

**Implementing Best Available Technology for Diesel
Emissions Reduction in Accordance with
New York City Local Law 77**

**NEW YORK CITY DEPARTMENT OF ENVIRONMENTAL PROTECTION
CROTON WATER TREATMENT PROJECT
CAPITAL PROJECT WM-11**

**Estimation of Cumulative Emission Reductions: 2005 - 2007
Draft Final Report**

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Abbreviations and Acronyms

ADPF – Active Diesel Particulate Filter
BAT – Best Available Technology
CARB – California Air Resources Board
CRT – Continuously Regenerating Technology
CWTP – Croton Water Treatment Plant
DEP – Department of Environmental Protection
DOC – Diesel Oxidation Catalyst
DOES2 – Dynamic Dilution On/Off-Road Exhaust Emission Sampling System
DPF – Diesel Particulate Filter
DPM – Diesel Particulate Matter
EC – Environment Canada
ECS – Engine Control Systems
ECT – Emission Control Technology
EF – Emissions Factor
Engine Emissions:
 CO – Carbon Monoxide
 CO₂ - Carbon Dioxide
 HC - Hydrocarbons
 NH₃ - Ammonia
 NO – Nitrogen Oxide
 NO_x – Oxides of Nitrogen
 NO₂ – Nitrogen Dioxide
 O₃ - Ozone
 PM – Particulate Matter
EPA – Environmental Protection Agency
g – grams
hp – horsepower
JM – Johnson Matthey
ISS – Integrated Sampling System
LL77 – Local Law 77
mg - milligram
mg/kg – milligram / kilogram
NYCDEP – New York City Department of Environmental Protection
NYSERDA – New York State Energy and Research Development Authority
NYSDEC – New York State Department of Environmental Conservation
PDPF – Passive Diesel Particulate Filter
PEMS – Portable Emission Measurement System
PM – Particulate Matter
ppm – parts per million
QA/QC – Quality Assurance / Quality Control
SCR – Selective Catalytic Reduction
SCRT – Johnson Matthey manufactured SCR+PDPF system
ULSD – Ultra Low Sulfur Diesel

Executive Summary

In late 2003, the City of New York promulgated Local Law 77 (“LL77”) requiring the installation of Best Available Technology (BAT) for reducing primarily particulate matter (PM) and secondarily oxides of nitrogen (NO_x) emissions from diesel-powered nonroad construction equipment that is either owned by the City or by private firms operating on City construction projects. The first implementation of BAT following the precepts of LL77 was subsequently undertaken in July, 2005, at the New York City Department of Environmental Protection (NYCDEP) Croton Water Treatment Plant Project (Croton) in the Bronx, New York. Over the two year project period from July, 2005 to July, 2007, a total of twenty-five nonroad construction machines were retrofitted with BAT emission controls, while six machines from this group were selected to undergo in-use emission testing using the Environment Canada DOES2 integrated sampling system (ISS) to quantify the emission reduction performance of the selected BAT operating under real-world conditions.

Emisstar submitted a final report of in-use emissions testing program to URS Malcolm Pirnie and NYDCEP in January, 2007, quantifying the emission reduction performance of the selected BAT on nonroad construction equipment operating under real-world conditions. This report provides a quantitative estimation of the cumulative emission reductions achieved during the project period 2005 through 2007, using an analytical approach that combines estimation techniques, in-use emission testing and real-world equipment operating data to develop equipment-specific emission factors to calculate the effect of BAT on site-wide equipment emissions.

Results from the analysis showed significant reductions in PM, HC and CO emissions from baseline mass emissions, over time, attributable to: 1) an increase in total number of installed BAT systems as a percentage of total equipment emitting pollution on-site; and 2) high pollution removal efficiency of the emission control technologies. On a mass basis, PM emissions trended down considerably, from a high of 58 kg/month in March, 2006, to a low of 2 kg/month in June, 2007, for a total reduction of 96.5 % from the baseline.

Programs such as this Emisstar study are beneficial for public health and environmental officials, enabling a quantitative assessment of implementing best available technology programs in achieving occupational health and air quality improvements. They also serve public entities and private industry alike in better quantifying the end results of instituting such programs in urban construction environments.

1. Introduction

Nonroad diesel equipment is found to be the single largest contributor of mobile source-based PM in New York City, according to a 2002 legislative report by the New York City Council, and this PM is associated with severe and multiple health risks. New York City LL77 was passed by the City Council and signed into law by Mayor Bloomberg in December, 2003. The law amends the City administrative code of New York by requiring that any diesel powered nonroad vehicle fifty (50) horsepower or greater, owned by, operated by or on behalf of, or leased by a City agency, be powered by (ultra-low sulfur diesel fuel) ULSD¹ and utilize BAT for reducing the emission of pollutants – primarily PM and secondarily NO_x.

In July, 2005, the New York City Department of Environmental Protection (DEP) issued its final rulemaking, promulgating Local Law 77 under Chapter 14 of Title 15 of the Rules of the City of New York, requiring the use of ULSD and emission control technologies for both nonroad vehicles used in city construction and all municipally owned nonroad vehicles regardless of whether they are being utilized on an active construction site.

During the period July 2005 through June 2007, Emisstar was contracted by the DEP to lead the first such implementation of BAT following LL77 by identifying and deploying emission control technologies (ECT) on nonroad, heavy duty construction equipment owned or leased, operated, and maintained by Schiavone Construction Company for construction activities at the Croton Water Treatment Project (CWTP) in the Bronx, New York (See Figure 1). Emisstar's work was performed to develop best available low-emission compliance practices and address the needs and concerns of the stakeholders, including DEP, Schiavone, URS Malcolm Pirnie, and the Croton facility monitoring committee (FMC).

There is a critical need to quantify the amount of emissions removed from projects like Croton to identify the effects of implementing LL77 on public health. This work can help public health and environmental officials to calculate the future expected value of implementing best available technology programs in achieving air quality improvements.

2. Project Objective

The main objective of this study was to quantify the cumulative mass emissions removed from the Croton site over the project period due to the application of BAT required by LL7. To answer this question, an analytical approach was used that combines estimation techniques, in-use emission testing and real-world equipment operating data to develop equipment-specific emission factors to calculate the effect of BAT on site-wide equipment emissions. Results of the estimation are also provided along with the methodology and corresponding protocols.

¹ Ultra low sulfur diesel fuel with up to 30 parts per million sulfur content is allowed until September 1, 2006. Thereafter, a 15 parts per million sulfur content limit is required.



Figure 1. Croton Water Treatment Project in the Bronx, New York

3. Equipment – Emission Control Technology Matrix

The target equipment group for this study includes 25 pieces of equipment retrofitted with the best commercially available emission control technologies for nonroad heavy duty diesel engines, both mobile and stationary. Table 1 provides a summary of the equipment retrofitted and the types of ECTs installed on each piece of equipment. The equipment-ECT matrix includes 3 compressors, 2 dozers, 4 excavators, 10 hydraulic drills, 2 line drills, 1 loader, and 3 quarry trucks. There are four types of ECTs installed on this engine population, including:

- Passive diesel particulate filters:
 - Purifilter manufactured by Engine Control Systems (ECS)
 - Selective Catalytic Reduction Technology (SCRT) manufactured by Johnson Matthey
 - JMI Continuously Regenerating Technology (CRT) manufactured by Caterpillar
- Active diesel particulate filter:
 - RT707 ADPF + DOC manufactured by RYPOS

4. Methodology

The methodology used for cumulative mass emissions estimation includes an estimation of emissions factors for each piece of equipment, development of an equipment-specific hours of operation database, and an estimate of “baseline” versus “controlled” cumulative mass emissions. The key elements for calculation of cumulative emissions reductions include estimation of mass emissions considering: (1) no ECTs installed on the equipment – the “baseline mass emissions”; and (2) ECTs installed on the equipment – the “controlled mass emissions.” The procedure for calculating “baseline” and “controlled” mass emissions is shown in Figure 2 as a flow diagram. The objective of this section is presented along with the requirements of the study.

Table 1- Equipment – Emission Control Technology Matrix

Ref No. ¹	Type	Manufacturer	Model	Model Year	Manufacturer	Model	Year	Rated hp	Type	Manufacturer	Model Name
E01	Compressor	Ingersoll Rand	IR 185	1999	John Deere	NA	1999	65	DPF	ECS	Purifilter
E38	Compressor	Ingersoll Rand	P600WIR	2005	John Deere	6IRF8TE	2005	170	SCRT+DPF	JMI	SCRT
E37	Compressor	Ingersoll Rand	IR 185	2006	John Deere	NA	2006	65	DPF	ECS	Purifilter
E03	Dozer	Komatsu	D155-Ax-5B	2004	Komatsu	SDA6D140E-3	2004	332	DPF	ECS	Purifilter
E04	Dozer	Komatsu	D275 Ax-5B	2005	Komatsu	SDA6D140E-3	2005	446	DPF	ECS	Purifilter
E07	Excavator	Komatsu	PC-750	2004	Komatsu	SAA6D140E-3	2004	474	DPF	ECS	Purifilter
E25	Excavator	Hitachi	Z-Axis 800	2005	Isuzu	GWG1XAB	2005	483	DPF	ECS	Purifilter
E26	Excavator	Hitachi	Z AXIS-800	2005	Isuzu	GWG1XAB	2005	483	DPF	ECS	Purifilter
E28	Excavator	Komatsu	PC-200	2005	Komatsu	N/A	2005	150	DPF	ECS	Purifilter
E13	Hydraulic Drill	Sandvik Tamrock	Pantera 1100	2002	Caterpillar	C9	2005	300	DPF	ECS	Purifilter
E14	Hydraulic Drill	Sandvik Tamrock	Pantera 1100	2005	Caterpillar	C9	2005	300	DPF	ECS	Purifilter
E23	Hydraulic Drill	Sandvik Tamrock	Scout 700-B	2005	Caterpillar	3126B	2005	200	DPF	ECS	Purifilter
E24	Hydraulic Drill	Sandvik Tamrock	Scout 700-B	2005	Caterpillar	3126B	2005	200	DPF	ECS	Purifilter
E29	Hydraulic Drill	Sandvik Tamrock	Super CHA 700	2005	Caterpillar	3506E	2005	173	DPF	ECS	Purifilter
E30	Hydraulic Drill	Sandvik Tamrock	Super CHA 700	2005	Caterpillar	3506E	2005	173	DPF	ECS	Purifilter
E31	Hydraulic Drill	Sandvik Tamrock	Super CHA 700	2005	Caterpillar	3506E	2005	173	DPF	ECS	Purifilter
E32	Hydraulic Drill	Sandvik Tamrock	Super CHA 700	2003	Caterpillar	3506E	2003	173	DPF	ECS	Purifilter
E39	Hydraulic Drill	Sandvik Tamrock	Super CHA 700	2005	Caterpillar	3506E	2005	173	DPF	ECS	Purifilter
E22	Hydraulic Drill	Furukawa	HT-1500	2005	Caterpillar	3126B	2005	200	DPF	ECS	Purifilter
E11	Line Drill	Ingersoll Rand	ECM-490	1997	Cummins	C8.3C	1997	185	DPF	ECS	Purifilter
E12	Line Drill	Ingersoll Rand	ECM-590	2004	Cummins	C8.8	2004	215	DPF	ECS	Purifilter
E15	Loader	Caterpillar	966G	2004	Caterpillar	3176CATAAC	2004	259	DPF	CAT	JMI CRT
E18	Quarry Truck	Terex	TR70	2005	Detroit Diesel	12V 2000	2005	700	ADPF	RYPOS	ADPF/C
E19	Quarry Truck	Terex	TR70	2005	Detroit Diesel	12V 2001	2005	700	ADPF	RYPOS	ADPF/C
E20	Quarry Truck	Terex	TR70	2005	Detroit Diesel	12V 2002	2005	700	ADPF	RYPOS	ADPF/C

¹ Equipment Retrofit ID No.

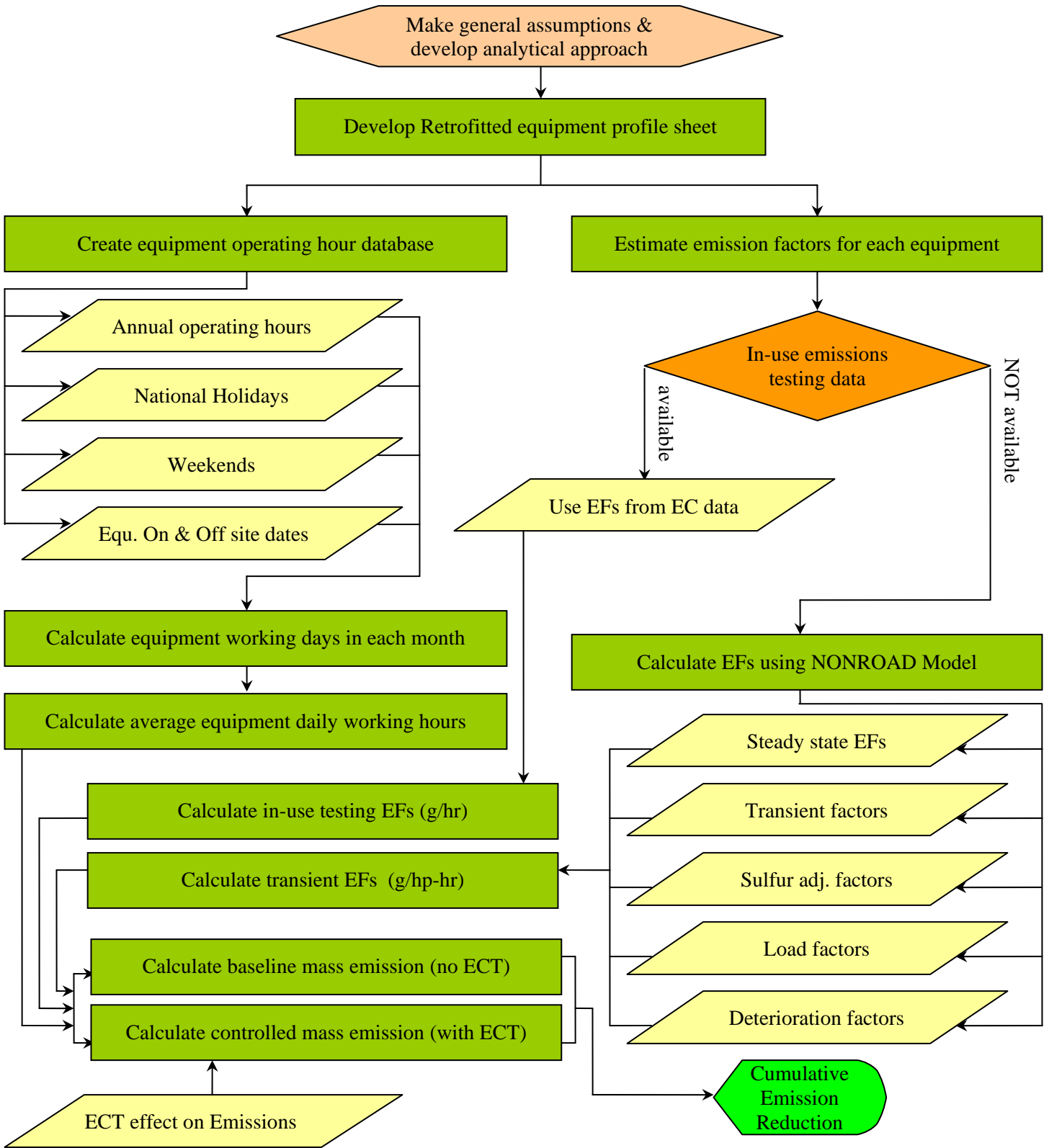


Figure 2. Conceptual Diagram of Cumulative Mass Emissions Reduction Estimation

4.1. Equipment specific emission factor estimation techniques

This section describes and documents the equipment specific emission factor estimation techniques used in the cumulative emission reduction calculations. Two different techniques were employed to calculate emission factors (EFs) for the nonroad equipment used at the Croton site: 1) for equipment where in-use emission testing results were not able to be obtained, the EPA NONROAD Model was used to estimate the average emission factors; 2) for equipment where in-use emissions testing was employed, actual test data was used in the calculation.² Both the NONROAD Model and the in-use emission testing methodologies are explained in the following sections.

4.1.1. In-use emission test data

After the first implementation of BAT under LL77 took place at Croton, six pieces of retrofitted nonroad construction equipment were selected to undergo in-use emission testing with the Environment Canada DOES2 integrated sampling system (ISS). The selected construction equipment is a representative sample of the six equipment types operating at the site, and included the following:

- 170 HP Ingersoll-Rand IR-600 Compressor with SCRT
- 332 HP Komatsu DX-275 Bulldozer with PDPF
- 474 HP Komatsu PC-750 Excavator with PDPF
- 700 HP Terex TR-70 Quarry Truck with ADPF
- 259 HP Caterpillar 966G Rubber Tire Loader with CRT-PDPF
- 173 HP Tamrock CHA700 Super Tiger Hydraulic Drill with PDPF

Testing was conducted over a two week period in September, 2006, with emissions sampling performed both before and after the selected emission control technologies. All four EPA regulated emissions – PM, NO_x, HC and CO – were sampled and analyzed, along with CO₂ as a surrogate for fuel consumption. Three test cycle types – simple, synthesized and in-use – were created for each of the six equipment/ECT combinations tested following a site-specific protocol developed using generic protocol guidelines established under the New York State Energy Research and Development Authority (NYSERDA) nonroad emission control technology retrofit and testing program. Detailed information regarding test methodology, portable emission measurement system, data quality assurance and quality control (QA/QC), is provided in Emisstar’s “In-Use Emission Testing Program” report.

Mass emission rates measured before the ECTs for the six above mentioned equipment were used as emission factors in this work. Table 2 identifies the equipment specific emission factors. Emisstar assumed that for any given equipment type, such as excavators, the identical piece of equipment will produce the same emission rates. Thus, for pieces of equipment given in Table 1 that are identical to the equipment listed in Table 2, the same emission factors were used for

² The NONROAD Model is a best estimate calculation of EFs; actual in-use testing is adjudged to be more accurate and was employed for as many equipment types – in this case six – as was economically and technologically feasible.

further calculations. For example, emission factors for E31 Tamrock CHA 700 Hydraulic Drill were used for the other identical hydraulic drills of E29, E30, E32, and E39.

Table 2 – Emission Factors Estimated from In-Use Emission Testing

Ref No. ¹	Equipment Information				Engine Information			Emission Factors			
	Type	Manufacturer	Model	Model Year	Manufacturer	Model	Rated hp	PM (g/hr)	NO _x (g/hr)	HC (g/hr)	CO (g/hr)
E38	Compressor	Ingersoll Rand	IR600	2005	John Deere	6IRF8TE	170	10.6	316.4	16.0	37.7
E03	Dozer	Komatsu	D155-Ax-5B	2004	Komatsu	SDA6D140 E-3	332	40.3	866.7	10.4	612.7
E07	Excavator	Komatsu	PC-750	2004	Komatsu	SAA6D140 E-3	474	35.0	1302.8	17.7	229.8
E31	Hydraulic Drill	Sandvik Tamrock	Super CHA 700	2005	Caterpillar	3506E	173	11.6	448.4	7.4	40.2
E15	Loader	Caterpillar	966G	2004	Caterpillar	3176C ATAAC	259	10.9	388.3	7.2	126.8
E19	Quarry Truck	Terex	TR70	2005	Detroit Diesel	12V 2000	700	21.2	1107.0	27.5	543.2

¹ Equipment Retrofit ID No.

4.1.2. EPA NONROAD Model Database

Emission factors were estimated using EPA’s NONROAD Model for equipment for which no in-use emissions data was available. The NONROAD model estimates air pollution from more than 80 types of compression ignition (CI) and spark ignition (SI) nonroad sources.

Furthermore, the NONROAD model provides a flexible tool that can be applied to a wide variety of air quality modeling and planning functions. Using information on construction vehicle populations, annual activity/use, fuel type, and emission factors, the NONROAD model estimates mass emissions of hydrocarbons (HC), nitrogen oxides (NO_x), sulfur dioxide (SO₂), carbon monoxide (CO), carbon dioxides (CO₂), and particulate matter (PM₁₀ and PM_{2.5}) for the US, specific states and counties, for past and future years.

For HC, CO, and NO_x, the exhaust emission factor for a given diesel equipment type in a given model year/age is calculated as follows:

$$EF_{adj(HC,CO,NO_x)} = EF_{SS} \times TAF \times DF \quad (1)$$

where,

EF_{adj} = final emission factor used in model, after adjustments to account for transient operation and deterioration; g/hp-hr

EF_{ss} = zero-hour, steady-state emission factor; g/hp-hr

TAF = transient adjustment factor, unitless

DF = deterioration factor, unitless

Since PM emissions are dependent on the sulfur content of the fuel the engine is burning, the equation used for PM is slightly modified from Equation (1) as follows:

$$EF_{adj(PM)} = EF_{SS} \times TAF \times DF - S_{PMadj} \quad (2)$$

where,

$S_{PM adj}$ = adjustment to PM emission factor to account for variations in fuel sulfur content; g/hp-hr

PM and SO₂ are the only diesel pollutants that are dependent on fuel sulfur content. The objective of the following sections is to explain how emission factors for retrofitted equipment were estimated using EPA’s NONROAD Model.

4.1.2.1. Zero-hour steady state emission factors

The U.S. EPA provides zero-mile, steady state exhaust and crankcase emission factors on a grams per brake horsepower hour basis (g/hp-hr) for nonroad engines which are mainly a function of model year and horsepower category that identifies the technology type.[1] The zero-mile emission factors are followed by adjustments (where applicable) to account for transient operation, deterioration, and variations in fuel sulfur level. For example, emission factors for a typical nonroad diesel engine horsepower range of 100 to 175 hp are shown below:

Engine Power (hp)	Technology Type	BSFC (lb/hp-hr)	Emission Factors (g/bhp-hr)			
			HC	CO	NO _x	PM
>100 to 175	Tier 2	0.367	0.34	0.87	4.1	0.18

4.1.2.2. Transient adjustment factor

In order to develop NONROAD Model’s emissions database, EPA primarily tested nonroad engines with steady state test cycles. However, the steady state operation typically used for emission testing is not always representative of the operation of engines in many nonroad applications. Some of the differences can be due to engine load or speed, while other differences can be due to transient demands. EPA has calculated “transient adjustment factors” (“TAFs”) to be applied to the steady-state emission factors previously described. EPA has provided the resulting TAFs assigned to each equipment application.[1] The steady state emission factors were multiplied by the appropriate TAFs to create NONROAD Model’s emission factor input files for CI engines.

4.1.2.3. Sulfur adjustment for PM emissions

Since PM emissions are influenced by the sulfur content of the fuel, an adjustment ($S_{PM adj}$) was calculated and subtracted from the PM emission factor to account for variations in fuel sulfur content (see Equation (2)). $S_{PM adj}$ corrects PM emissions from the steady state default fuel sulfur level to the episodic fuel sulfur level found at Croton. $S_{PM adj}$ was calculated from the following equation:

$$S_{PM_{adj}} = BSFC \times 453.6 \times 7.0 \times soxcnv \times 0.01 \times (soxbas - soxds1) \quad (3)$$

where:

$S_{PM_{adj}}$ = PM sulfur adjustment; g/hp-hr

BSFC = in-use adjusted brake-specific fuel consumption; lb fuel/hp-hr

453.6 = conversion from lb to grams

7.0 = grams PM sulfate/grams PM sulfur

soxcnv = grams PM sulfur/grams fuel sulfur consumed = 0.02247 for diesel

0.01 = conversion from percent to fraction

soxbas = default fuel sulfur weight percent = 0.33 for diesel

soxds1 = episodic fuel sulfur weight percent at Croton = 15 ppm (or mg/kg)

4.1.2.4. Load factor

Engine rated power is the maximum power level that an engine is designed to produce at its rated speed. Engines typically operate at a variety of speeds and loads, and operation at rated power for extended periods is rare. In order to take into account the effect of operation at idle and/or partial load conditions, as well as transient operation, load factors were developed by the EPA to indicate the average proportion of rated power used.[2] For instance, a load factor of 0.3 indicates that an engine rated at 200 hp will produce an average of 60 hp over the course of normal operation. The U.S. EPA provides load factors for variety of nonroad construction equipment applications.[2]

4.1.2.5. Deterioration factor

Emisstar considered the effect of engine deterioration by multiplying a zero hour emission factor for each category of engine by a deterioration factor (DF), provided by EPA in the NONROAD Model database.[1] DF varies as a function of engine age. The following equation is used to calculate DF as a function of engine age:

$$\begin{aligned} DF &= 1 + A \times (\text{Age Factor})^b \quad \text{for Age Factor} \leq 1 \\ DF &= 1 + A \quad \quad \quad \text{for Age Factor} > 1 \end{aligned} \quad (4)$$

where,

$$\text{Age Factor} = \text{fraction of median life expended} = \frac{\text{cumulative hours} \times \text{load factor}}{\text{median life at full load, in hrs}}$$

A = constants for a given pollutant/technology type. "A" can be varied to reflect differences in maximum deterioration

b = for compression-ignition engines, b is always equal to 1

Deterioration is capped at the end of an engine's median life (age factor = 1), under the assumption that an engine deteriorates to a point where any increased deterioration is offset by maintenance. To calculate age factor for the Croton equipment, cumulative hours were

calculated from equipment annual activity (operation hours) provided by the EPA.[2] For newer equipment, 2005 and newer, cumulative hours were used from the annual operating hours recorded in the field by URS Malcolm Pirnie.

4.2. Baseline vs. controlled mass emissions estimates

As explained previously, mass emissions are estimated for two cases in this study. In the first case, mass emissions are estimated assuming no ECTs are installed on target nonroad construction equipment. This case is referred to as the “baseline” emissions case. In the second case, where ECTs are installed on the target equipment, the amount of mass emissions is referred to as the “controlled” emissions case. A key purpose of this section is to demonstrate the methodology used for mass emission estimates and present the underlying assumptions made for these estimates where applicable.

4.2.1. Develop equipment hours of operation database

To calculate “baseline” and “controlled” mass emissions, equipment specific “hours of operation” are multiplied by transient and real world in-use emission factors estimated for each piece of targeted nonroad equipment, as explained in Section 4.1. A decision was made to present results of this study as “baseline” and “controlled” trends of mass emissions on a monthly basis from 2005 to 2007. For this reason, the average monthly hours of operation for a given month and equipment were calculated from annual equipment hours of operation provided by URS Malcolm Pirnie. Table 3 summarizes annual equipment operating hours used for this study. Equipment monthly hours of operation were calculated using the following equation with the key assumption that equipment operating hours are uniformly distributed across equipment operating days.

$$MHO_i = ADHO_i \times (\text{Equipment working days in month})_i \quad (5)$$

where,

MHO = equipment monthly hours of operation; hr

ADHO = Average daily hours of operation; hr. This factor is calculated from Equation (6)

i = any given month from July 2005 to June 2007

$$ADHO_j = \frac{\text{Annual operating hours}}{(\text{Equipment operating days in year})_j} \quad (6)$$

where,

j = 2005 (from July to December), 2006 (January to December), 2007 (from January to June)

Annual operating hours = provided by Malcolm Pirnie; see Table 3

Equipment operating days in a year = total equipment on site days – (national holidays + weekends + equipment off site days)

In order to calculate yearly equipment operating days, it was assumed that none of the target equipment was operated on national holidays and weekends. Offsite equipment days were also taken into account.

Table 3 - Croton Project Nonroad Equipment Annual Operating Hours

Equipment Retrofit ID No.	Equipment Information				Cumulative Annual Hours of Operation (hr)		
	Type	Manufacturer	Model	Model Year	2005 ¹	2006	2007 ²
E01	Compressor	Ingersoll Rand	IR 185	1999	210	60	0
E38	Compressor	Ingersoll Rand	P600WIR	2005	0	500	220
E37	Compressor	Ingersoll Rand	IR 185	2006	0	540	755
E03	Dozer	Komatsu	D155-Ax-5B	2004	850	2000	900
E04	Dozer	Komatsu	D275 Ax-5B	2005	1000	1800	850
E07	Excavator	Komatsu	PC-750	2004	1050	2200	760
E25	Excavator	Hitachi	Z-Axis 800	2005	900	1600	680
E26	Excavator	Hitachi	Z AXIS-800	2005	280	1100	0
E28	Excavator	Komatsu	PC-200	2005	1050	2200	680
E13	Hydraulic Drill	Sandvik Tamrock	Pantera 1100	2002	1300	1800	440
E14	Hydraulic Drill	Sandvik Tamrock	Pantera 1100	2005	867	800	440
E23	Hydraulic Drill	Sandvik Tamrock	Scout 700-B	2005	500	1500	500
E24	Hydraulic Drill	Sandvik Tamrock	Scout 700-B	2005	533	1500	400
E29	Hydraulic Drill	Sandvik Tamrock	Super CHA 700	2005	0	160	0
E30	Hydraulic Drill	Sandvik Tamrock	Super CHA 700	2005	0	1500	525
E31	Hydraulic Drill	Sandvik Tamrock	Super CHA 700	2005	0	1500	530
E32	Hydraulic Drill	Sandvik Tamrock	Super CHA 700	2003	0	1500	625
E39	Hydraulic Drill	Sandvik Tamrock	Super CHA 700	2005	0	1500	380
E22	Hydraulic Drill	Furukawa	HT-1500	2005	170	2000	240
E11	Line Drill	Ingersoll Rand	ECM-490	1997	560	70	0
E12	Line Drill	Ingersoll Rand	ECM-590	2004	560	70	0
E15	Loader	Caterpillar	966G	2004	1008	2016	520
E18	Quarry Truck	Terex	TR70	2005	693	1560	640
E19	Quarry Truck	Terex	TR70	2005	693	1560	640
E20	Quarry Truck	Terex	TR70	2005	693	1560	640

¹ Hours of operation from July 1st to December 31st 2005

² Hours of operation from January 1st to June 11th 2007

4.2.2. Baseline mass emissions estimation

Monthly based equipment specific “baseline” mass emissions were estimated using Equations (7) and (8), denoted below, depending on availability of real world emission factors for a given piece of equipment. Table 4 provides a list of equipment for which real world in-use emission factors were available from the Croton in-use emission testing program. As explained previously, for identical equipment the same emission factors were used for the remaining calculations.

From EPA’s NONROAD Model, “baseline” mass emissions were estimated using the following equation:

$$NBEE_{e,m,p} = EF_{e,p} \times HP_e \times LF_e \times MHO_{e,m} \times 0.4536 \quad (7)$$

where,

$NBEE_{e,m,p}$ = baseline emission estimation for a given equipment, month, and pollutant using the EPA NONROAD Model; kg/month

$EF_{e,p}$ = transient emission factor estimated from Equations (1) and /or (2) depending on the pollutant; g/bhp-hr.

HP_e = equipment horsepower; HP

LF_e = equipment load factor, unitless; see Section 4.1.2.4.

$MHO_{e,m}$ = equipment monthly hours of operation for a given equipment and month; hrs/month

0.4536 = conversion from lb to kilograms

Table 4 - Equipment for Which Real World In-Use Emission Factors Were Calculated

Emisstar Retrofit ID No.	Equipment Information		Emission Factors (In-use)			
	Type	Model Year	PM (g/hr)	NOx (g/hr)	HC (g/hr)	CO (g/hr)
E38	Compressor	2005	10.6	316.4	16.0	37.7
E03	Dozer	2004	40.3	866.7	10.4	612.7
E04	Dozer	2005	40.3	866.7	10.4	612.7
E07	Excavator	2004	35.0	1302.8	17.7	229.8
E25	Excavator	2005	35.0	1302.8	17.7	229.8
E26	Excavator	2005	35.0	1302.8	17.7	229.8
E29	Hydraulic Drill	2005	11.6	448.4	7.4	40.2
E30	Hydraulic Drill	2005	11.6	448.4	7.4	40.2
E31	Hydraulic Drill	2005	11.6	448.4	7.4	40.2
E32	Hydraulic Drill	2003	11.6	448.4	7.4	40.2
E39	Hydraulic Drill	2005	11.6	448.4	7.4	40.2
E15	Loader	2004	10.9	388.3	7.2	126.8
E18	Quarry Truck	2005	21.2	1107.0	27.5	543.2
E19	Quarry Truck	2005	21.2	1107.0	27.5	543.2
E20	Quarry Truck	2005	21.2	1107.0	27.5	543.2

From real world emission factors given in Table 4, monthly based “baseline” emissions estimations were performed using the following equation:

$$IBEE_{e,m,p} = EF_{e,p} \times MHO_{e,m} \quad (8)$$

where:

$IBEE_{e,m,p}$ = baseline emission estimation for a given equipment, month, and pollutant using in-use emission data; kg/month

$EF_{e,p}$ = emission factor estimated from Croton Project in-use emission testing program
depending on the pollutant; kg/hr
 $MHO_{e,m}$ = equipment monthly hours of operation for a given equipment and month; hrs/month

To calculate the Croton target equipment “baseline” mass emissions for a given month, the sum of equipment specific mass emissions is calculated from Equations (7) and (8). Equation (9) represents this calculation:

$$TBEE_m = \sum (NBEE_{m,p})_e + \sum (IBEE_{m,p})_e \quad (9)$$

where,

$TBEE_m$ = total baseline emission estimation for a given month; kg/month
 $\sum (NBEE_{m,p})_e$ = total baseline emission estimation for equipment for which NONROAD Model database was used for emission estimation; kg/month
 $\sum (IBEE_{m,p})_e$ = total baseline emission estimation for equipment for which in-use emissions data was used for emission estimation; kg/month

4.2.3. Controlled mass emission estimation

To estimate “controlled” mass emissions, the following key factors were evaluated:

- ECT date of installation
- ECT removal efficiency
- Equipment on and off site operating time

Equipment specific “controlled” mass emissions were calculated considering days of operation with and without ECTs. For example, Table 5 presents data from May 2006 in which ECTs were installed on some of the equipment. As a result, equipment operating days are split into days with and without ECTs.

Mass emissions were estimated from Equation (10) where in-use emissions factors were not available and from Equation (11) where in-use emission factors were available (see Table 4).

$$CNEE_{e,m,p} = EF_e \times HP_e \times LF_e \times (MHO_{e,m,withoutECT} - MHO_{e,m,withECT} \times ERF_{e,p}) \times 0.4536 \quad (10)$$

where:

$CNEE_{e,m,p}$ = controlled emission estimation for a given equipment, month, and pollutant using NONROAD Model; kg/month
 EF_e = transient emission factor estimated from Equations (1) and /or (2) depending on the pollutant; g/bhp-hr
 HP_e = equipment horsepower; HP
 LF_e = equipment load factor, unitless; see Section 4.1.2.4.
0.4536 = conversion from lb to kilograms

$MHO_{e,m, \text{ without ECT}}$ = equipment monthly hours of operation for a given equipment and month without ECT installed; hrs/month

$MHO_{e,m, \text{ with ECT}}$ = equipment monthly hours of operation for a given equipment and month with ECT installed; hrs/month

$ERF_{e,p}$ = emission reduction factor (or ECT removal efficiency) for a given equipment and pollutant. As previously explained, removal efficiency for each ECT was obtained from Emisstar's Croton in-use emission testing program. Table 6 summarizes ECTs and removal efficiencies for targeted equipment and pollutants.

Table 5 – Operating Days for Targeted Equipment, May 2006

Emisstar Retrofit ID No.	Type	Manufacturer	Days of operation in May-06		
			Without ECT	With ECT	Total
E01	Compressor	Ingersoll Rand	0	0	0
E38	Compressor	Ingersoll Rand	22	0	22
E37	Compressor	Ingersoll Rand	20	2	22
E03	Dozer	Komatsu	0	22	22
E04	Dozer	Komatsu	0	22	22
E07	Excavator	Komatsu	0	22	22
E25	Excavator	Hitachi	0	22	22
E26	Excavator	Hitachi	0	22	22
E28	Excavator	Komatsu	22	0	22
E13	Hydraulic Drill	Sandvik Tamrock	0	22	22
E14	Hydraulic Drill	Sandvik Tamrock	0	22	22
E23	Hydraulic Drill	Sandvik Tamrock	22	0	22
E24	Hydraulic Drill	Sandvik Tamrock	18	4	22
E29	Hydraulic Drill	Sandvik Tamrock	8	14	22
E30	Hydraulic Drill	Sandvik Tamrock	13	9	22
E31	Hydraulic Drill	Sandvik Tamrock	12	10	22
E32	Hydraulic Drill	Sandvik Tamrock	11	11	22
E39	Hydraulic Drill	Sandvik Tamrock	0	0	0
E22	Hydraulic Drill	Furukawa	0	22	22
E11	Line Drill	Ingersoll Rand	0	0	0
E12	Line Drill	Ingersoll Rand	0	0	0
E15	Loader	Caterpillar	0	22	22
E18	Quarry Truck	Terex	0	22	22
E19	Quarry Truck	Terex	0	22	22
E20	Quarry Truck	Terex	0	22	22

$$CIEE_{e,m,p} = EF_e \times (MHO_{e,m, \text{ without ECT}} + MHO_{e,m, \text{ with ECT}} \times ERF_{e,p}) \quad (11)$$

where:

$CIEE_{e,m,p}$ = controlled emission estimation for a given equipment, month, and pollutant using in-use emission data; kg/month

EF_e = transient emission factor estimated from Equations (1) and /or (2) depending on the pollutant; kg/hr

$MHO_{e,m, \text{without ECT}}$ = equipment monthly hours of operation for a given equipment and month without ECT installed; hrs/month

$MHO_{e,m, \text{with ECT}}$ = equipment monthly hours of operation for a given equipment and month with ECT Installed; hrs/month

$ERF_{e,p}$ = emission reduction factor (or ECT removal efficiency) for a given equipment and pollutant. As previously explained, removal efficiency for each ECT was found from Emisstar’s Croton Project in-use emission testing program. Table 6 lists the equipment specific emission removal efficiencies of various ECTs used on the targeted equipment, by pollutant.

Table 6 – Equipment Specific Emissions Removal Efficiencies of ECTs

Emisstar Retrofit ID No.	Equipment Type	Emission Control Technology (ECT) Information					ECT's Removal Efficiency (%)			
		Type	Manufacturer	Model Name	Model #	Installation Date	PM ¹	NOx	HC	CO
E01	Compressor	DPF	ECS	Purifilter	SC6	1/7/2006	98	7	75	99
E38	Compressor	SCRT+DPF	JMI	SCRT	NA	6/27/2006	97	67	94	99
E37	Compressor	DPF	ECS	Purifilter	SC6	5/27/2006	98	7	75	99
E03	Dozer	DPF	ECS	Purifilter	SC20	3/10/2006	97	5	93	99
E04	Dozer	DPF	ECS	Purifilter	DSC26	1/21/2006	98	7	75	99
E07	Excavator	DPF	ECS	Purifilter	SC20	3/3/2006	99	12	79	98
E25	Excavator	DPF	ECS	Purifilter	DSC34	1/15/2006	98	7	75	99
E26	Excavator	DPF	ECS	Purifilter	DSC34	1/14/2006	98	7	75	99
E28	Excavator	DPF	ECS	Purifilter	SC17	12/17/2006	99	5	52	99
E13	Hydraulic Drill	DPF	ECS	Purifilter	SC20	3/26/2006	97	0	93	99
E14	Hydraulic Drill	DPF	ECS	Purifilter	SC20	3/25/2006	97	0	93	99
E23	Hydraulic Drill	DPF	ECS	Purifilter	SC17	5/31/2006	99	0	52	99
E24	Hydraulic Drill	DPF	ECS	Purifilter	SC17	5/23/2006	99	0	52	99
E29	Hydraulic Drill	DPF	ECS	Purifilter	SC17	5/10/2006	99	0	52	99
E30	Hydraulic Drill	DPF	ECS	Purifilter	SC17	5/17/2006	99	0	52	99
E31	Hydraulic Drill	DPF	ECS	Purifilter	SC17	5/16/2006	99	0	52	99
E32	Hydraulic Drill	DPF	ECS	Purifilter	SC17	5/15/2006	99	0	52	99
E39	Hydraulic Drill	DPF	ECS	Purifilter	SC17	8/26/2006	99	0	52	99
E22	Hydraulic Drill	DPF	ECS	Purifilter	DSC34	4/8/2006	98	7	75	99
E11	Line Drill	DPF	ECS	Purifilter	SC17	1/10/2006	99	5	52	99
E12	Line Drill	DPF	ECS	Purifilter	SC17	1/7/2006	99	5	52	99
E15	Loader	DPF	CAT	JMI CRT	None	9/5/2005	99	0	52	99
E18	Quarry Truck	ADPF	RYPOS	ADPF/C	RH707	3/11/2006	65/85	0	31	34
E19	Quarry Truck	ADPF	RYPOS	ADPF/C	RH708	3/12/2006	65/85	0	31	34
E20	Quarry Truck	ADPF	RYPOS	ADPF/C	RH709	3/18/2006	65/85	0	31	34

¹ PM removal factor (reduction percent) for Terex Quarry Trucks is 65% before re-installation of the filters and 85% for remaining time on site

The Croton targeted equipment “controlled” mass emissions for a given month was estimated by summing equipment specific mass emissions calculated from Equations (10) and (11). Equation (12) represents this calculation:

$$TCEE_m = \sum (CNEE_{m,p})_e + \sum (CIEE_{m,p})_e$$

where,

$TCEE_m$ = total controlled emission estimation for a given month; kg/month

$\sum (NCEE_{m,p})_e$ = total controlled emission estimation for equipment for which NONROAD Model database was used for emission estimation; kg/month

$\sum (ICEE_{m,p})_e$ = total controlled emission estimation for equipment for which in-use emissions data was used for emission estimation; kg/month

5. Results

Results of this analysis are presented and discussed in this section. Over the course of the Croton project, cumulate mass emission reductions of 0.7 metric tons of PM were achieved, while NOx was reduced by 1.2 tons, HC by 0.4 tons, and CO by 7.1 tons, respectively.

Figures 3 through 5 provide a graphical illustration of the monthly trend of site-wide emissions of PM, NO_x, HC, and CO from diesel nonroad equipment, along with cumulative hours of operation from July 2005 to June 2007. Cumulative “baseline” and “controlled” mass emissions are shown in kilograms per month. As expected, the “baseline” mass emissions trend follows the hours of operation trend for all pollutants. Monthly hours of operation peaks in February and August of 2006 and declines thereafter through June of 2007.

For PM emissions, significant reductions start in December 2006 and continue to the end of the project period, coinciding with the start of full-scale BAT implementation. On average, the gap between “baseline” and “controlled” mass emission trends does not change from January to June 2007 because the majority of equipment had already been retrofitted with ECTs. The average PM removal efficiency of 97% for all equipment results in a significant reduction in PM emissions for this project.

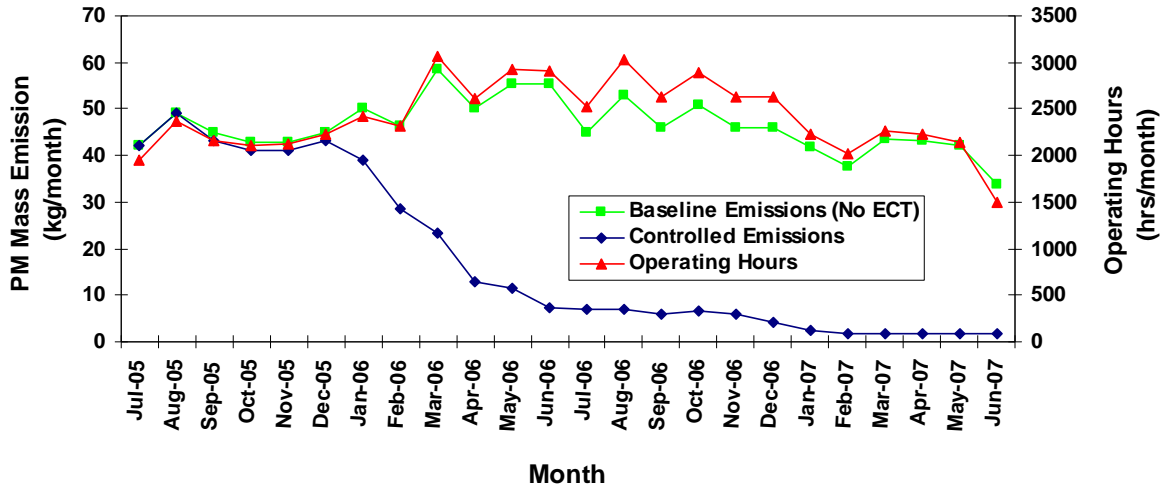


Figure 3. Cumulative Particulate Matter (PM) Mass Emissions Reductions Over the Croton Project Period, Monthly from 2005 to 2007

For NO_x emissions, we did not anticipate any significant NO_x reductions because of the application of primarily PM reduction only ECTs, with the exception of the Ingersoll Rand IR600 Compressor which was equipped with SCR in addition to a DPF. Figure 4 shows the trend in “baseline” versus “controlled” NO_x emissions which confirmed our hypothesis. As shown, “baseline”, “controlled”, and “hours of operation” trends follow each other closely since there is only a slight reduction in NO_x over the course of the project.

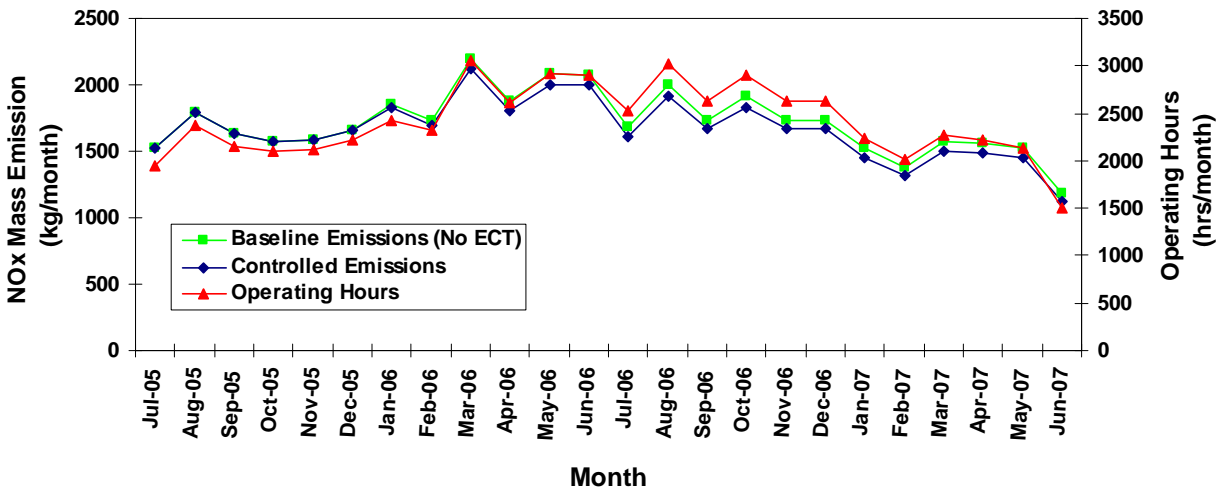


Figure 4. Cumulative Nitrogen Oxides (NO_x) Mass Emissions Reductions Over the Croton Project Period, Monthly from 2005 to 2007

HC and CO emissions follow similar trends in both “baseline” and “controlled” emissions; however, there is a significantly higher reduction in CO emissions due to the overall CO removal efficiency of the ECT types implemented. In both cases, emission reductions trend significantly downward starting in March of 2006.

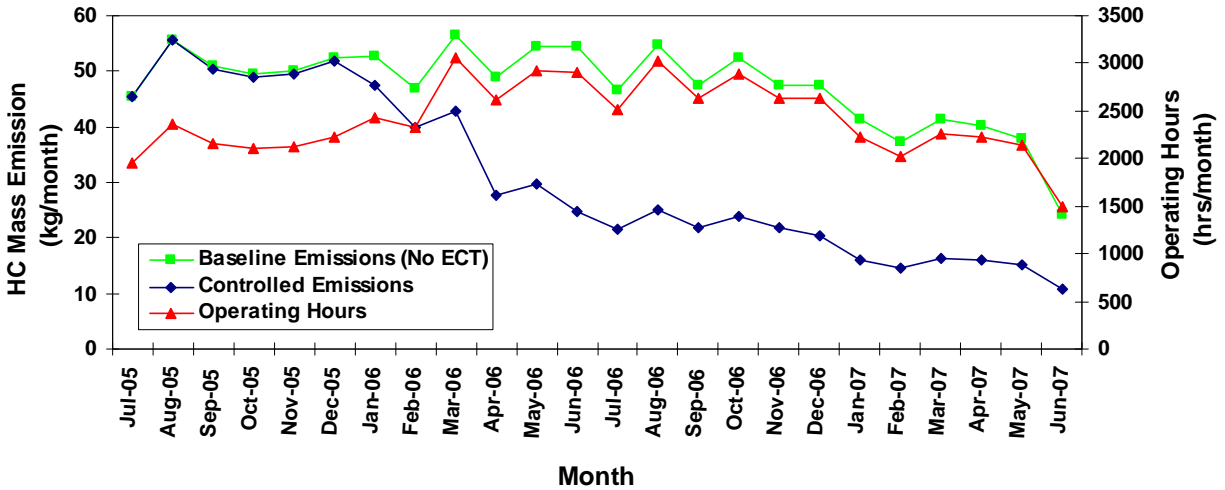


Figure 5. Cumulative Hydrocarbons (HC) Mass Emissions Reductions Over the Croton Project Period, Monthly from 2005 to 2007

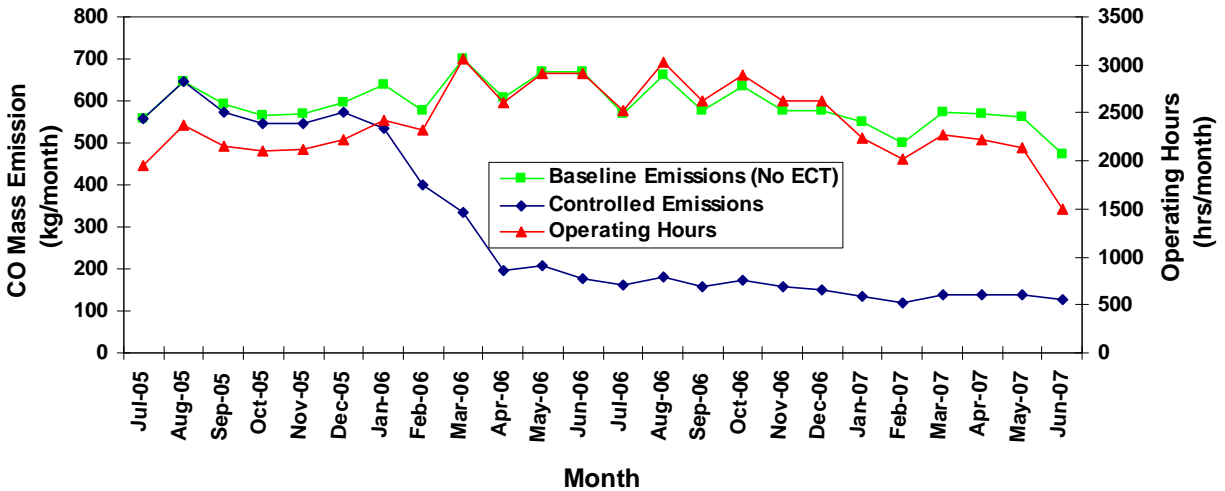


Figure 6. Cumulative Carbon Monoxide (CO) Mass Emissions Reductions Over the Croton Project Period, Monthly from 2005 to 2007

6. Conclusions

Based upon the analysis performed in this report, Emissstar is able to make the following conclusions:

- This project successfully demonstrated the control of diesel exhaust emissions on a macro scale;
- Cumulative mass emission reductions of 0.7 tons of PM were achieved, while NO_x was reduced by 1.2 tons, HC by 0.4 tons, and CO by 7.1 tons, respectively;

- Most importantly, the resultant data and analysis provides quantitative support for the continued application of BAT as an effective approach to aggressive reduction in PM, HC, CO and NO_x, where applicable.

From a diesel emission reduction perspective, the test data validates LL77 as an effective regulation that protects public health and improves air quality. Additionally, the techniques, methodologies and approaches demonstrated at Croton stand to serve as a paradigm for additional projects and testing of this type in the future.

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2. Environmental Protection Agency, *Median Life, Annual Activity, and Load Factor Values for Nonroad Engine Emissions Modeling*; EPA-420-P-04-005, Office of Transportation and Air Quality U.S. Environmental Protection Agency, Ann Arbor, MI, 2004.