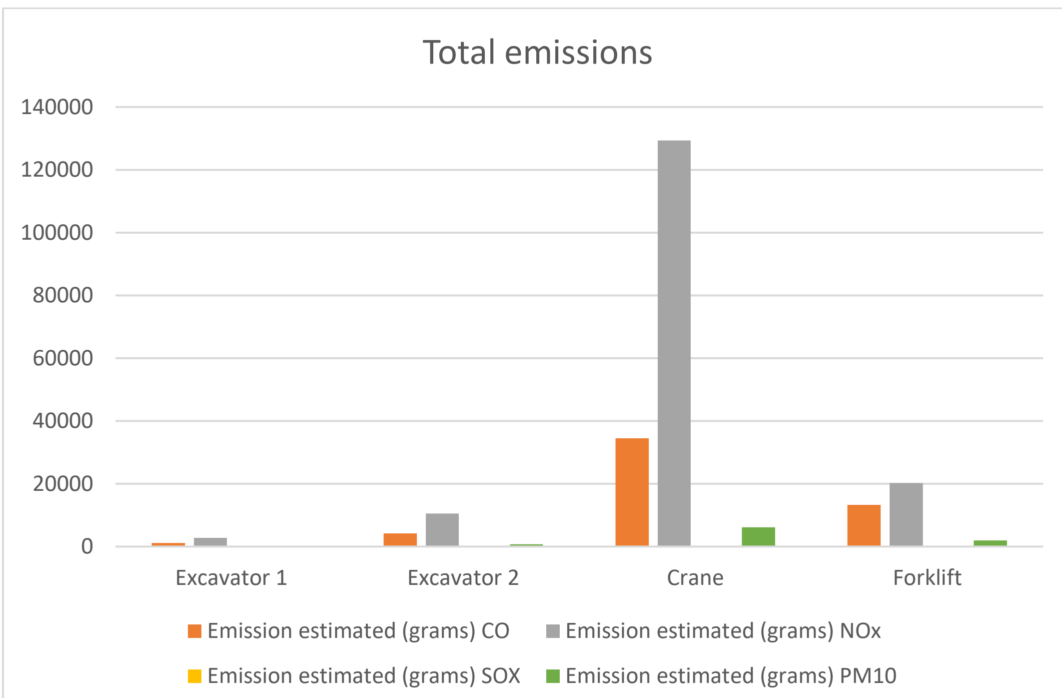


Figure 4.6: Emission quantities per equipment for August

Both July and August show the same results in terms of highest emitted pollutant and equipment. Figures 4.5 and 4.6 looks similar with a different magnitude. This indicates the same activities occurred during these two months with usage of equipment.

However, CO_2 was not plotted in these two charts because of its high magnitude of values for total emissions. Figure 4.7 shows the graph for total emissions of CO_2 for the months of July and August.

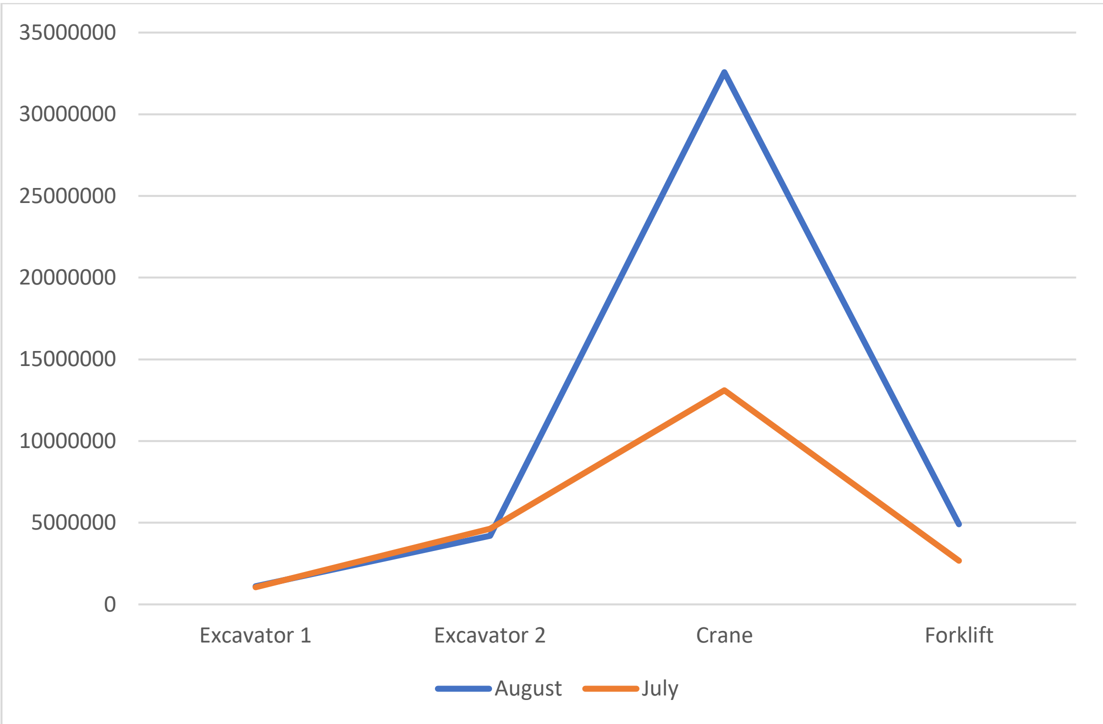


Figure 4.7: Total emissions of CO_2

The line graph in Figure 4.7 for both the months bear same shape but with different magnitudes. The difference in magnitude was due to the difference in number of days the data collected in two months. The graph shows that crane produced highest emissions in both the months.

A cumulative line graph was plotted for CO_2 represented in Figure 4.7. The emission rates started in a slow pace and escalated in the middle of the project and towards the end. The cumulative graphs for other pollutants are similar for all the four equipment.

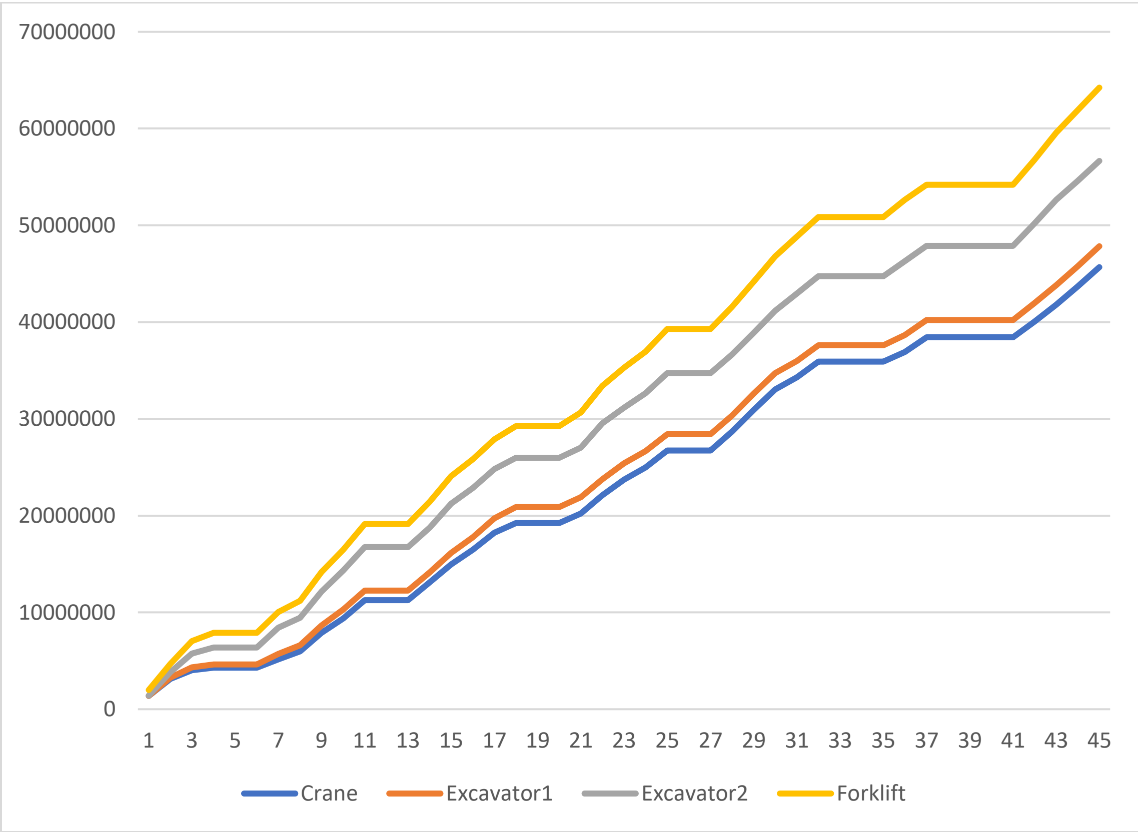


Figure 4.8: Cumulative emissions for CO_2

5.0 Conclusions and Recommendations

Based on the analysis from the previous section, following conclusions are made about the equipment, the pollutants and their emissions, and the project.

5.1 Conclusions

The first step of this study was to collect required data from a building construction site. Focus is laid on the active equipment on site. The model number and the year of manufacture of each equipment were obtained from the Project Manager. The engine specifications were looked for in the respective manuals. The number of hours each equipment worked per day was collected either by direct observation or from OSU webcams.

The second objective of this study, Methodology to use MOVES was clearly explained, making it easy for the future researchers in the understanding of its user interface, especially for non-road equipment. Methodology section stated step by step procedure to estimate emission rates from each equipment for all the selected pollutants. Though the emission rates were estimated from MOVES for this study, it was difficult to extract data directly. SQL was used to process the post processing output from MOVES. There is a huge scope for the development of MOVES which is discussed in the following section.

The third objective states that using information from the first and second objectives, total emission quantities per day and total emission quantities per equipment were calculated. The following conclusions could be drawn for the third part of this study.

- CO_2 was produced in large quantities compared to other pollutants. Keeping in mind the ill effects of CO_2, measures should be taken to keep its levels in the safe limit. The high levels of CO_2 were expected based on the previous studies. But, NO_x emission quantities were surprisingly high. The adverse effects of NO_x were discussed in the literature review and it is important to track NO_x emissions and take proper measures to keep it in safe limits.
- From Figure 4.2, forklift emitted all the pollutants in large quantities when compared to other equipment. After calculating total emissions from the project for 30 days, Figure 4.6 clearly indicates that mobile crane emitted pollutants in large quantities out of all the four equipment. The reason behind this change could be different total number of working hours of each equipment and different horsepower of their engines. Therefore, the emission rates obtained from MOVES doesn't give a clear picture of emissions pattern for a project. Conclusions cannot be drawn from MOVES output alone. The total emission quantities depend on the nature of the project, characteristics of the engine, and usage of individual equipment per day or per project.
- Figures 4.4 and 4.5 were the total emissions quantities plotted for the months of July and August. Both the graphs bear the same shape despite the difference in the magnitudes of the pollutants emissions. The graph clearly concludes that the activities the equipment were working on, were same throughout 35 days, which is true.
- A cumulative line graph is plotted for total CO_2 emissions which is shown in Figure 4.7. All the equipment followed same trend of emitting pollutants throughout the project. It is clearly seen that the production of emissions is less in the beginning of the project and escalated in the middle of the project and continued the same till the end.

5.2 Recommendations

This section states recommendations for each objective of this study. Few strategies are suggested for the improvement of steps involved in each objective.

5.2.1 Suggestions for the improvement of MOVES

Few strategies are proposed in this section to support future research on emissions measurement from the non-road equipment. Improvement is required in several steps of the MOVES. It will be useful if the equipment names are incorporated in addition to SCC numbers. Fuel usage is not considered in this study. MOVES have an option to change the fuel type and check the change in emission quantities. This might be a useful study to focus on in the future. Idle time of the equipment plays a major role in the change of the emission quantities measured. Idle time must be considered while estimating emissions. There should be an input variable in MOVES for idle time too.

5.2.2 Emissions reduction strategies

5.2.2.1 Change in fuel used

As mentioned above, fuel used can be changed in the MOVES input to compare emission rates for different fuel types. This helps contractors save time on experimenting different types of fuel to reduce emissions from the equipment. There are many alternate fuels suggested by researchers that are known to reduce emissions. One among such fuels is Biodiesel. Biodiesel can either be used as pure 100% fuel, or it can be used in 10% or 20% blend with regular fuel. While 100% biodiesel has more benefits, it is costly. Therefore, blends of biodiesel with regular fuels are tested to study the difference in emissions and researchers found a considerable decrease in emissions from the equipment.

5.2.2.2 Change in the equipment used

From results, it is concluded that forklift produced highest total emissions. One of the ways to control the usage of this equipment and thereby control emissions from this equipment is to look up for such equipment on RS Means or CAT manuals which satisfies all the functions of the forklift but produces lesser emissions. For example, there is a mobile crane on the project site and crane serves the purpose of moving the heavy material same as forklift. Based on feasibility and project site conditions, forklift and mobile crane usage can be balanced in terms of emissions.

5.2.2.3 Controlling NO_x emissions

Diesel Forum (2017) developed a strategy called clean diesel. A part of this technology is to control NO_x emissions from diesel exhaust. Selective Catalytic Reduction (SCR) is a process developed to control emissions from diesel engines. Figure 5.1 is a schematic representation of how SCR works. Nearly zero NO_x emissions can be achieved using this technique.

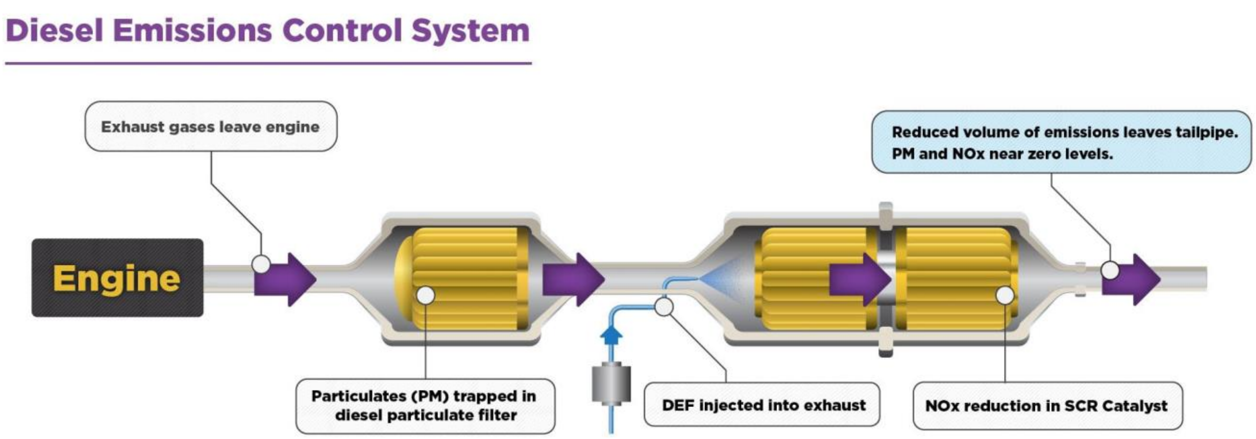


Figure 5.1: Diesel Emissions Control System [Diesel Forum 2017]

5.2.3 Future work

One major issue that is being studied from past several years is reduction of CO_2 emissions from diesel exhaust. Several means and methods are proposed to reduce CO_2 emissions but the problem doesn't seem to be controlled so far. With the growing population of construction equipment fleet, emissions are increasing equally. There is a lot of scope to work on the reduction of CO_2 emissions. MOVES can be used to simulate emission rates under different conditions like: change in fuel, change in model year and change in the equipment type. This helps researchers study the nature of the emissions without real world measurements of the emissions.

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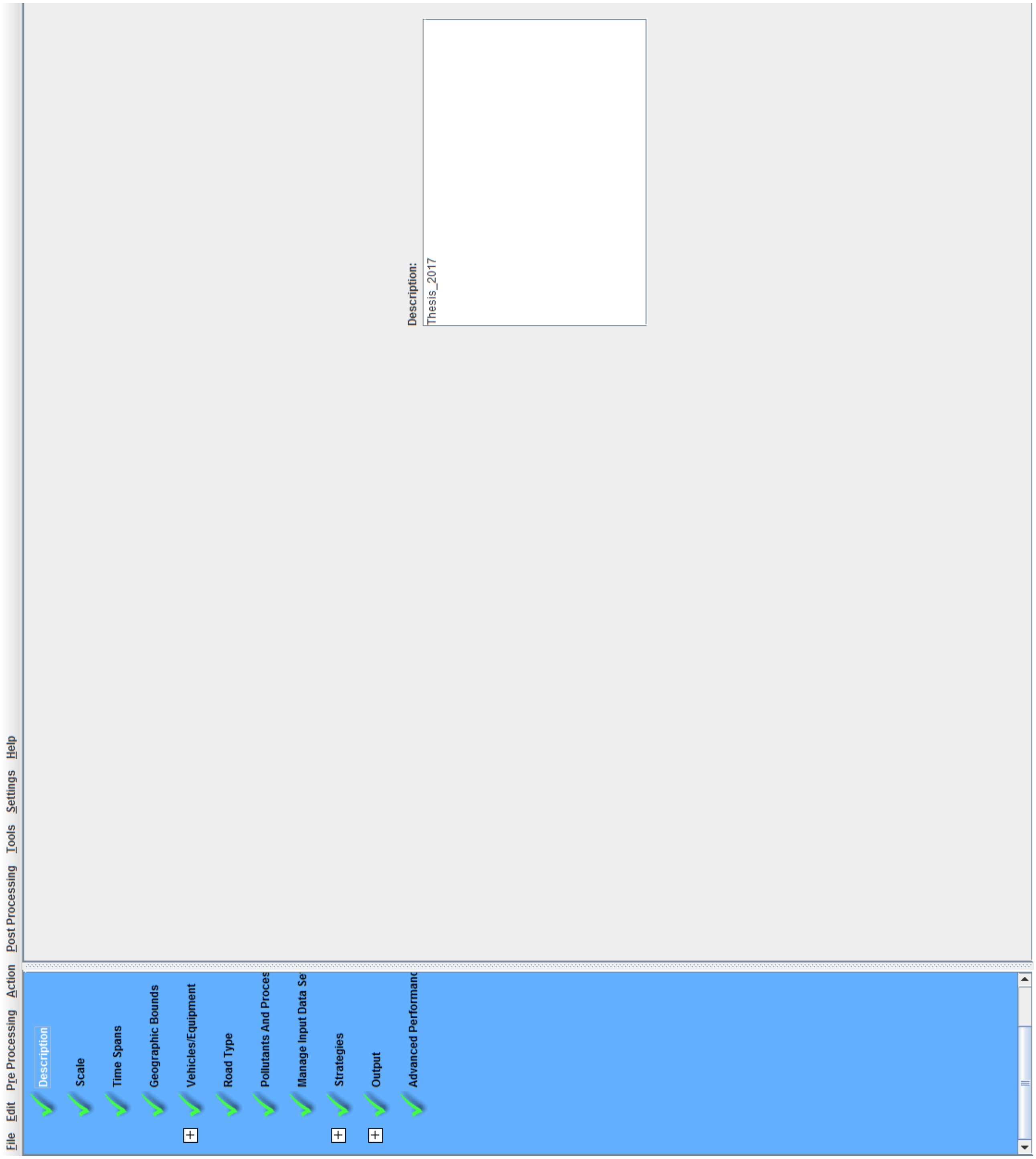
Appendix

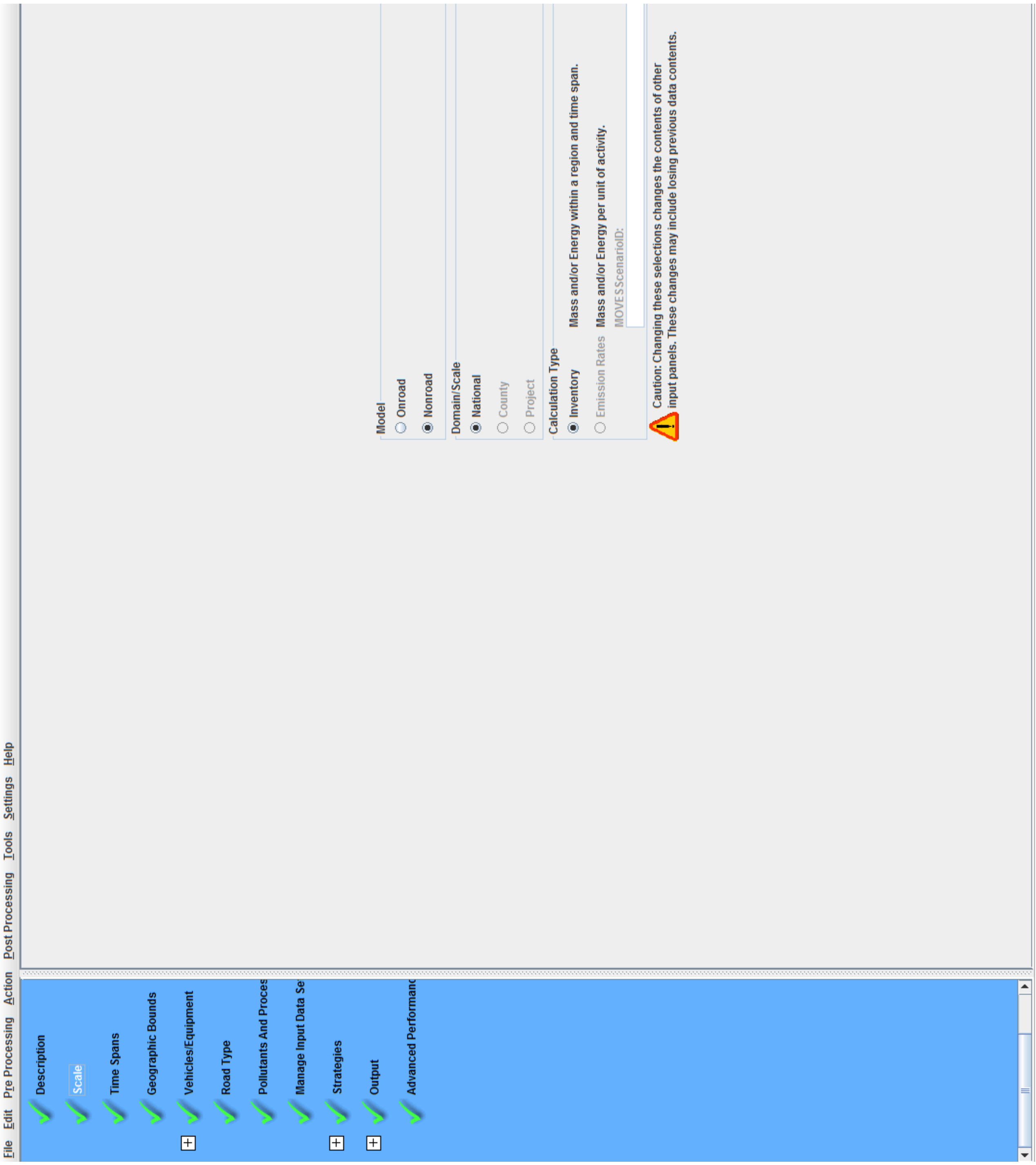
A. Emissions of eight pollutants for different industry sectors in Oregon for the year 2014

Major Source Sectors	Detailed Category Names
Agriculture	Crops & Livestock Dust
	Fertilizer Application
	Livestock
Dust	Construction Dust
	Paved Road Dust
	Unpaved Road Dust
Fires	Agricultural Field Burning
	Prescribed Fires
	Wildfires
Fuel Combustion	Comm/Institutional - Biomass
	Comm/Institutional - Coal
	Comm/Institutional - Natural Gas
	Comm/Institutional - Oil
	Comm/Institutional - Other
	Electric Generation - Biomass
	Electric Generation - Coal
	Electric Generation - Natural Gas
	Electric Generation - Oil
	Electric Generation - Other
	Industrial Boilers, ICEs - Biomass
	Industrial Boilers, ICEs - Coal
	Industrial Boilers, ICEs - Natural Gas
	Industrial Boilers, ICEs - Oil
	Industrial Boilers, ICEs - Other
	Residential - Natural Gas
	Residential - Oil
	Residential - Other
	Residential - Wood
Industrial Processes	Cement Manufacturing
	Chemical Manufacturing
	Ferrous Metals
	Mining
	NEC
	Non-ferrous Metals

	Oil & Gas Production
	Petroleum Refineries
	Pulp & Paper
	Storage and Transfer
Miscellaneous	Bulk Gasoline Terminals
	Commercial Cooking
	Gas Stations
	Miscellaneous Non-Industrial NEC
	Waste Disposal
Mobile	Aircraft
	Commercial Marine Vessels
	Locomotives
	Non-Road Equipment - Diesel
	Non-Road Equipment - Gasoline
	Non-Road Equipment - Other
	On-Road Diesel Heavy Duty Vehicles
	On-Road Diesel Light Duty Vehicles
	On-Road Gasoline Heavy Duty Vehicles
	On-Road Gasoline Light Duty Vehicles
Solvent	Consumer & Commercial Solvent Use
	Degreasing
	Dry Cleaning
	Graphic arts
	Industrial Surface Coating & Solvent Use
	Non-Industrial Surface Coating

B. MOVES graphical representation

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Nonroad
Domain/Scale
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County
Project
Calculation Type
Inventory
Mass and/or Energy within a region and time span.
Emission Rates
Mass and/or Energy per unit of activity.
MOVES ScenarioID:
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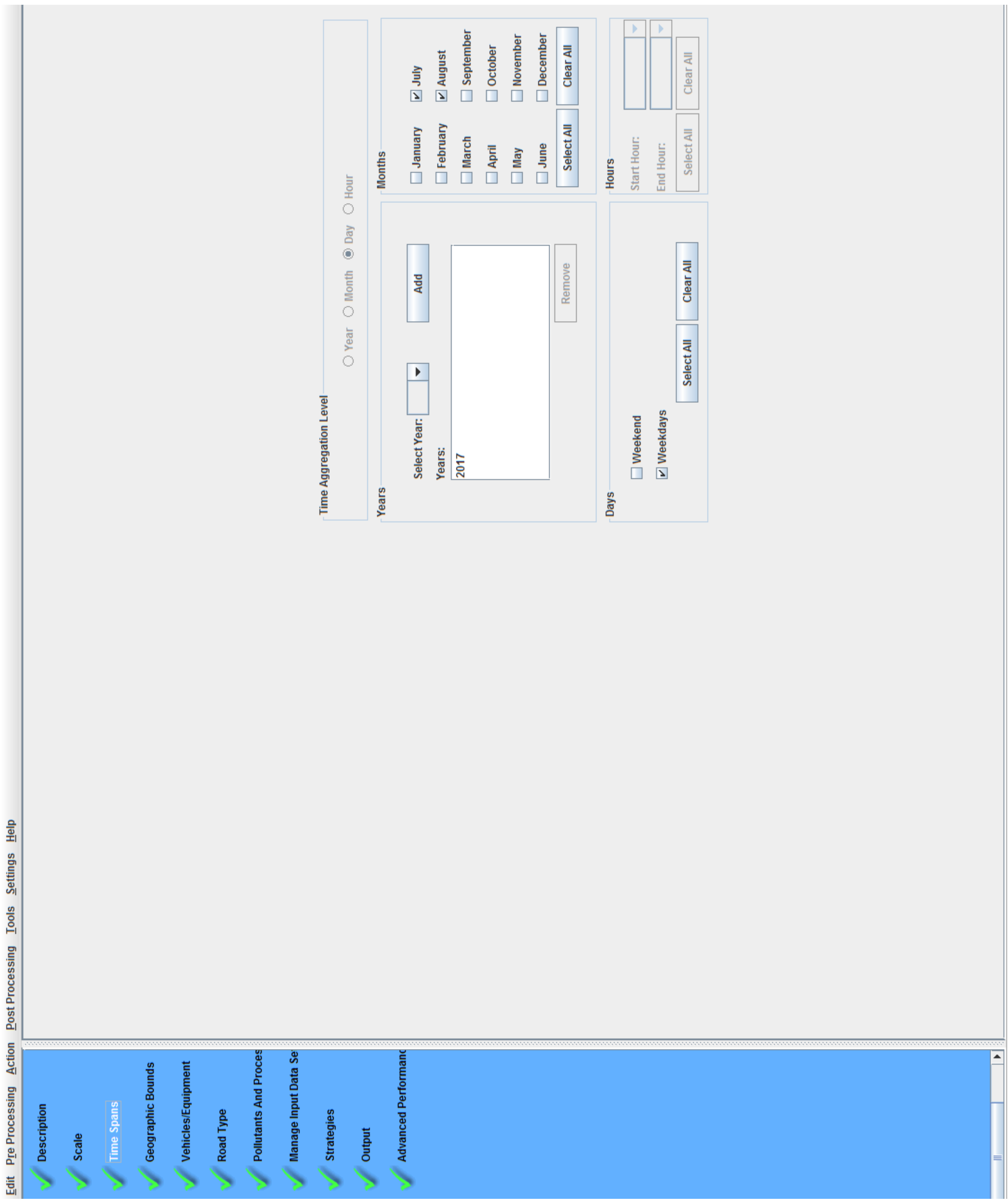
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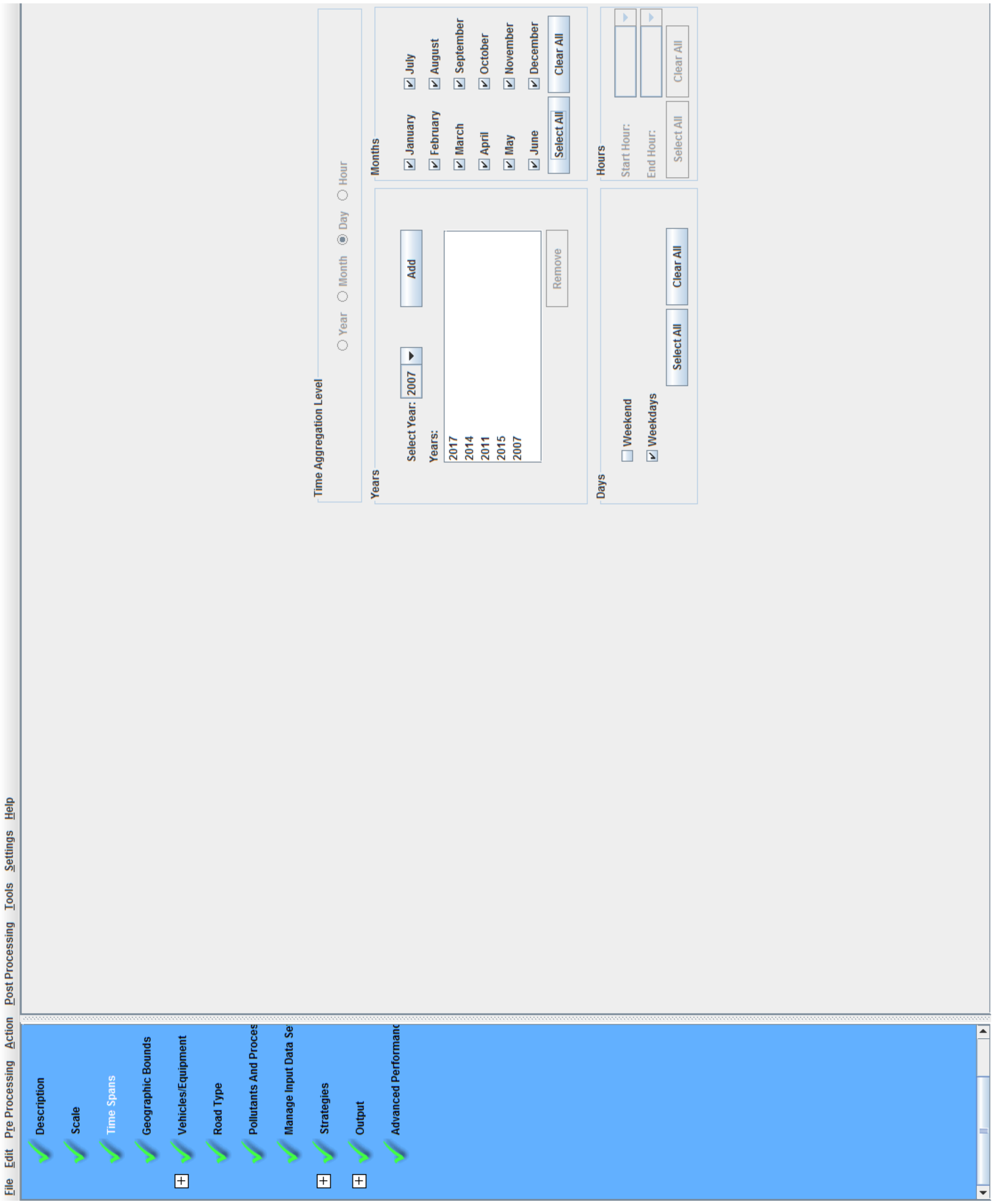
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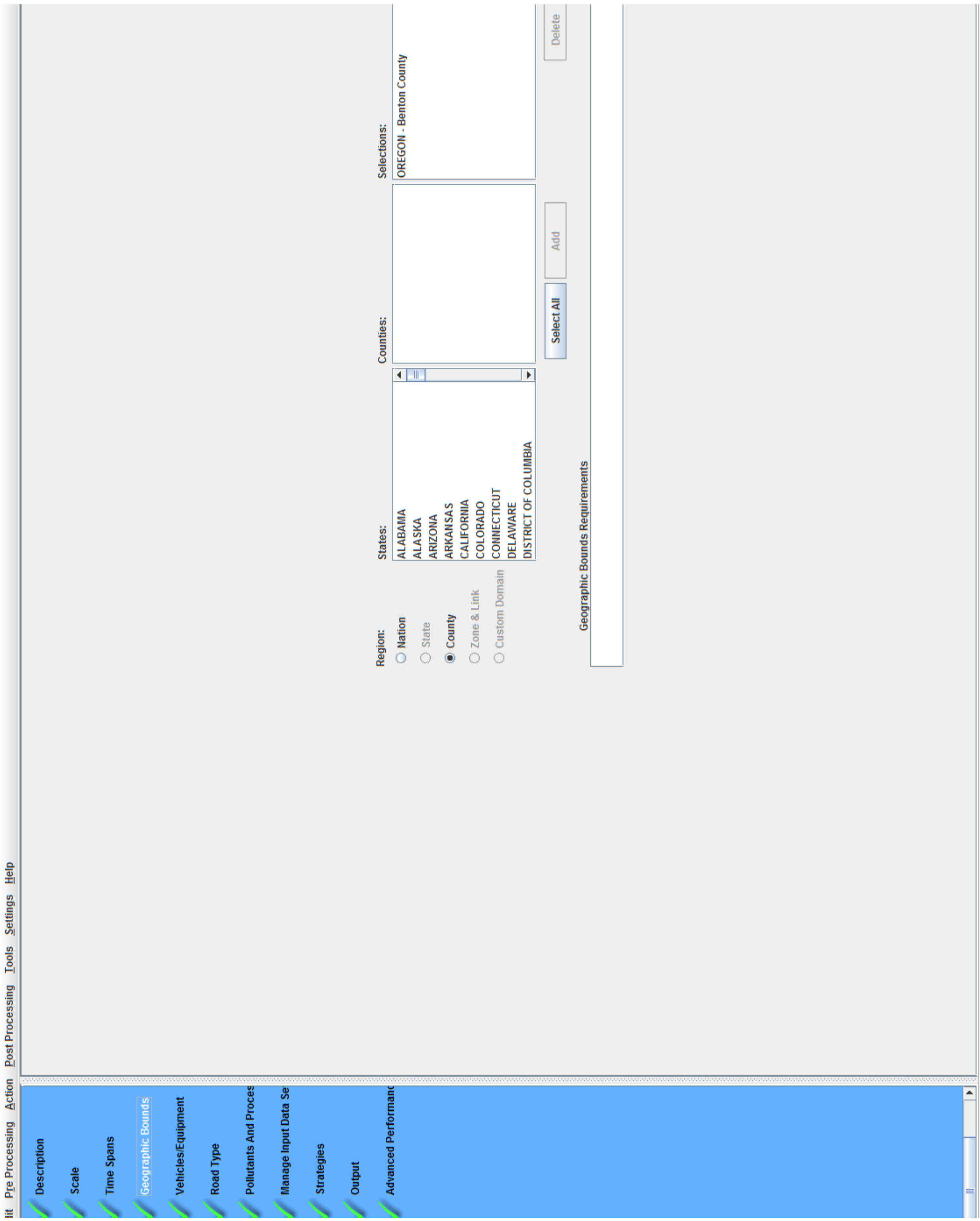
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ALASKA
ARIZONA
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CALIFORNIA
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DISTRICT OF COLUMBIA
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OREGON - Benton County
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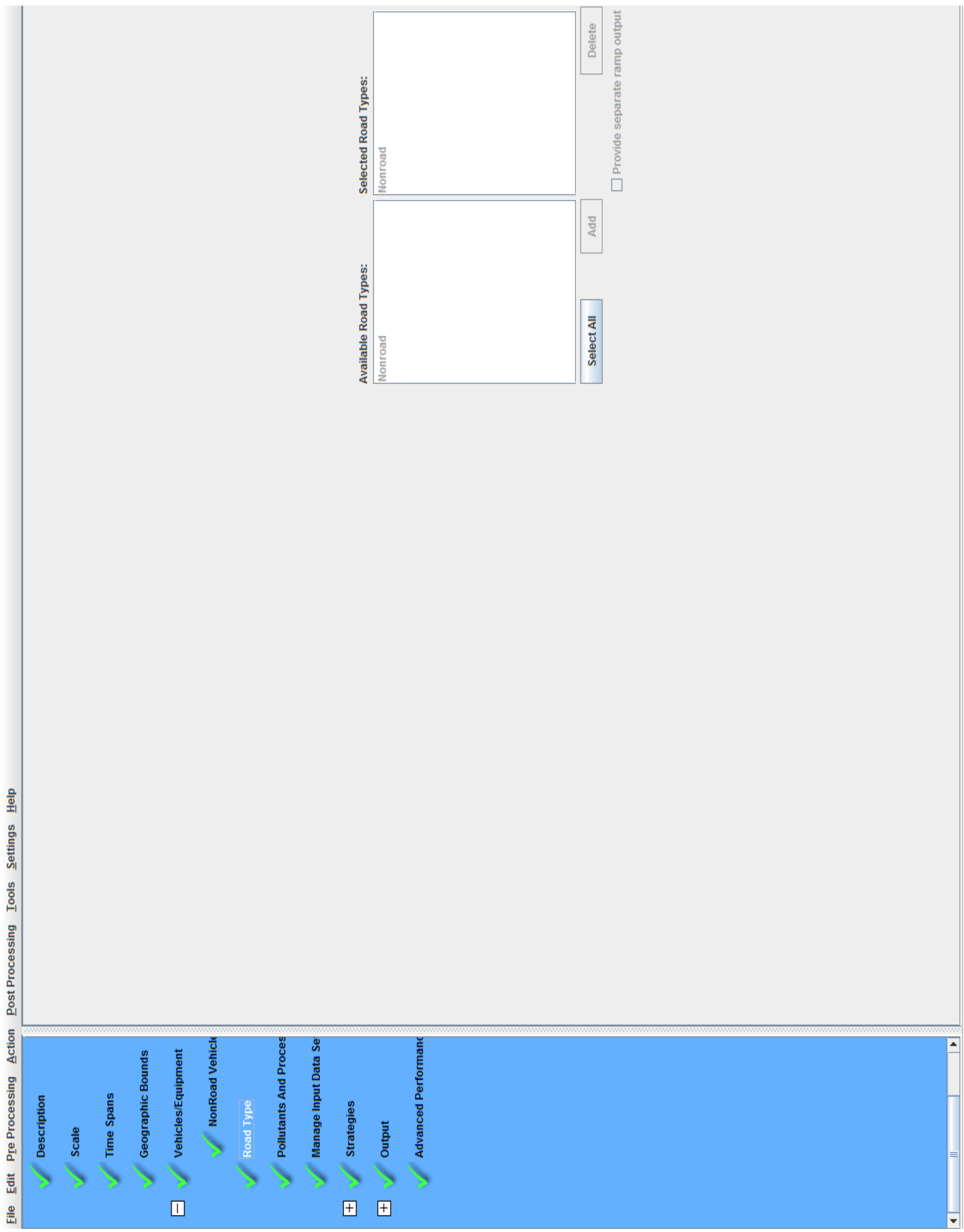
Fuels:
Compressed Natural Gas (CNG)
Gasoline
Liquefied Petroleum Gas (LPG)
Marine Diesel Fuel
Nonroad Diesel Fuel
Sectors:
Agriculture
Airport Support
Commercial
Construction
Industrial
Lawn/Garden
Logging
Oil Field
Pleasure Craft
Railroad
Recreational
Underground Mining
Selections:
Nonroad Diesel Fuel - Construction
Select All
Select All
Add Fuel/Sector Combinations



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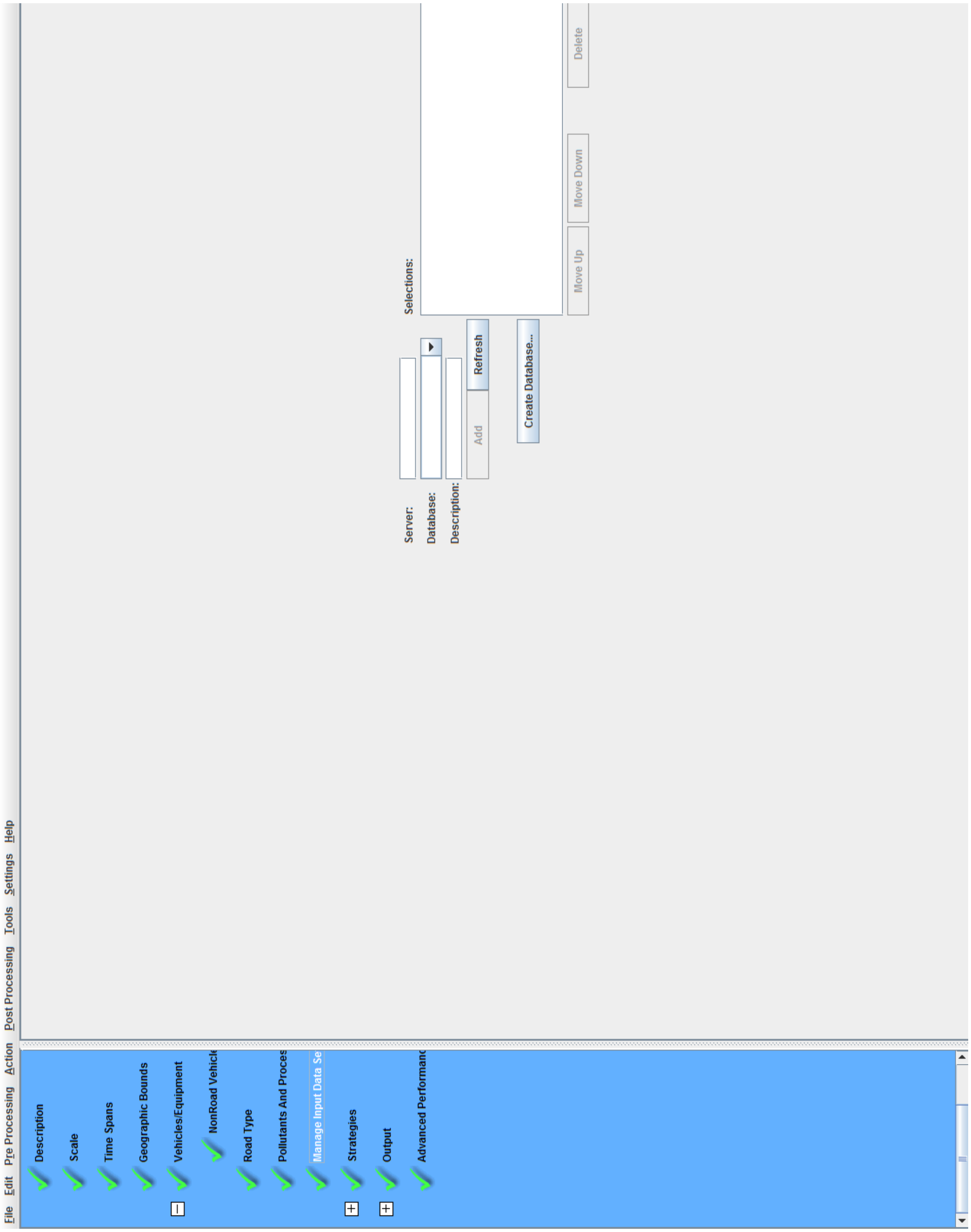
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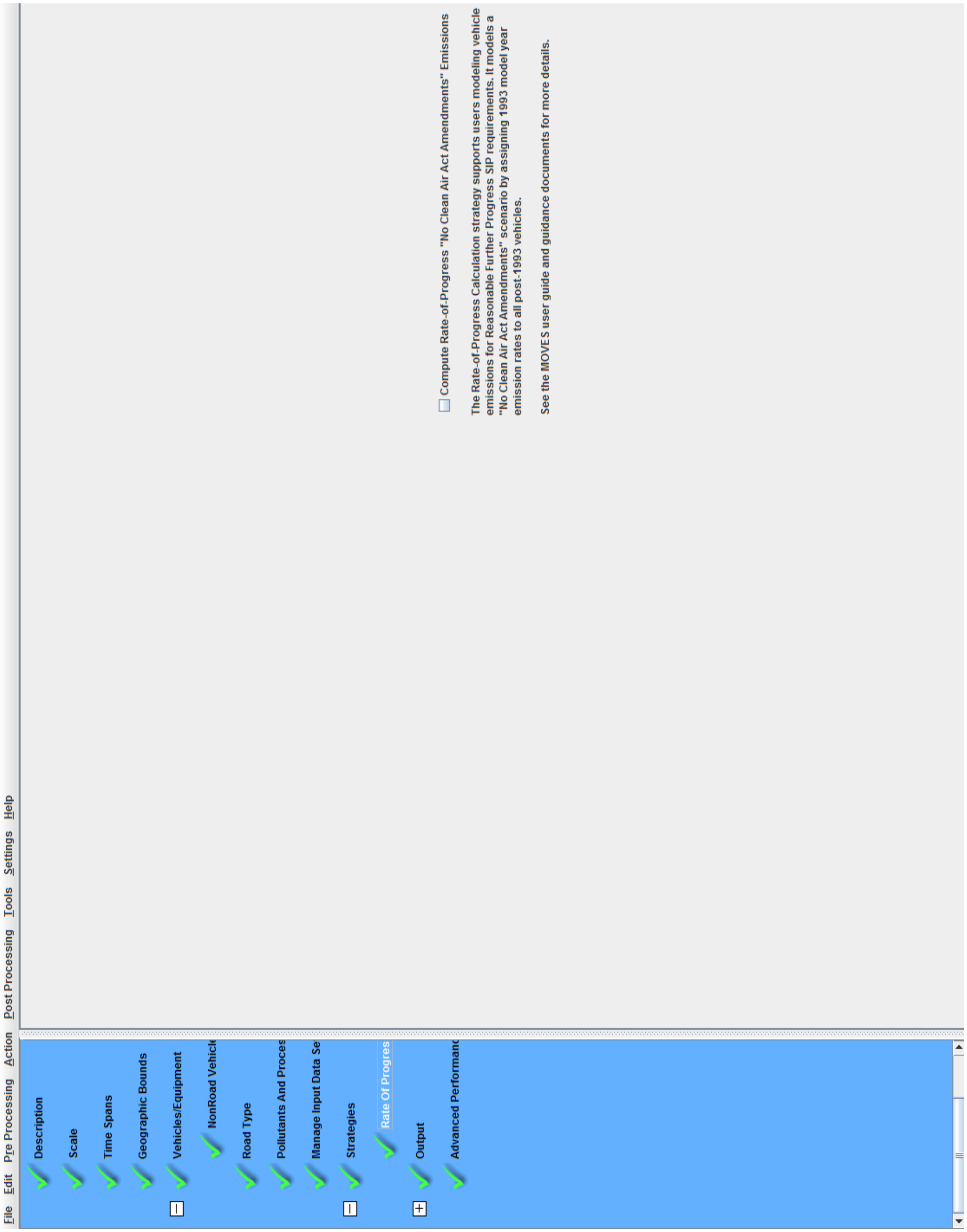
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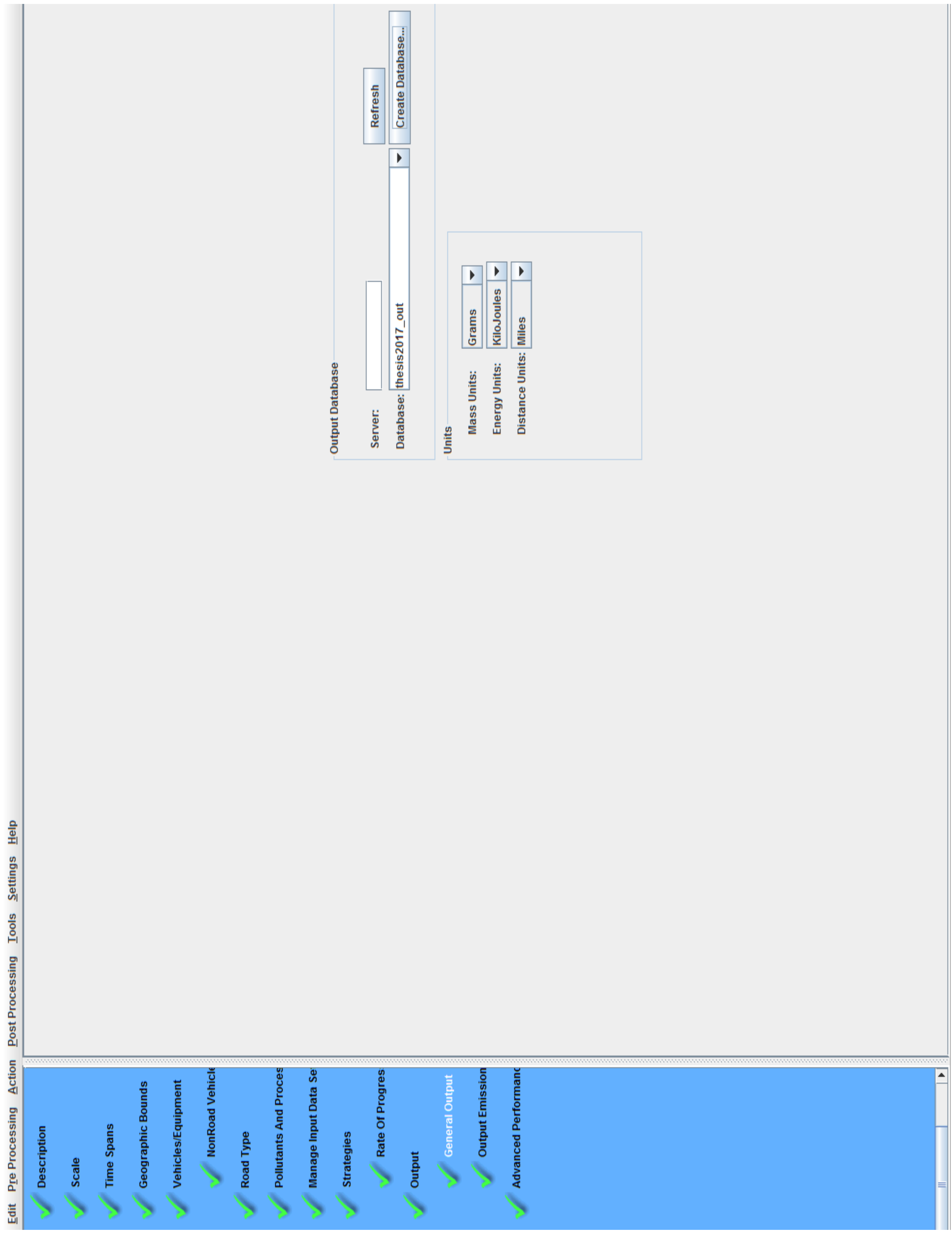
Compute Rate-of-Progress "No Clean Air Act Amendments" Emissions
The Rate-of-Progress Calculation strategy supports users modeling vehicle emissions for Reasonable Further Progress SIP requirements. It models a "No Clean Air Act Amendments" scenario by assigning 1993 model year emission rates to all post-1993 vehicles.
See the MOVES user guide and guidance documents for more details.



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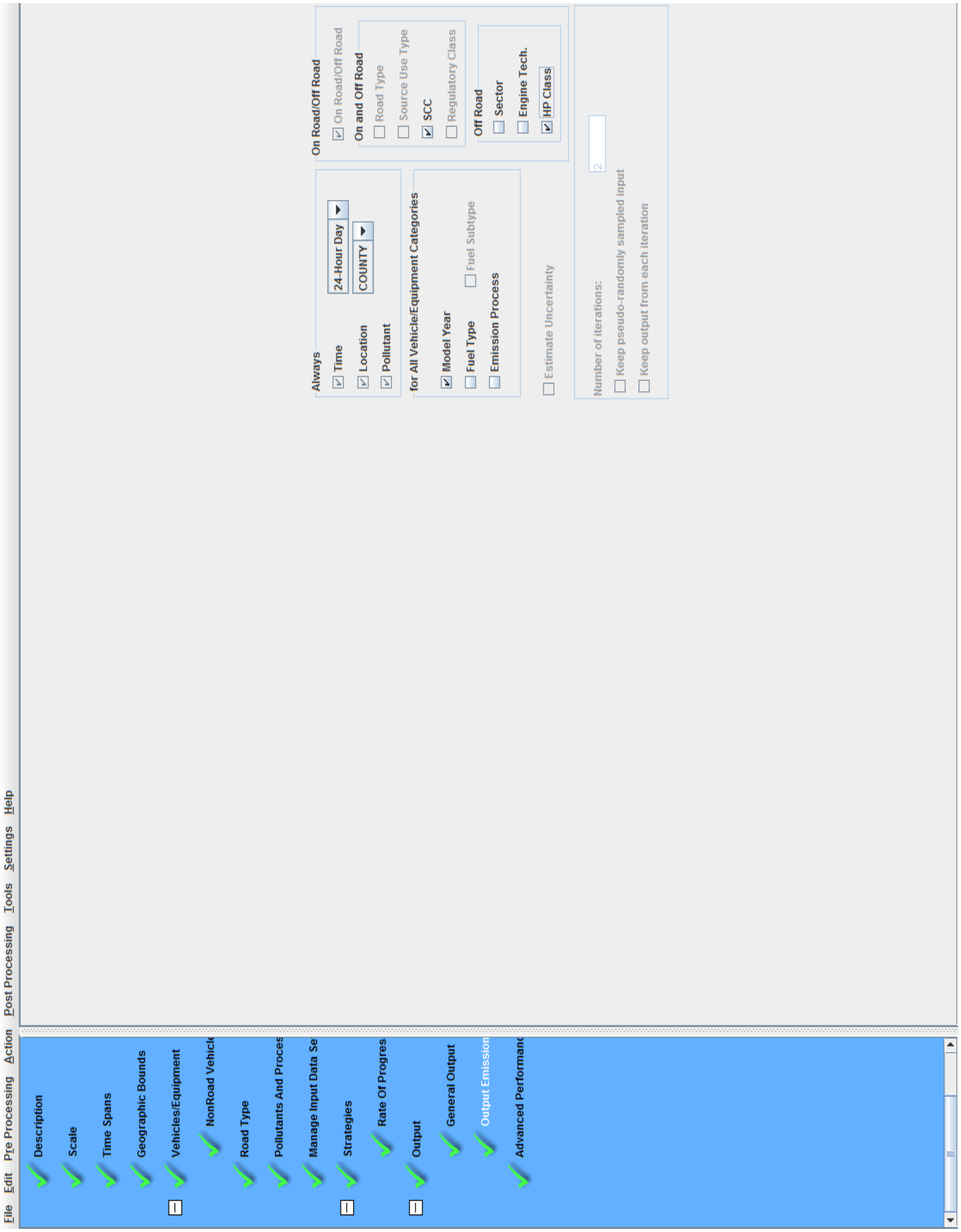
Energy Units: KiloJoules
Distance Units: Miles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Emission Process
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On Road/Off Road
On and Off Road
Road Type
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SCC
Regulatory Class
Off Road
Sector
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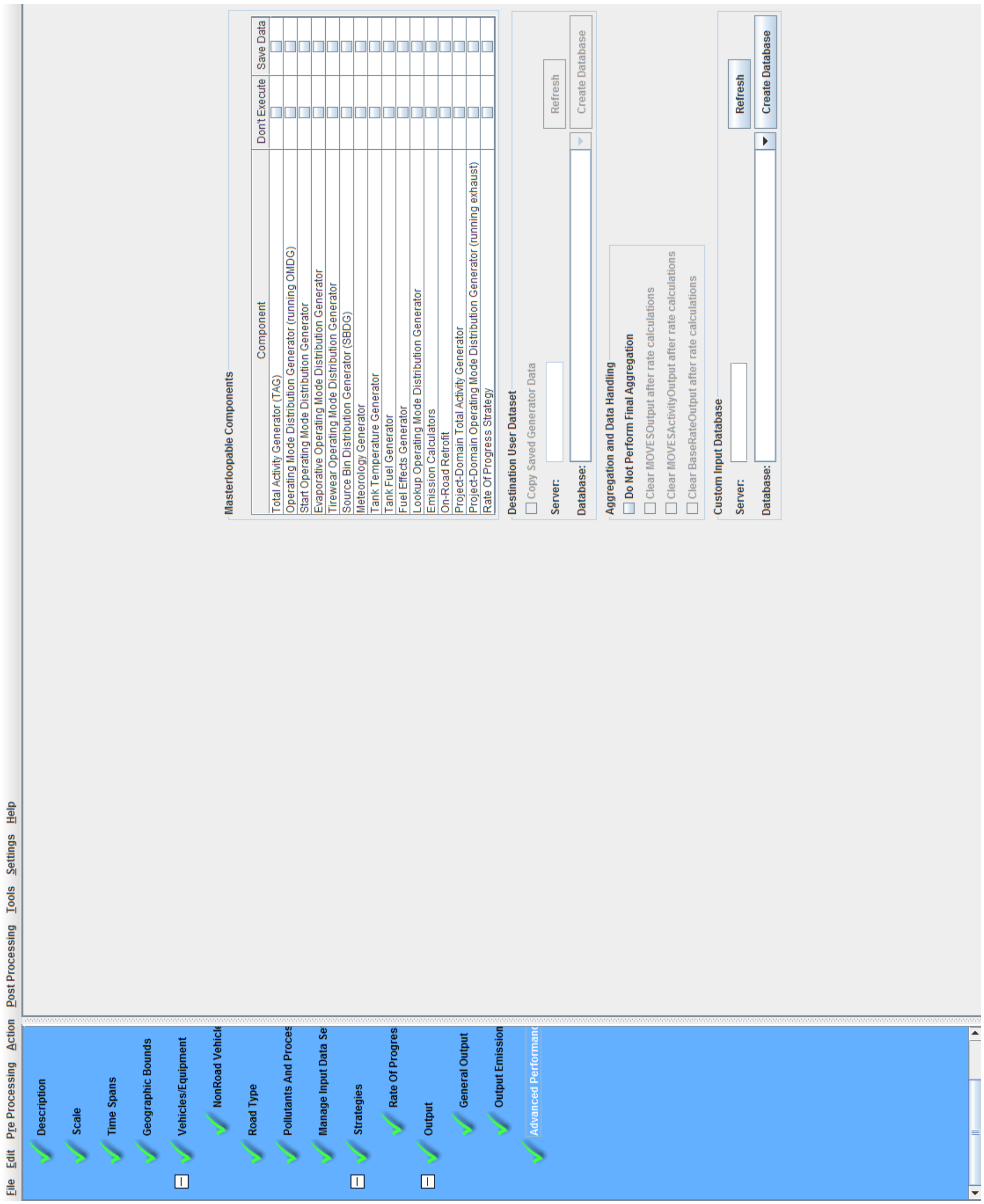
HP Class
Estimate Uncertainty
Number of iterations:
2
Keep pseudo-randomly sampled input
Keep output from each iteration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Don't Execute
Save Data
Total Activity Generator (TAG)
Operating Mode Distribution Generator (running OMDG)
Start Operating Mode Distribution Generator
Evaporative Operating Mode Distribution Generator
Tirewear Operating Mode Distribution Generator
Source Bin Distribution Generator (SBDG)
Meteorology Generator
Tank Temperature Generator
Tank Fuel Generator
Fuel Effects Generator
Lookup Operating Mode Distribution Generator
Emission Calculators
On-Road Retrofit
Project-Domain Total Activity Generator
Project-Domain Operating Mode Distribution Generator (running exhaust)
Rate Of Progress Strategy
Destination User Dataset
Copy Saved Generator Data
Server:
Database:
Refresh
Create Database
Aggregation and Data Handling
Do Not Perform Final Aggregation
Clear MOVESOutput after rate calculations
Clear MOVESActivityOutput after rate calculations
Clear BaseRateOutput after rate calculations
Custom Input Database
Server:
Database:
Refresh
Create Database

C. Number of working hours of each equipment for 30 days

Day	Number of working hours			
	Mobile crane	Excavator 1	Excavator 2	Forklift
July 18	5.5	0	0.25	4.33
19	7	4.5	4	5
20	3.66	5	6.5	6.5
21	1	2	2.5	3.5
24	3.5	7	7.33	2
25	3.25	2.9	0.93	1.76
26	7.66	5	5	4
27	6	5	4	2.5
28	7.5	2	3.5	4
31	7.33	2.5	1	4.5
August 1	7.5	4	3.5	3
2	6	5	0	1.5
3	7	6	0	2
4	4	6	0	3
7	4	0	0.25	6
8	7.5	0	5	3.75
9	6.5	0	0	4
10	5	0.5	1.5	3
11	7	0	2.5	4.5
14	7.75	0	0	5.5
15	9	0	0	5.5
16	8.5	0	1	6
17	5	0	4	4
18	6.5	0	1.25	4
22	4	1.5	4	3
23	6	2	0	0.25
28	6.5	5	4.25	3.75
29	7	3.5	4.5	5.75
30	7.5	2	0	6.5
31	8	2.5	0	4

D. MySQL commands

SELECT

FROM