ABSTRACT

BAMMI, SACHIN. Quantitative Analysis of Variability and Uncertainty in On-Road and Non-Road Mobile Source Emission Factors. (Under the direction of Dr. H Christopher Frey.)

The goal of this research is to demonstrate a methodology for quantifying variability and uncertainty in mobile source emissions. Emission factors and emission estimates are subject to both variability and uncertainty. Variability in emissions deals with real differences in emissions among multiple emission sources at any given time or over time for any individual emission source. Variability is the heterogeneity of values of a quantity with respect time space or across a population. Uncertainty in emissions on the other hand implies the lack of knowledge regarding the true value of emissions. In this research variability and uncertainty are treated separately since their sources are different and as such they affect the decision making process in a different way. For example, sources of variability in mobile source emissions include: vehicle make; ambient temperature; vehicle model; fuel used; vehicle age; and/or driving behavior. Sources of uncertainty may include: small sample sizes; lack of precision and/or accuracy in measurements; non-representativeness; or lack of data.

In this work a methodology for simultaneous characterization of variability and uncertainty in mobile source emission factors is described. Variability is characterized by fitting probability distributions to the data sets. Uncertainty due to random sampling error is characterized by using the parametric Bootstrap technique.

This methodology is demonstrated for emission factors for three categories: (1) Onroad mobile source exhaust air toxic emissions (2) nonroad lawn and garden equipment emissions and (3) nonroad construction farm and industrial equipment emissions. For the first category a database of vehicular exhaust emissions developed by the California Air Resources Board (CARB) was used. For the second and third categories emission factor databases were developed by reviewing reports and/or technical papers from U.S. Environmental Protection Agency (EPA), Southwest Research Institute (SwRI), CARB and Society of Automotive Engineers (SAE).

The main results regarding the demonstrated methodology and related statistical analysis in this research include: (1) emission factor groupings were determined statistically (e.g. by engine size for lawn and garden engines); (2) substantial inter-engine variability in emissions was discovered; and (3) large ranges of uncertainty in mean emissions were found in many cases. In particular, uncertainty ranges for the mean emission factors were in excess of ±20 percent in most cases and as high as minus 49 percent to plus 89 percent.

QUANTITATIVE ANALYSIS OF VARIABILITY AND UNCERTAINTY IN ON-ROAD AND NON-ROAD MOBILE SOURCE EMISSION FACTORS

by

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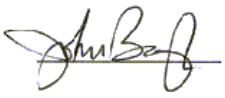

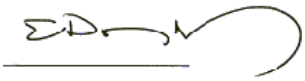

Chair of Advisory Committee

Biography

Sachin Bammi was born on 19th day of May in 1977 to Gautam Kumar Bammi and Shakti Bammi in the city of Bhopal, India. He completed his initial schooling in 1995 at Campion Higher Secondary School, Bhopal. After that he attended the Indian Institute of Technology (IIT), Bombay for his Bachelors degree in Civil Engineering. While at IIT, he was in his college's soccer team and represented IIT in Bombay's IIIrd Division Soccer League. After finishing his Bachelors, he decided to pursue graduate studies at North Carolina State University, Raleigh, NC, USA. At State he majored in Environmental Engineering and minored in Computer Science. He has accepted a position with Oil Services Company, Schlumberger Technology Corporation, at Houston, Texas.

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The size of the "*people sets*" that I want to thank unlike the size of the data sets that I analyzed for this research is large. Though there is a lot of variability amongst the people in the people sets I want to thank, there is no uncertainty in the fact that without their co-operation and help this work would not have been possible.

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1.0 INTRODUCTION

Mobile sources, both onroad and nonroad, are majors contributors to the total national emissions of Volatile Organic Compounds (VOCs), Nitrogen Oxides (NO_x) and Carbon Monoxide (CO) (EPA, 2000 b). They also contribute significantly to the total emissions of the Hazardous Air Pollutants (HAPs) (EPA, 2001 b). Table 1-1 shows the contribution of the mobile sources as a percentage of the total national emissions. The percentages shown for HAPs are 1996 figures while those of the others are 1998 numbers. It is clear that mobile sources contribute substantially to the total national emissions of several key pollutants.

Table 1-1. Contribution of Mobile Sources in the total National Emissions of air pollutants: VOCs, NO_x, CO and HAPs.

Mobile Source	**Emissions of**			
	VOC [a]	**NO_x [a]**	**CO [a]**	**HAP [b]**
On-Road Contribution (%)	29	31	57	30
Non-Road Contribution (%)	14	22	22	20
Total Contribution (%)	43	53	79	50

[a] Values for year of 1998, (EPA, 2000 b).
[b] Values for the year of 1996, (EPA, 2001 b).

Section 112(k) of Title III of the Clean Air Act Amendments of 1990 requires EPA to develop a strategy for controlling emissions of 188 listed air toxics or HAPs. Section 112 focuses on stationary and area sources. Other sections of the act in particular, Section 202(1) contains two specific requirements for motor vehicles (Sierra Research, 1999):

- EPA was to complete a study of the need for and feasibility of controlling air toxic pollutants from motor vehicles and motor vehicle fuels by May 15th, 1992.

- EPA was to promulgate regulations containing requirements to control air toxic emissions from motor vehicles and motor vehicle fuels by May 15th, 1995.

Presently EPA is concentrating on 33 air toxics that present the greatest threat to public health in largest number of urban areas under a national scale air toxics assessment program (EPA, 2001 a). Mobile sources are one of the major contributors to air toxic emissions. They account for 50 percent (30% highway vehicles or onroad mobile sources + 20% nonroad mobile sources) of the total 1996 annual air toxic emissions of 4.6 million tons, for all the 188 listed air toxics. Of the annual 1996 emissions of the 33 air toxics (1.1 million tons/year) the mobile sources account for 51 percent (29% highway vehicles or onroad mobile sources + 22% nonroad mobile sources) (EPA, 2001 b). Acetaldehyde, Benzene, 1,3-butadiene and formaldehyde figure in this list of top 33 HAPs mentioned above.

The 1990 Clean Air Act Amendments specifically directed the U.S. Environmental Protection Agency (EPA) to study the contribution of nonroad engines to urban air pollution, and regulate them if warranted. "Nonroad" is a term that covers a diverse collection of engines, equipment, and vehicles. Also referred to as "off-road" or "off-highway," the nonroad category includes outdoor power equipment, recreational equipment, farm equipment, construction equipment, lawn and garden equipment, and marine vessels (EPA, 2000 a). According to an EPA report, small (at or below 19 kW/25 hp) nonroad gasoline fueled spark ignited (SI) engines contribute about 20 percent of HC emissions and 23 percent of CO emissions from mobile sources. These engines are

primarily used in lawn and garden applications. While diesel fueled nonroad compression ignition (CI) engines contribute to about 20 percent NO_x emissions from mobile sources. These engines are primarily used in construction, farm and industrial applications (EPA, 2000 a). Currently, neither uncertainty nor variability is properly quantified in these HAP and nonroad emission factors and emission inventories.

Emission factors and emissions estimates are subject both to variability and uncertainty. Variability refers to real differences in emissions among multiple emission sources at any given time or over time for any individual emission source. Variability in emissions can be attributed to variation in: fuel or feedstock composition; ambient temperature; process design; process maintenance; and/or process operation. Uncertainty refers to lack of knowledge regarding the true value of emissions. Sources of uncertainty include: small sample sizes; lack of precision and/or accuracy in measurements; non-representativeness; or lack of data (Bammi and Frey, 2001).

Emission Inventories (EIs) are an important part of environmental decision making. They are used for temporal emissions trend characterization, emissions budgeting for regulatory and compliance purposes and in air quality models for estimating ambient air quality. Non-quantified errors and biases in the EIs can lead to erroneous conclusions regarding emissions trends, apportionment of emissions, compliance, and the relationship between emissions and the ambient pollutant concentration. Hence, characterization and evaluation of the quality of data should be an integral part of emissions inventory work (Bammi and Frey, 2001). The National Research Council, in a recent report on modeling of mobile source emissions, has

recommended that efforts be conducted to quantify uncertainties in mobile source emissions (NRC 2000). In this work, a quantitative approach to the characterization of variability and uncertainty is presented and used as an important means to convey the quality of estimates to analysts and decision makers. This work focuses on the application of quantitative analysis of variability and uncertainty to different case studies for mobile source emission categories.

1.1 Probabilistic Analysis of Emission Inventories

The quantitative approach to probabilistic analysis of both variability and uncertainty employed in this work differs from the conventional approach to emission factor and inventory data quality ratings (Frey *et al.*, 1999). Qualitative "A" through "E" ratings are defined and reported by EPA (US EPA, 1995). The Data Attribute Rating System (DARS) is a method for combining data quality scores for both emission factor and activity data to develop an overall quality score for an emission inventory (Beck and Wilson, 1997). While DARS can be used to compare quality ratings for EIs, it can neither be used to quantify the precision of an inventory nor to evaluate the robustness of a decision to uncertainty. Other efforts have focused on characterizing the mean and variance of emission estimates and using simplified approaches for combining uncertainties in activity and emission factor data to arrive at an aggregate uncertainty estimate (Dickson and Hobbs, 1989; NRC 2001; Balentine and Dickson, 1995). The applications of these approaches suffer from many shortcomings including: restrictive assumptions about the shape of probability distribution models; failure to distinguish between variability and uncertainty estimates; and improperly analyzed small sample data. The probabilistic approach presented here will remedy these shortcomings.

EPA, the National Academy of Sciences (NAS), and others recognize the important role of probabilistic analysis (NRC 1994; NRC 2000) In March 1997, EPA issued "Guiding Principles for Monte Carlo Analysis" (EPA 1997). The policy supports "good scientific practices" in quantifying variability and uncertainty. Therefore it is critically important that research be undertaken in the development and application of probabilistic methods. An overview of probabilistic analysis methods is given by Cullen and Frey (1999). The recent NRC recommendations regarding uncertainty analysis for mobile sources also motivate this work (NRC 2000). There have been some efforts to quantify uncertainty in mobile sources, focused on highway vehicles (Kini and Frey, 1997; Pollack *et al*., 1999; Frey *et al*., 1999). In addition, there has been work to quantify uncertainties in emissions of stationary point and area sources (Frey *et al*., 1999; Frey and Rhodes, 1996; Rhodes and Frey, 1997; Frey and Li, 2001). In this thesis, a methodology for simultaneous characterization of both variability and uncertainty is presented, with applications to on-road and non-road mobile emission sources.

1.2 Methodology for Characterizing Variability and Uncertainty

A methodology for characterizing variability and uncertainty in quantities such as emission factors is presented in this section. For a more detailed discussion on the topic the reader is directed to Frey and Rhodes (1996), Frey and Rhodes (1998) and Frey and Burmaster (1999). This methodology is based on statistical analysis of data in order to develop input assumptions for probabilistic modeling. Hence compilation and evaluation of data needed to develop probability distributions is presumed.

1.2.1 General Approach

The following are the major steps of the general approach described by Frey *et al*. (1999) to characterize variability and uncertainty in emission factors and emission inventories. It was applied where applicable to the data sets analyzed in this work.

1 Compilation and evaluation of database for emission and activity factors.

2 Developing empirical cumulative distribution functions (CDF) for each emission and activity factor to visualize the data. To test for dependencies between pairs of activity and emission factors. Scatter plots are also developed.

3 Representing variability in activity and emission factor data by fitting, evaluating and selecting from alternative parametric probability distribution models.

4 Characterizing uncertainty in the distributions for variability.

5 Estimation of uncertainty in emissions from a population of emission sources by propagating uncertainty and variability in activity and emissions factors.

1.2.2 Visualization of Data

All data sets used in this work were plotted as empirical CDFs and in some cases also as scatter plots. Some of the main advantages of visualizing data sets using empirical CDFs and scatter plots are: (1) evaluation of central tendency and dispersion of the data; (2) potential aid in selecting parametric probability distribution models to fit the data by visually inspecting the shape of the empirical distribution; (3) identifying possible anomalies in the dataset (e.g. outliers); and (4) identifying possible dependencies among

variables. All the quantities considered in this study are assumed to be continuous random variables.

1.2.3 Empirical Cumulative Distribution Functions

Distributional data may often be summarized using empirical cumulative distribution functions (Cullen and Frey, 1999). These functions provide a relationship between fractiles (or percentiles) and quantiles. A quantile is a value of a random variable associated with a given fractile. To get an indication of the dispersion of the distribution we may, for example, be interested in knowing the range enclosed by the 0.01 and 0.99 fractiles.

1.2.3.1 Plotting Position

To estimate the fractile or percentile from data requires rank ordering of the data. The methods used for estimating the percentile of an empirically observed data point are called "plotting positions." The plotting position is an estimate of the cumulative probability of a data point. As described by Cullen and Frey (1999), Harter (1984) provides an overview of the various types of plotting positions. A commonly used plotting position, proposed by Hazen (1914), is used in this study.

$$F_x(x_i) = Pr(X < x_i) = (i - 0.5)/n \qquad (1\text{-}1)$$

$$\text{for } i = 1,2,\ldots,n \text{ and } x_1 \leq x_2 \leq \ldots \leq x_n$$

where,

i = Rank of the data point when the data set is arranged in an ascending order

n = number of data points

$x_1 \leq x_2 \leq \ldots \leq x_n$ are data points in the rank ordered set

$Pr(X \leq x_i)$ = Cumulative probability of obtaining a data point whose value is less than or equal to x_i

As an example, empirical distribution function for 16 data points of the NO_x emission factor of 2-Stroke Lawn and Garden (L & G) engines in units of g/hp-hr, based on Equation (1.1), is shown in Figure 1.1. The data used in this example is discussed in detail in Chapter 3. The figure illustrates that the central tendency of the emission factors is toward a value of approximately 0.73 g/hp-hr, as reflected by the median (50^{th} percentile). The 95 percent probability range indicates the dispersion of the emission factors range from approximately 0.08 g/hp-hr to 2.5 g/hp-hr. In this case the distribution is positively skewed, with a heavier tail of values to the right.

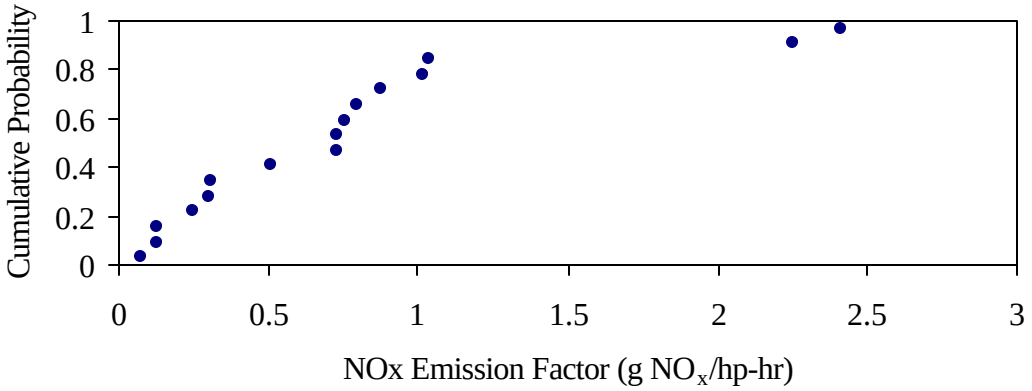

Figure 1-1. Empirical Distribution Function for NO_x Emission Factor of 2-Stroke Lawn & Garden Engines in Units of g/hp-hr.

1.2.3.2 Parametric Probability Distribution Models

A probability distribution model is a description of the probabilities of all possible sets of outcomes in a range space (Cullen and Frey, 1999). One class of probability distribution models is continuous parametric distributions. These probability distribution

models are described by their parameters. The advantage of using them is that data sets containing potentially large numbers of samples can be described by a probability model that is defined by typically one to four parameters. Two of the most common approaches for estimating the parameters of a distribution are the method of matching moments (MoMM) and maximum likelihood estimation (MLE). MoMM is based upon matching moments or central moments of a fitted parametric distribution (like mean, variance) to the moments or central moments of the data set. Usually MoMM estimators are easy to calculate. For example Hahn and Shapiro (1967) present convenient solutions for MoMM parameter estimates for Normal, Lognormal, Gamma and Weibull distributions. The maximum likelihood estimation approach involves selecting values of distribution parameters to define a distribution that is most likely to yield the observed data set (Cohen and Whitten, 1988). For independent samples, a likelihood function is defined as the product of the Probability Density Function (PDF) evaluated at each of the sample values. For a continuous random variable for which independent samples have been obtained, the likelihood function is:

$$\boldsymbol{L}(\theta_1, \theta_2,\ldots,\theta_k) = \prod_{i=1}^{n} f(x_i \mid \theta_1,\theta_2,\ldots,\theta_k), \qquad (1\text{-}2)$$

where,

$\theta_1, \theta_2,\ldots,\theta_k$ = Parameters of the parametric probability distribution

k = number of parameters for the parametric probability distribution model

x_i = Values of the random variable, for i = 1,2, …, n

n = number of data points in the data set

f = Probability density function

The value of k usually is either two (for a two-parameter distribution) or three (for a three-parameter distribution). Standard techniques of calculus are used sometimes to determine the values of the parameters that maximize the likelihood function. However, usually log transformations of the likelihood functions (referred to as log likelihood functions) are used because of the convenience involved with working with them. For cases when an analytical solution is not readily available, the MLE parameters can be found using numerical techniques such as Newton-Raphson method or non-linear programming optimization (Bharvirkar, 1999).

Table 1-2 presents the log-likelihood functions for estimating the parameters of Normal, Lognormal, Gamma and Weibull distributions (Bharvirkar, 1999). The number of data points is n and each data point is represented as x_i, where *i* takes the values 1 through *n*.

The maximum likelihood estimates do not always yield minimum variance or unbiased estimates for small sample sizes. However, for larger sample sizes the maximum likelihood method is more consistent, efficient, robust, unbiased and sufficient than other methods. A sufficient estimator means an estimator that makes maximum use of the information contained in the data set. MoMM estimators, in comparison to MLE tend to be more robust and less efficient (Frey and Burmaster, 1999; Bharvirkar, 1999). In the present study the MLE method has been used.

Table 1-2 Expressions for Log-Likelihood Functions for Data Belonging to Various Probability Distribution Models.

Name of the Distribution [a]	**Log-Likelihood Function** [b]
Normal (μ = mean, σ = standard deviation)	$J(m,s) = -n\ln s - \frac{n}{2}\ln(2p) - \sum_{i=1}^{n}\left\{\frac{(x_i - m)^2}{2s^2}\right\}$
Lognormal (μ = mean, σ = standard deviation, of log-transformed data)	$J(m,s) = -n\ln s - \frac{n}{2}\ln(2p) - \sum_{i=1}^{n}\left\{\frac{((\ln x_i) - m)^2}{2s^2}\right\}$
Gamma (α = shape, β = scale, parameters)	$J(a,b) = -n\{a\ln(b) + \ln[\Gamma(a)]\} + \sum_{i=1}^{n}\left\{(a-1)\ln(x_i) - \frac{x_i}{b}\right\}$
Weibull (α = shape, β = scale, parameters)	$J(a,b) = -n\left(\frac{a}{b}\right) + \sum_{i=1}^{n}\left\{(a-1)\ln\left(\frac{x_i}{b}\right) - \left(\frac{x_i}{b}\right)^a\right\}$

[a] Note: Parameter values are different for different distributions even though the same symbol has been used to represent their parameters.
[b] Source: Masters Thesis (Chapter 2) of Ranjit Bharvirkar (Bharvirkar, 1999).

1.2.4 Bootstrap Methodology

In order to characterize uncertainty in the mean emission factors and to evaluate the adequacy of the fit of a parametric distribution to the data, bootstrap simulation is performed in this work. Bootstrap simulation is a numerical technique originally developed for the purpose of estimating confidence intervals for statistics (Efron and Tibshirani, 1993) This method can provide solutions for confidence intervals in situations where exact analytical solutions may be unavailable and in which approximate analytical solutions are inadequate. Example applications of bootstrap simulation are available elsewhere (Frey and Rhodes, 1996; Frey and Li, 2001; Frey and Burmaster, 1999; Zheng and Frey, 2001).

Bootstrap simulation uses a conceptually straightforward approach. By fitting a parametric distribution to a dataset, an estimated population distribution is developed. A simulated random sample of data points of the same sample size as the original data is drawn from the assumed population distribution. This data set is referred to as a "bootstrap sample." Any statistics of interest, such as the mean, standard deviation, distribution parameters, distribution percentiles, or others, are calculated from the bootstrap sample. For each bootstrap sample, the estimate of a statistic is referred to as the "bootstrap replication" of the statistic. Multiple bootstrap samples are simulated using Monte Carlo simulation. Typically, one may simulate 500 to 2000 bootstrap samples. Thus one would sample 500 to 2000 bootstrap replications of each statistic of interest. The bootstrap replications of a given statistic are used to describe a probability distribution for the statistic. A probability distribution for a statistic is referred to as a "sampling distribution." Confidence intervals for a statistic are inferred from its sampling distribution. For example, the 2.5^{th} and 97.5^{th} percentiles of the sampling distribution would enclose a 95% confidence interval. Using bootstrap simulation, confidence intervals are constructed for the mean emission factor estimates and for the fitted cumulative distribution functions.

1.3 Overview of Thesis

In Chapter 2, variability and uncertainty in air toxic emissions from light duty vehicles are studied. This is followed in Chapter 3 by a study of variability and uncertainty in emission factors for the Lawn and Garden nonroad emission source category. In Chapter 4, variability and uncertainty in nonroad emission factors in the

Construction, Farm and Industrial source categories are developed. Chapter 5 summarizes the conclusions from this work.

2.0 AIR TOXIC EMISSIONS FROM ON-ROAD MOBILE SOURCES

Currently, neither uncertainty nor variability are properly quantified in HAP emission inventories. There is no quantitative indication of the degree of confidence that should be placed in the estimates. In this chapter, quantitative methods for characterizing both variability and uncertainty are demonstrated and these methods are applied to case studies of emission factors for the air toxics namely Benzene, 1-3, Butadiene, Methyl Tertiary Butyl Ether (MTBE), Formaldehyde and Acetaldehyde. This study was conducted on a set of data collected by California Air Resources Board (CARB), which performed a substantial number of speciated emissions tests over both Unified Cycle (UC), and Federal Test Procedure (FTP) cycles. This data set was chosen because it has been used by the EPA to develop off-cycle (aggressive driving) adjustment factors (Sierra Research, 1999). The purpose of this exercise is to study variability and uncertainty in selected urban air toxics, which are ranked very high in the list of top 33 HAPs as discussed in Chapter 1. This is being done for the following reasons:

- To quantify inter-vehicle variability in emissions of Benzene, 1-3, Butadiene, Methyl Tertiary Butyl Ether (MTBE), Formaldehyde and Acetaldehyde;
- To quantify uncertainty in mean emissions;
- To evaluate alternative methods for reporting emissions and to select one that is most robust;
- To compare emissions from normal and high emitters and test difference in emissions from vehicles running on selected fules.

2.1 Exhaust Toxics Emissions Modeling Methodology

There are three sources of toxic emissions: (1) exhaust emissions, (2) evaporative emissions, and (3) diesel Particulate Matter (PM) emissions (Sierra Research, 1999). The Sierra Research study includes only Benzene and MTBE as toxics in evaporative emissions, which are caused during the refueling of mobile sources. Diesel PM emission occur from diesel-fueled mobile sources. These emissions have been modeled using the EPA's PART5 model. However, this work concentrates on only exhaust emissions, as evaporative emissions data was not available for HAPs. Also since focus of the study was on gasoline-fueled vehicles, diesel PM was not included in the analysis. In the following sections, the methodology used to model exhaust toxic emissions from on-road mobile sources is presented. Some of the previous efforts made by EPA for this are discussed. This is followed by a discussion of the Complex Model. After that the development of Toxic-TOG curves and their use in estimating air toxic emissions from the on-road mobile source exhaust emissions is presented.

2.1.1 Previous EPA Estimates

For the development of the 1993 Motor Vehicle Related Air Toxics Study (MVRATS), EPA put in a lot of effort in developing estimates of on-road motor vehicle air toxics (EPA, 1993). Since most of the available data was from low-mileage, well-maintained vehicles, EPA did not develop direct gram/mile or milligram/mile toxic emission rates that would be reflective of the in-use fleet. Instead, EPA used available emissions data to estimate air toxics emissions as a fraction of the total organic gases (TOG) emitted by the test vehicles. Those estimates were then applied to the output from an emission factor model (MOBILE 4.1 in the case of the EPA's MVRATS) to estimate

air toxics from the in-use fleet. During development of emission estimates for motor vehicle air toxics, EPA discovered that the toxics fractions were a function of a vehicle's emission control system design and fuel type (i.e., gasoline versus diesel). Hence toxics fractions were developed separately for each of the following technologies (EPA, 1993; Sierra Research, 1999):

- Gasoline fueled vehicle with Three-way catalyst (TW CAT)
- Gasoline fueled vehicle with Oxidation Catalyst (OX CAT)
- Gasoline fueled vehicle with three-way plus oxidation catalyst (TW+OX CAT)
- Gasoline fueled vehicle with no Catalyst (NO CAT)
- Light Duty Diesel vehicle (LD Diesel), and
- Heavy Duty Diesel vehicle (HD Diesel).

A summary of the toxics fraction for benzene, 1-3-butadiene, formaldehyde, and acetaldehyde from the 1993 MVRATS is contained in Table 2-1.

Table 2-1. Exhaust Toxics Fractions as a % of TOG Emissions used by EPA in 1993 MVRATS

Technology	**Air Toxic**			
	Benzene	**1,3-Butadiene**	**Formaldehyde**	**Acetaldehyde**
TW CAT	5.27	0.57	0.87	0.47
TW+OX CAT	2.87	0.44	1.37	0.45
OX CAT	4.05	0.44	1.39	0.44
NO CAT	4.05	0.98	2.69	0.62
LD Diesel	2.29	1.03	3.91	1.25
HD Diesel	1.06	1.58	2.80	0.75

Source: (Sierra Research, 1999)

2.1.2 Complex Model for Reformulated Gasoline

After releasing the MVRATS, the reformulated gasoline (RFG) regulations were finalized by EPA. The Complex Model, developed as part of these regulations, allows refiners to assess compliance of particular fuel formulations with the RFG performance standards (i.e., percent reductions of VOC, NO_x, and toxics). It calculates the emissions impacts of alternative gasoline formulations relative to the baseline 1990 industry average fuel. This baseline fuel is defined in 1990 Clean Air Act Amendments. Some of the fuel parameters included in the calculations are (Sierra Research, 1999):

- Oxygenate content (wt %) and type (i.e., MTBE, ethanol, ETBE, or TAME)
- Sulfur content (ppm)
- Reid Vapor Pressure (psi)
- Aromatics (vol %)
- Olefins (vol %)
- Benzene (vol %)

The Complex Model also estimates the impact of varying fuel formulations on benzene, acetaldehyde, formaldehyde, 1,3-Butadiene, and polycyclic organic matter (POM) exhaust emissions. The Complex Model was based on a much larger database compared to the toxic fractions used in the MVRATS by EPA. The Complex Model is the most robust tool available for estimating toxics emissions from late-model vehicles, especially when alternative fuel formulations are being investigated. However, one of its

limitations are that it uses a database having only 1986 to 1990 model year vehicles. Hence it cannot be used to predict toxic emission rates from older technology vehicles, and forecasting results onto future technologies causes uncertainty to be introduced in the analysis. Secondly, its database includes only gasoline-fueled light-duty cars and trucks. Thus it cannot be used to predict toxics emissions from diesel vehicles, heavy-duty gasoline vehicles, or motorcycles (Sierra Research, 1999).

2.1.3 Treatment of Normal and High Emitters: "Toxic-TOG Curves"

A normal emitter is a vehicle whose measured emission rate of pollutants is less than or equal to a predefined standard. A high emitter is a vehicle whose measured emission rate is higher than the predefined standard. This standard is different for different pollutants and hence while a vehicle can be grouped as a high emitter of NO_x, it may still be a normal emitter of THC. It was not clear what standard was used to define the high emitters for different pollutants in the report consulted for this study (Sierra Research, 1999). A model known as the T2ATTOX was used by EPA to generate on-road motor vehicle toxic pollutant emission factors (in mg/mi). T2ATTOX is a modified version of EPA's MOBILE5b emission factor model revised to model the impact of off-cycle fractions (e.g. aggressive driving, effects of whom are not included in the standard test procedures like FTP or UC) and fuel sulfur effects (Sierra Research, 1999).

Normal emitters and high emitters need to be treated separately as they may have different characteristics in terms of their response to fuel parameters (and corresponding toxics fractions). Inspection and Maintenance (I/M) scenarios impact the distribution of normal and high emitters in the fleet. EPA uses data for normal and high emitters as a

basis for linear interpolation and extrapolation of emissions. EPA has also developed a procedure for linear estimation of emissions for a "target" fuel based upon data for a base

-TOG" curves are used to estimate the emission rate of a specific HAP for the target fuel based upon knowledge of the TOG emission rate for the base fuel (Sierra Research, 1999). The T2ATTOX model uses this methodology. A summary of the methodology is presented below. The baseline fuel is the fuel that the model T2ATTOX assumes to be used in the fleet for generating the air toxic emission factors. The target fuel is the fuel for which the air toxic emission factors are needed. For this analysis, industry-average fuel defined in the 1990 Clean Air Act Amendments was considered as the baseline fuel. As an example to illustrate the calculation of Toxic-TOG curves, let us assume that the TOG emission rates, benzene emission rates, and benzene fractions for normal and high emitters corresponding to the baseline fuel and target fuel are as listed in the Table 2-1 (Sierra Research, 1999).

Table 2-2. Example Data for development of Benzene Toxic-TOG curves.

Fuel	**TOG (g/mi)**		**Benzene Fraction**		**Benzene (mg/mi)**	
	Normal	High	Normal	High	Normal	High
Base	0.17	1.48	4 %	3 %	4.62	58.1
Target	0.13	1.88	4 %	3 %	3.87	72.8

To explain the approach used, it is considered useful to start with a simple example and work backward from there. Assuming that T2ATTOX calculated a fleet-average emission rate of 1.0 g/mi TOG for the baseline fuel, the fraction of normal and high emitters making up the 1.0 g/mi emission rate could be calculated as follows:

$$TOG_{Flt,\ Base\ Fuel} = 1.0\ g/mi = F_N * TOG_{N,\ Base\ Fuel} + F_H * TOG_{H,\ Base\ Fuel} \quad (2\text{-}1)$$

$$F_H = 1 - F_N \quad (2\text{-}2)$$

where,

F_N = The fraction of normal emitters

F_H = The fraction of high emitters

$TOG_{N,\ Base\ Fuel}$ = The TOG emission rates for normal emitters on base fuel (g/mi)

$TOG_{H,\ Base\ Fuel}$ = The TOG emission rates for high emitters on base fuel (g/mi)

$TOG_{Flt,\ Base\ Fuel}$ = The fleet average TOG emission rate for both Normal and High Emitters (g/mi)

From Table 2-2, $TOG_{N,\ Base\ Fuel} \equiv 0.1662$ g/mi and $TOG_{H,\ Base\ Fuel} \equiv 1.4803$ g/mi). The fraction of highs is just (1- F_N). Substituting these into the Equation 2-1 we get:

$1.0 = F_N*[0.17(g/mi)] + [1 - F_N]*1.48(g/mi)$, solving this for F_N we get,

$F_N = (1.48 – 1) / (1.48 – 0.17)$

$F_H = 1 – F_N = 1 – 0.37 = 0.63$

Hence, solving for F_H and F_N, we get F_N equal to 0.37 and F_H equal to 0.63.

Using these fractions with the benzene emission rate for normal and high emitters, one can obtain the mean benzene emission rate for the target fuel presented in this example, i.e.,

$$BZ_{Flt, Target} = F_N * BZ_{N, Target} + F_H * BZ_{H, Target} \quad (2\text{-}3)$$

where,

$BZ_{Flt, Target}$ = The fleet average benzene emission rate for the target fuel (g/mi)

$BZ_{N, Target}$ = The average benzene emissions from normal emitters operating on the target fuel (g/mi)

$BZ_{H, Target}$ = The average benzene emissions from high emitters operating on the target fuel (g/mi)

Now plugging in the values from Table 2-2 of 3.87 mg/mile for $BZ_{N, Target}$ and 72.8 mg/mile for $BZ_{H, Target}$, and values of $F_N = 0.37$ and $F_H = 0.63$ as calculated above in Equation 2-3 we get:

$$BZ_{Flt, Target} = 0.37*[3.8733(mg/mi)] + 0.63*[72.7795(mg/mi)]$$

This gives $BZ_{Flt, Target}$ equal to a value of 47 mg/mi (or 0.047 g/mi). It may be noted that in this approach the benzene emission rate for the target fuel was used directly

without first adjusting the base fuel TOG levels for the target fuel (Sierra Research, 1999).

The emissions data given in above table can also be thought of in graphical terms as illustrated in the Figure 2-1.

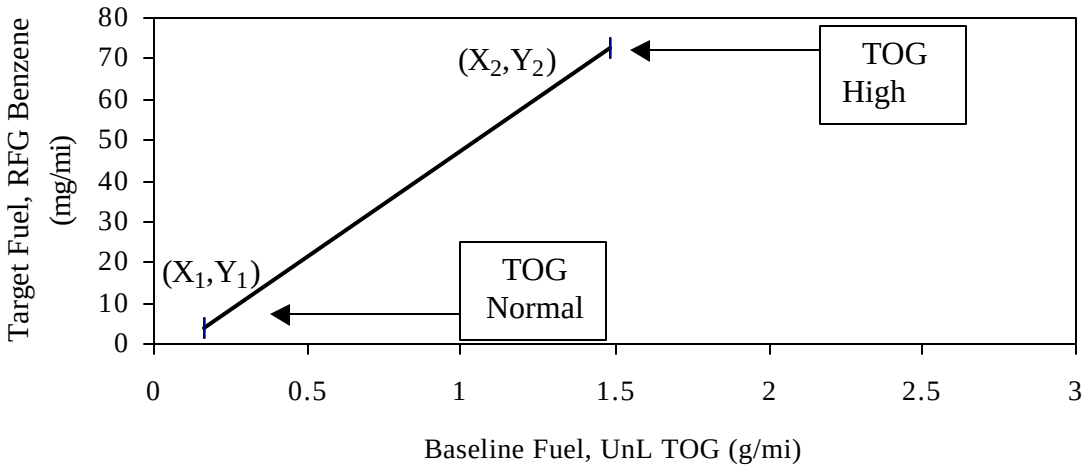

Figure 2-1. An Example of Benzene-TOG Curve

The emissions data in presented in Table 2-2 can also be thought of in graphical terms as that of a straight line. Keeping this in mind, the target fuel benzene emission level (in g/mi or mg/mi) can be thought of as a linear function of the baseline fuel TOG emission rate. This linear function is presented as the Toxic-TOG curve. The lower end of the curve is defined by the baseline fuel normal emitter TOG emission rate, while the upper end is defines by the baseline fuel high emitter TOG emission rate. This means that the two points used to define the Toxic-TOG curve are ($TOG_{N,\ Base\ Fuel}$, $BZ_{N,\ Target\ Fuel}$) $\equiv (X_1, Y_1)$ i.e. the lower end and ($TOG_{H,\ Base\ Fuel}$, $BZ_{H,\ target\ Fuel}$) $\equiv (X_2, Y_2)$ i.e. the

upper end. Since these Toxic-TOG curves are a straight line they can also be defined using the coordinate geometry formula for a straight lines:

$$Y = m(X) + c \qquad (2\text{-}4)$$

where,

c = the intercept that the line make with the y-axis

m = slope of the line

Hence for the Toxic-TOG curve which is a straight line the intercept (c) and a slope (m), are given by the following coordinate geometry formulae:

$$c = (X_2 Y_1 - X_1 Y_2) / (X_2 - X_1) \qquad (2\text{-}5)$$

$$m = (Y_2 - Y_1) / (X_2 - X_1) \qquad (2\text{-}6)$$

where,

X_1 = $TOG_{N,\ Base\ Fuel}$ (g/mi)

Y_1 = $BZ_{N,\ Target\ Fuel}$ (mg/mi)

X_2 = $TOG_{H,\ Base\ Fuel}$ (g/mi)

Y_2 = $BZ_{H,\ target\ Fuel}$ (mg/mi)

Using baseline fuel normal and high emitter TOG emission rates (in g/mi) and the target fuel normal and high emitter benzene emission rates (in mg/mi) defined in Table 2-2 as example, the value of c is calculated equal to – 0.0048 (g/mi) and m is equal to 0.05.

$$c = \frac{[1.48(g/mi) * 3.87(mg/mi) \; 0.17(g/mi) * 72.8(mg/mi)]}{[1000(mg/g) * [1.48(g/mi) \; 0.17(g/mi)]]}$$

$$m = \frac{[72.8(mg/mi) \; 3.87(mg/mi)]}{[1000(mg/mi) * [1.48(g/mi) \; 0.17(g/mi)]]}$$

The factor of 1000 in the denominator is for converting $BZ_{N, Target\ Fuel}$ and $BZ_{H, target\ Fuel}$ from mg/mi units to g/mi units.

Using the above example of a fleet-average TOG emission rate of 1.0 g/mi on the base fuel, the fleet-average benzene emission rate (in mg/mi) is calculated as:

$$Y\ (\text{i.e. } BZ_{Flt, target}) = m^* X\ (\text{i.e. } TOG_{Flt, base\ Fuel}) + c$$

$$= 0.0524*(1) + (-0.0048)$$

$$= 0.047 \text{ g/mi}$$

$$= 47 \text{ mg/mi}$$

which gives the same result as the calculation performed above.

An important issue related to the methodology presented above is how to deal with baseline TOG values above the high emitter point and below the normal emitter point. For these cases a linear relationship is assumed and the Toxic-TOG curve is extrapolated to make it go through the origin. Applying these assumptions to the Toxic-TOG curve shown in Figure 2-1, the new curve is presented in Figure 2-2:

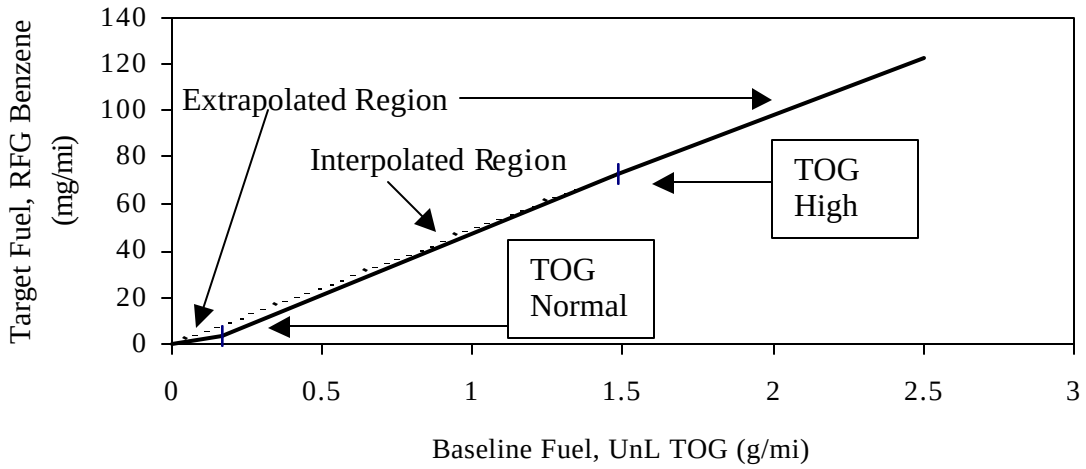

Figure 2-2. Corrected Example Benzene-TOG Curve

The above approach was used to estimate toxic emissions as a function of baseline fuel TOG emission rates for all categories of vehicles (Sierra Research, 1999).

2.2 Methodology Used to Analyze CARB Data

CARB provided results from 36 speciated emissions tests, half of which were performed using the Federal Test Procedure (FTP) and the other half were performed over the Unified Cycle (UC). A total of 13 different test vehicles are represented. The database reported the concentrations of Total Hydrocarbon (THC), TOG, Benzene, 1,3-Butadiene, MTBE, Formaldehyde and Acetaldehyde (Sierra Research, 1999).

2.2.1 Finding Most Useful Measure of Emissions

Variability analysis was conducted for the mass per mile emissions of the individual pollutants and for their percent fractions of TOG and THC for both the UC and FTP cycles. Between TOG and THC, TOG was chosen to calculate the percent fractions of the air toxics, since TOG is more widely used in the literature as a measure of exhaust emissions than THC. Different probability distributions includinig the Normal, Lognormal, Gamma and Weibull, were fitted to the data sets of all the five pollutant emissions in units of g/mi and as percent of TOG for both UC and FTP procedures. The ones that were judged to fit the best were chosen for the variability analysis. This was done to quantify variability and to determine the most useful measure of emissions from vehicles. The most useful measure of emissions should have the least amount of variability. Table 2-3 and 2-4 present a summary of the variability analysis done for all the five pollutants for FTP and UC procedures.

Table 2-3. Summary of the Variability Analysis Done for all the Five Pollutants Using Data Collected by the Federal Test Procedure.

Pollutants	Unit as mg/mile			Unit as % of TOG		
	Mean of data	95% Prob. Range [a]	Variability Factor [b]	Mean of data	95% Prob. Range [a]	Variability Factor [b]
Benzene	21.0	1.11 to 101	91	3.25	2.13 to 4.75	2
1,3-Butadiene	3.25	0.13 to 15.4	118	0.46	0.19 to 0.95	5
MTBE	12.6	0.17 to 52.3	308	2.39	0.47 to 5.0	11
Formaldehyde	11.5	0.5 to 58.6	117	1.9	0.55 to 4.75	9
Acetaldehyde	3.11	0.08 to 18.2	228	0.39	0.17 to 0.75	4

[a] Range between 2.5^{th} percentile and 97.5^{th} percentile based on fitted distribution.
[b] Ratio of the 97.5^{th} percentile to the 2.5^{th} percentile based on fitted distribution.
Note: Except for MTBE all the other pollutants have Lognormal as fitted distribution for variability analysis. For MTBE Weibull distribution was used.

Table 2-4. Summary of the Variability Analysis Done for all the Five Pollutants Using Data Collected by the Unified Cycle Procedure.

Pollutants	Unit as mg/mile			Unit as % of TOG		
	Mean of data	95% Prob. Range [a]	Variability Factor [b]	Mean of data	95% Prob. Range [a]	Variability Factor [b]
Benzene	25.2	1.75 to 119	68	4.17	1.96 to 7.85	4
1,3-Butadiene	2.61	0.13 to 113	103	0.40	0.12 to 1	8
MTBE	12.3	016 to 50.8	312	2.03	0.22 to 5.1	23
Formaldehyde	11.3	0.41 to 72.2	177	2.11	0.28 to 7.8	28
Acetaldehyde	3.00	0.13 to 15.6	124	0.39	023 to 0.64	3

[a] Range between 2.5^{th} percentile and 97.5^{th} percentile based on fitted distribution.
[b] Ratio of the 97.5^{th} percentile to the 2.5^{th} percentile based on fitted distribution.
Note: Except for MTBE all the other pollutants have Lognormal as fitted distribution for variability analysis. For MTBE Weibull distribution was used.

To characterize the range of variability, a "variability factor" was calculated based on the ratio of the 97.5^{th} percentile value to that of 2.5^{th} percentile value. A larger ratio implies greater variability. A variability factor of 10 implies that the variability spans one order of magnitude. On comparing the results of variability analysis of the CARB database it was found that the variability in the pollutant emissions concentrations (in units of mg/mi) was typically an order of magnitude more than the variability in the pollutant emissions in units of percent of TOG. For example, the variability in the %TOG for benzene has a variability factor of 2, whereas for mg/mile emissions it is 91, or more than 45 times larger. Similar results for the variability analysis were obtained using the air toxic emissions data collected by the Unified Cycle (see Table 2-4). For example, the variability in the %TOG for benzene has a variability factor of 4, whereas for mg/mile emissions it is 68, or more than 17 times larger.

Figures 2-3, 2-4, 2-5 and 2-6 present graphically some of the typical results obtained in the variability analysis. Figure 2-3 shows the benzene emission values range from approximately 2 mg/mi to approximately 75 mg/mi (i.e. an order of magnitude of variability) while the benzene emission values range from approximately 2.3 % of TOG to about 5 % of TOG in Figure 2-4. Similarly, in Figure 2-5 the benzene emission values range from approximately 3 mg/mi to approximately 80 mg/mi (i.e. an order of magnitude of variability) while the benzene emission values range from approximately 2.4 % of TOG to about 8 % of TOG in Figure 2-6. Also the data sets shown in Figures 2-3 and 2-5 seem to be positively skewed. Hence the variability analysis gave similar results for both the UC and FTP cycles.

Scatter plots of pollutant concentrations versus TOG and THC concentrations were made for data collected using the FTP cycles. Figures 2-7 and 2-8 present some of the typical examples. In Figure 2-7 for example, if the benzene emissions were a constant percentage of TOG emissions, then all the data points would fall on a straight line. Although there does appear to be a linear trend of an increase in benzene emissions with an increase in TOG emissions, there is some scatter in the trend. Similar results are obtained when comparing benzene emissions to the THC emissions. Since TOG and THC based approaches give similar results, and since TOG is a more commonly used measure, benzene emissions could be calculated based upon TOG emissions.

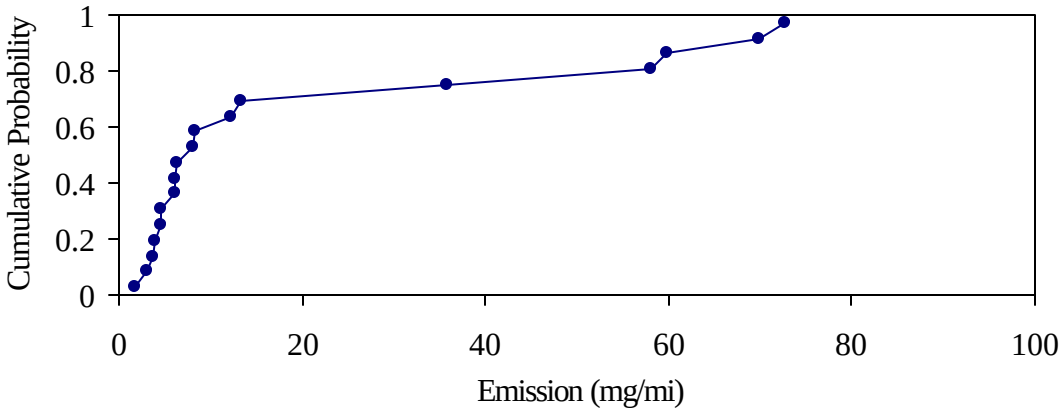

Figure 2-3. Variability in Benzene Emissions (mg/mi) Using FTP Cycle

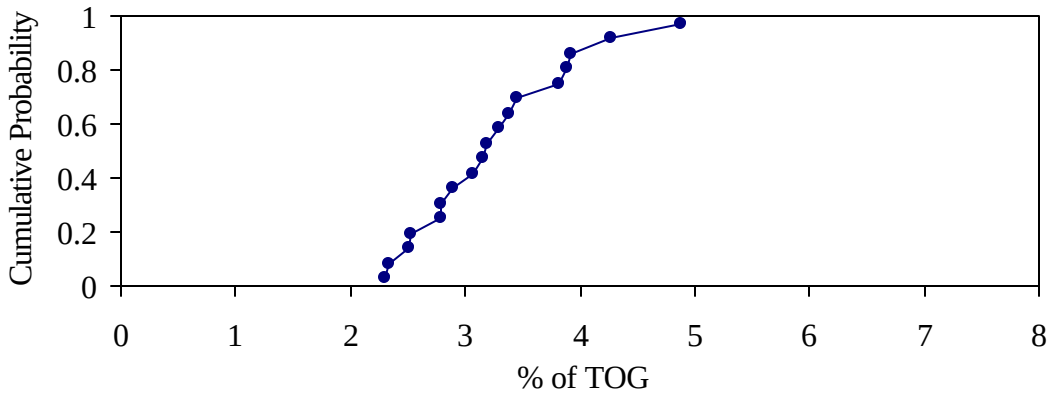

Figure 2-4. Variability in Benzene Emissions (Percent of TOG) Using FTP Cycle

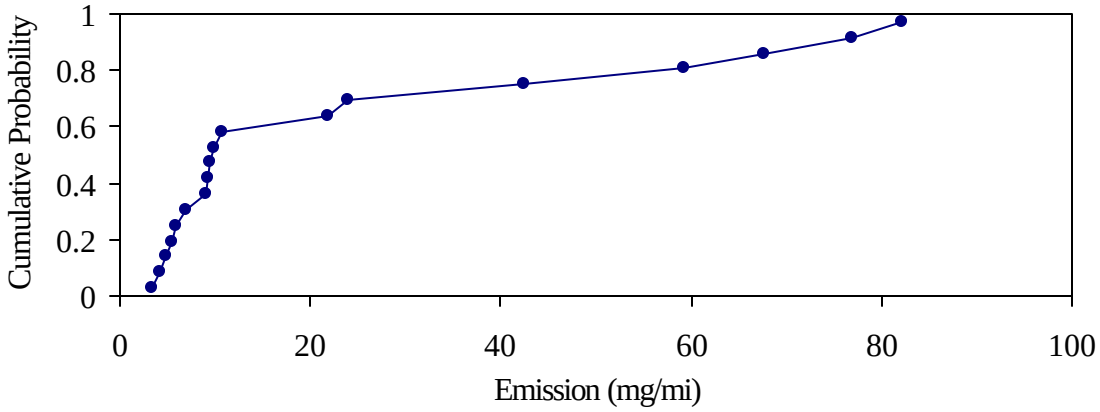

Figure 2-5. Variability in Benzene Emissions (mg/mi) Using Unified Cycle

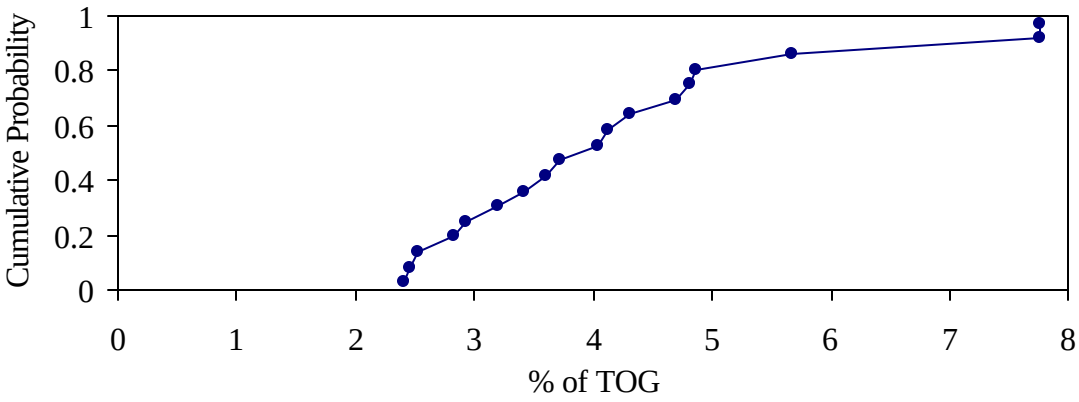

Figure 2-6. Variability in Benzene Emissions (Percent of TOG) Using Unified Cycle

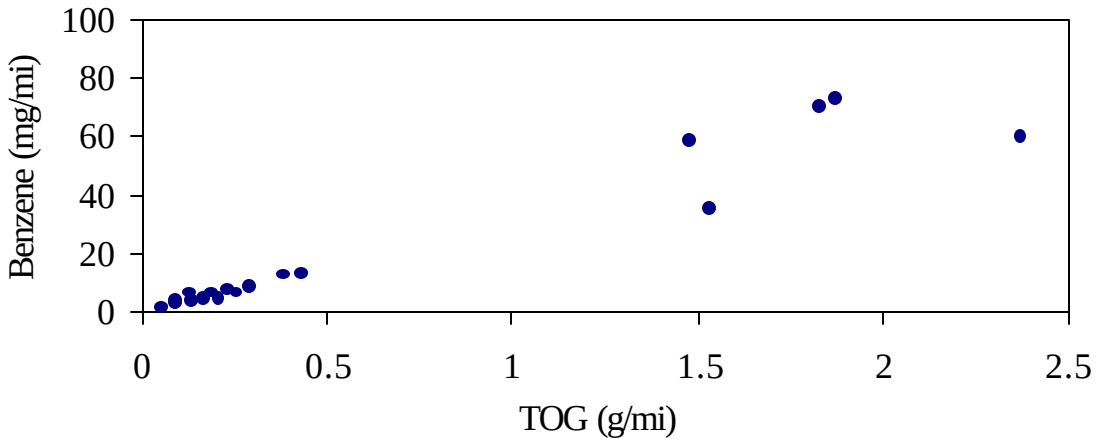

Figure 2-7. Scatter Plot of Benzene Concentration vs TOG for FTP Cycle

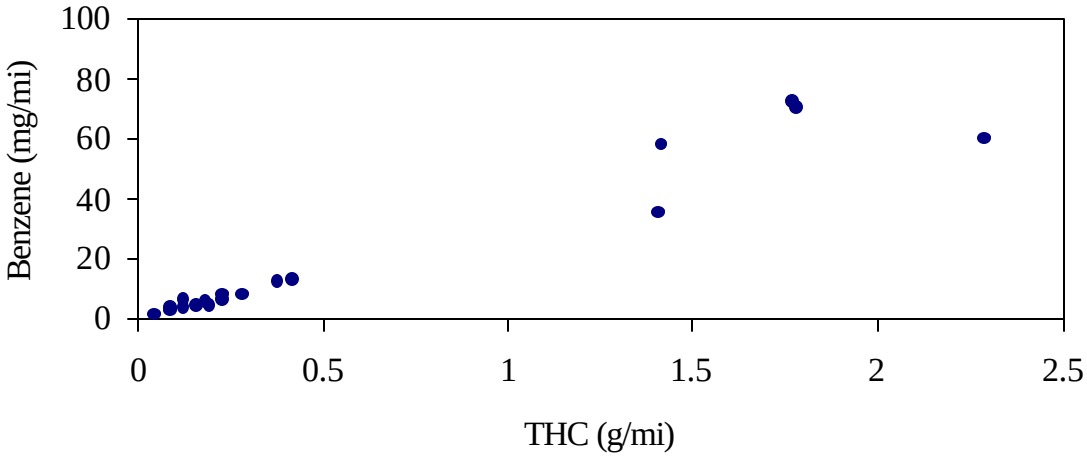

Figure 2-8. Scatter Plot of Benzene Concentration. vs THC for FTP Cycle

Figures 2-9 and 2-10 show scatter plots of pollutant concentrations versus TOG and THC concentrations that were made for data collected using the UC cycle. In Figure 2-9 for example, if the benzene emissions were a constant percentage of TOG emissions, then all the data points would fall on a straight line. Although there does appear to be a linear trend of an increase in benzene emissions with an increase in TOG emissions, there is some scatter in the trend. Similar results are obtained when comparing benzene emissions to the THC emissions. Thus it can be seen that similar trends are obtained in this analysis for both FTP and UC cycles.

Some of the typical scatter plots of the toxic percent of TOG versus TOG for the five pollutants are shown in Figures 2-11 and 2-12. In Figure 2-11, the benzene emissions as a percentage of TOG emissions for the FTP cycle indicate that the percentage does not appear to vary with the TOG emissions. For example the benzene emissions are approximately 3.2 percent of the TOG emissions regardless of whether TOD emissions are low (e.g. less than 0.5 g/mi) or high (e.g. greater than 1.5 g/mi). Thus it appears reasonable to treat the percentage of TOG emissions in the form of benzene as a quantity that is statistically independent of the magnitude of the TOG emissions.

Similar results are obtained by using data collected from the UC cycle. In Figure 2-12, the benzene emissions as a percentage of TOG emissions for the UC cycle indicate that the percentage does not appear to vary with the TOG emissions. For example the benzene emissions are approximately 3.8 percent of the TOG emissions regardless of whether TOG emissions are low (e.g. less than 0.5 g/mi) or high (e.g. greater than 1.5

g/mi). This analysis thus shows that it is reasonable to assume that percent of TOG is a statistically independent measure of emissions compared to TOG (g/mi) for UC cycle data. The graphs for other pollutants are presented in the Appendix A.

An important result of this data analysis is that air toxics emissions data collected by from either of the two test cycles (FTP or UC) had similar properties in terms of the inter-vehicular variability in terms of emissions involved and other relationships between data as discussed above. Hence data from either of the two test procedures could be used for the uncertainty analysis. Also this analysis establishes "toxic percent of TOG" as the most useful measure of HAP emissions from on-road vehicles. Since FTP is more widely used cycle, only FTP toxic percent of TOG data was used for the uncertainty analysis presented in the next section.

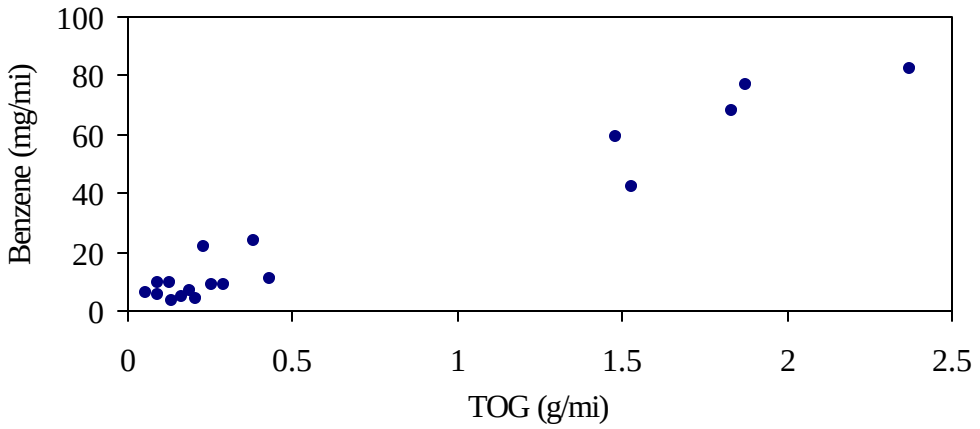

Figure 2-9. Scatter Plot of Benzene conc. vs TOG for UC Cycle

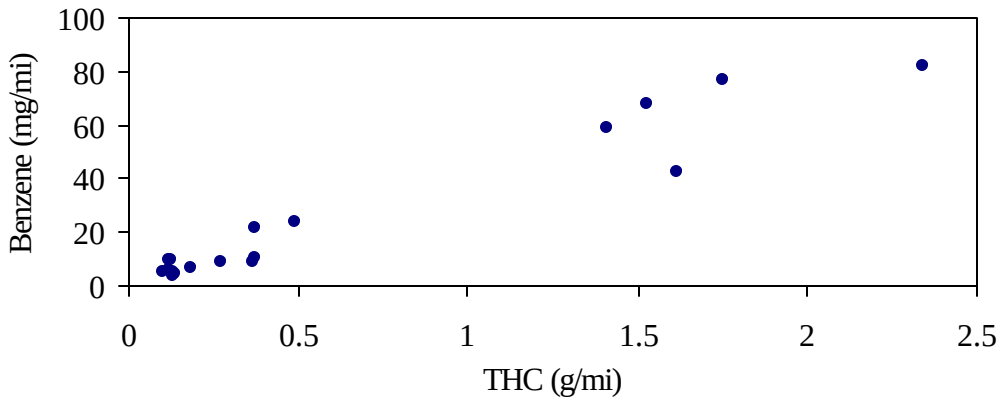

Figure 2-10. Scatter Plot of Benzene conc. vs THC for UC Cycle

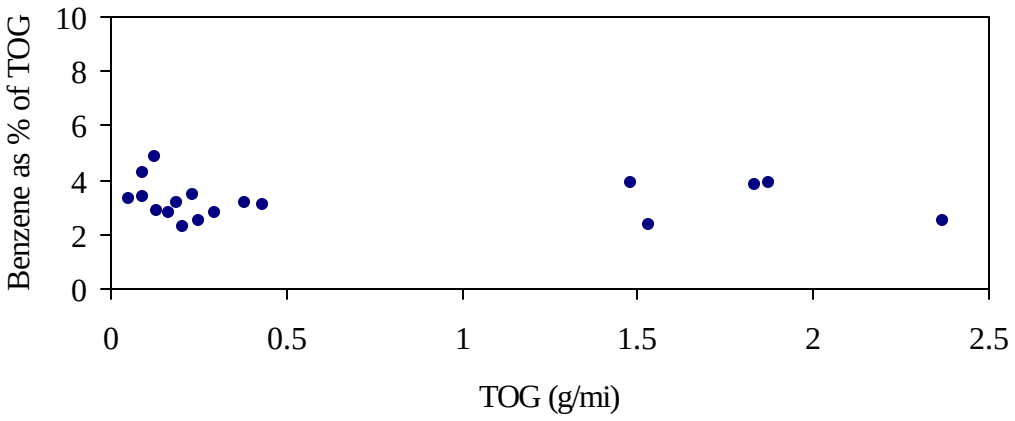

Figure 2-11. Scatter Plot of Benzene Concentration as Percent of TOG vs. TOG (g/mi) for the FTP cycle

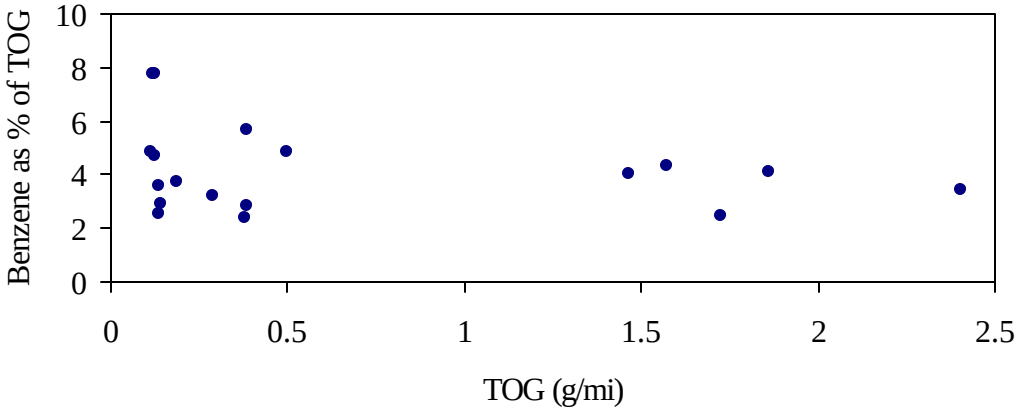

Figure 2-12. Scatter Plot of Benzene Concentration as Percent of TOG vs. TOG (g/mi) for the Unified cycle

2.2.2 Characterization of Uncertainty

In this section the work done to characterize uncertainty in the air toxic emissions data expressed as percentage of TOG emissions from FTP cycle data is discussed. This data was collected from vehicles running on different fuels including reformulated gasoline (RFG), unleaded gasoline (UnL) and Indolene. The uncertainty was characterized using the technique of Bootstrap simulation discussed in Chapter 1. Of the eighteen vehicles that were tested by CARB, five were defined to be high emitters and the remaining thirteen were defined to be normal emitters. It was not clear from the report as to what was the basis of this classification (Sierra Research, 1999). Hence for the purpose of uncertainty analysis in this study three cases were taken under consideration. In the first case the both the high and the low emitters in the CARB database were considered together, in the second case the only the high emitters were considered and in the third case only the normal emitters were considered. This classification gave three groups of data sets for each pollutant. The results of this uncertainty analysis for the three groups for each pollutant were subsequently used to decide whether the high and the normal emitters should be separately considered.

2.2.3 Development of Probabilistic Toxic-TOG Curves

The Toxic-TOG curves have been used to predict the toxic emission rate for a target fuel from the TOG emission rate for baseline fuel. These curves are developed by the EPA using the data for normal and high emitters as discussed in Section 2.1.3. For developing these curves, there can be many data for normal and high emitters available to choose from. This implies that there can be multiple Toxic-TOG curves for an air toxic.

In this section, the procedure used to develop these multiple Toxic-TOG curves using probability distributions is presented. Toxic emission rates for target fuel are then calculated from these toxic-TOG curves and analyzed for variability. The magnitude of variability in these predicted toxic emissions is compared with that of the actual data to evaluate the usability of this technique.

The Toxic-TOG curves were developed using the methodology discussed in Section 2.1.3. For this purpose Commercial Unleaded Gasoline (UNL) was used as the baseline fuel and California Phase 2 Reformulated Gasoline (RFG) was used as the target fuel. The emission data were regrouped into normal and high emitters. The CARB database had provided information to distinguish between vehicles as Normal and High emitters. The probabilistic Toxic-TOG curves were developed using the following steps:

1. From the discussion presented in Section 2.1.3, a Toxic-TOG curve requires four data points:
    a. TOG (g/mi) emission for Baseline fuel, i.e. UnL for normal emitters (X_1)
    b. Toxic (mg/mi) emission for Target Fuel, i.e. RFG for normal emitters (Y_1)
    c. TOG (g/mi) emission for Baseline fuel, i.e. UnL for high emitters (X_2)
    d. Toxic (mg/mi) emission for Target Fuel, i.e. RFG for high emitters (Y_2)

    Using these four points, an initial Toxic-TOG curve can be drawn which can be then made to pass through the origin for the extrapolated regions as also discussed in section 2.1.3. Thus the first step was to collect the data from the database, to characterize X_1, X_2, Y_1, and Y_2 as described above. Table 2-5 gives the values for X_1, X_2, Y_1, and Y_2 for all the five pollutants and TOG, respectively. In the Table

2-5 the values of X_1 and X_2 are the same for all the pollutants. There was only one value in the CARB database for X_2.

2. The next step was to fit probability distributions to these datasets. Parameters of the fitted probability distributions to these different data sets are given in Table 2-6. Figure 2-13 gives a fitted distribution to the Y_1 data set for benzene. Probability distributions that were fit to the data sets of Y_1 and Y_2 for the five pollutants and X_1 for TOG emission rates were chosen from among Normal, Lognormal, Weibull and Gamma. The ones that were judged to fit best were chosen for developing the probabilistic Toxic-TOG curves.
3. Multiple possible Toxic-TOG curves were simulated using Monte Carlo simulation. This was done by randomly simulating values of X_1, X_2, Y_1, and Y_2 from the corresponding fitted distributions and drawing a Toxic-TOG curve for each simulated set of values for these variables. X_1, Y_1, and Y_2 are independent datasets and hence each dataset was fitted with a separate probability distribution. Since there was only one data point for X_2, no probability distribution was fit for X_2. Hence all the probabilistic Toxic-TOG curves have the same value for X_2. This process is repeated a hundred times to generate a hundred Toxic-TOG curves. Figures 2-14, 2-15, 2-16, 2-17 and 2-18 show the probabilistic Toxic-TOG curves thus developed for the Benzene, 1,3-Butadiene, MTBE, Formaldehyde and Acetaldehyde, respectively. These curves once drawn were forced through the origin for the extrapolated regions as shown in Figure 2-2.

Table 2-5. Values of X_1, X_2, Y_1, and Y_2 for all the Five Pollutants and TOG

Pollutant	Variable	Mean	Values
Benzene	X_1	0.22	0.17, 0.13, 0.09, 0.25, 0.23, 0.43
	Y_1	6.4	3.87, 4.69, 3.10, 8.20, 12.15
	X_2		1.48
	Y_2	56.1	72.7, 35.7, 59.9
1,3-Butadiene	X_1	0.22	0.17, 0.13, 0.09, 0.25, 0.23, 0.43
	Y_1	0.81	0.47, 0.95, 0.47, 1.35, 0.80
	X_2		1.48
	Y_2	12.2	17.6, 14.6, 4.43
MTBE	X_1	0.22	0.17, 0.13, 0.09, 0.25, 0.23, 0.43
	Y_1	7.13	4.00, 6.51, 2.75, 10.8, 11.6
	X_2		1.48
	Y_2	38.8	24.5, 70.4, 21.5
Formaldehyde	X_1	0.22	0.17, 0.13, 0.09, 0.25, 0.23, 0.43
	Y_1	3.15	1.59, 4.44, 2.07, 4.02, 3.61
	X_2		1.48
	Y_2	39.5	42.1, 51.3, 25.0
Acetaldehyde	X_1	0.22	0.17, 0.13, 0.09, 0.25, 0.23, 0.43
	Y_1	0.83	0.50, 1.10, 0.39, 1.21, 0.95
	X_2		1.48
	Y_2	10.2	11.3, 11.6, 7.78

All values of X_1, X_2 and the corresponding mean are in g/mi units.
All values of Y_1, Y_2 and the corresponding mean are in mg/mi units
Source: (Sierra Research, 1999)

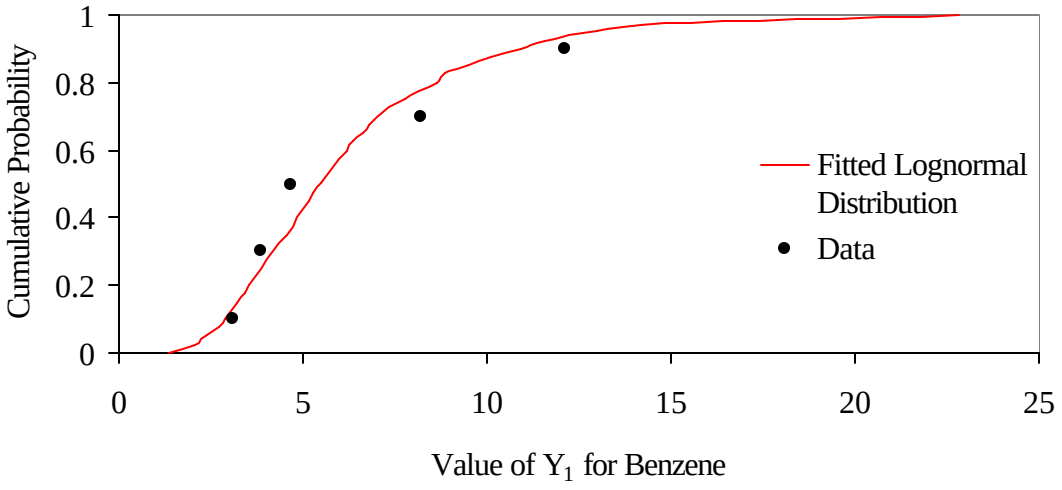

Figure 2-13. Fitted Lognormal Distribution to the Values of Y_1 for Benzene

Table 2-6. Summary of Probabilistic Distributions used to Develop Toxic-TOG curves

Pollutants	Category	Fitted Distribution		
		Name	Parameter 1	Parameter 2
Benzene	Y_1	Lognormal	1.7269	0.5614
	Y_2	Lognormal	3.9852	0.3672
1,3-Butadiene	Y_1	Lognormal	-0.2984	0.4563
	Y_2	Lognormal	2.3456	0.7484
MTBE	Y_1	Weibull	2.1835	8.0928
	Y_2	Weibull	1.8846	44.13
Formaldehyde	Y_1	Lognormal	1.0715	0.4496
	Y_2	Lognormal	3.6324	0.3706
Acetaldehyde	Y_1	Lognormal	-0.2811	0.5071
	Y_2	Lognormal	2.3110	0.2254
TOG	X_1	Lognormal	-1.6521	0.5475
	X_2	*	*	*

* For this case there was only one data point available and hence no distribution could be fitted. Hence all the Toxic-TOG curves in Figure 2-13 to 2-17 have the same value for X_2. This data point was for the vehicle with Engine Family # = C1G5.7V5NBM2 (Make = GM, Model = Corvette, Model Year = 1982) in the CARB database (Sierra Research, 1991).

The spread of the Toxic-TOG curves along both axes depends on the range of variation of the values of X_1, X_2, Y_1, and Y_2. For X_2 there is no variation since there is only one data point associated with it. The range of variation in X_1 as defined by the difference between the 2.5^{th} and the 97.5^{th} percentile is 0.07 to 0.56 for all the pollutants. The range of variation for Y_1 and Y_2 for the five pollutants is summarized in Table 2-6.

Table 2-7. Variability Analysis of Y_1 and Y_2 Values for All the Five Pollutants.

Pollutant	Value of Y_1		Value of Y_2	
	95% Prob. Range [a]	Variability Factor [b]	95% Prob. Range [a]	Variability Factor [b]
Benzene	1.87 to 16.9	9	26.2 to 111	4
1,3-Butadiene	0.3 to 1.81	6	2.4 to 45.2	19
MTBE	1.5 to 14.7	10	6.28 to 88.2	14
Formaldehyde	1.21 to 7.05	6	18.3 to 78.2	4
Acetaldehyde	0.28 to 2.04	7	6.48 to 15.7	2

[a] Range between 2.5^{th} percentile and 97.5^{th} percentile based on fitted distribution.
[b] Ratio of the 97.5^{th} percentile to the 2.5^{th} percentile based on fitted distribution.

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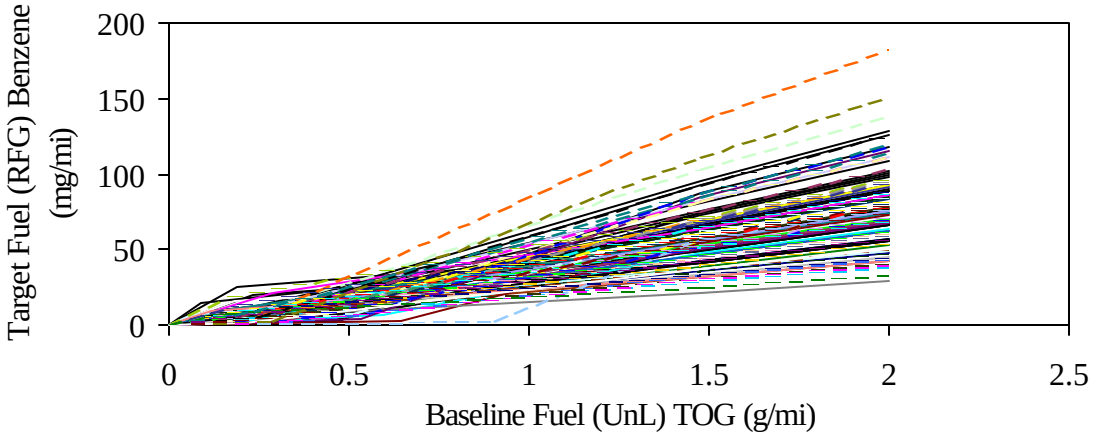

Figure 2-14. Probabilistic Benzene Toxic-TOG Curves

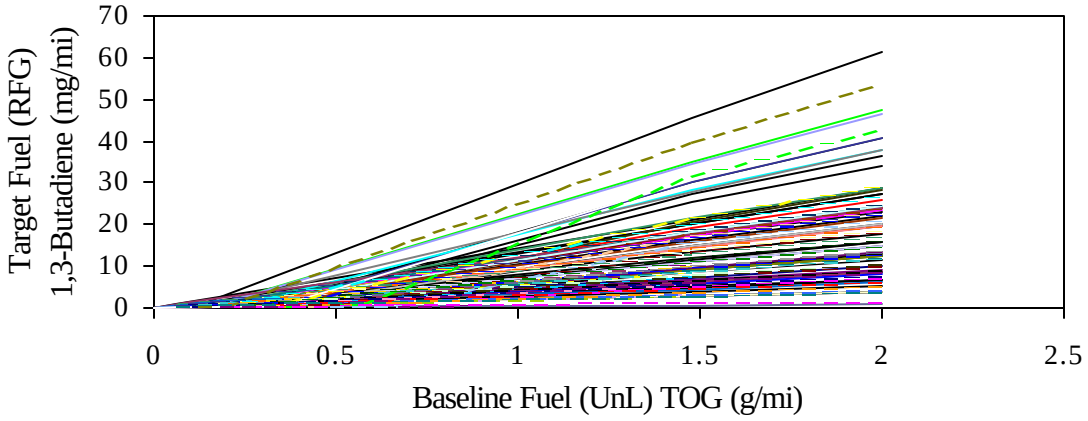

Figure 2-15. Probabilistic 1,3-Butadiene Toxic-TOG Curves

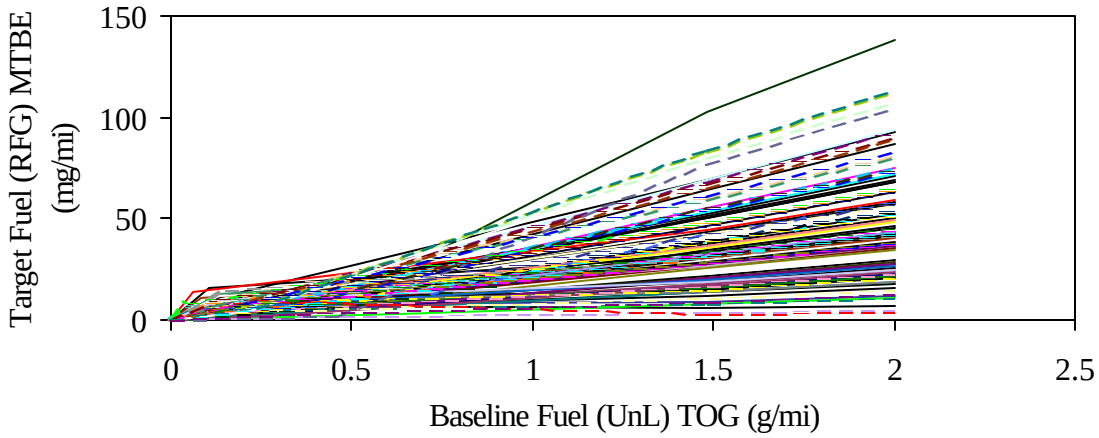

Figure 2-16. Probabilistic MTBE Toxic-TOG Curves

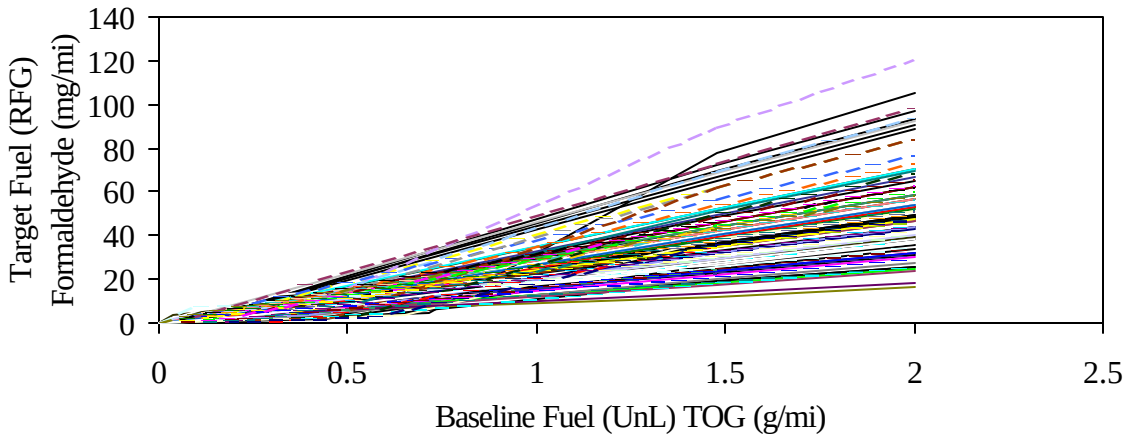

Figure 2-17. Probabilistic Formaldehyde Toxic-TOG Curves

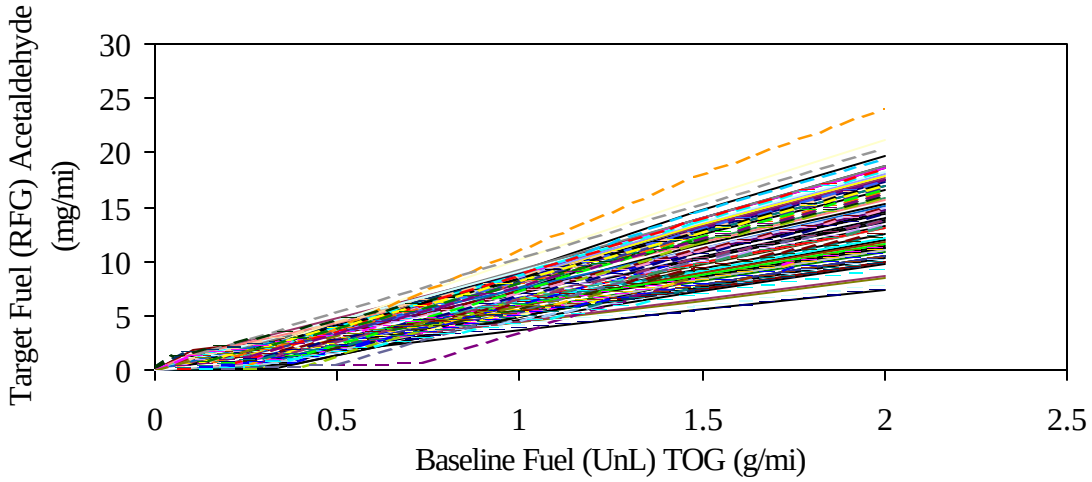

Figure 2-18. Probabilistic Acetaldehyde Toxic-TOG Curves

Concentrations of the air toxics were predicted from the corresponding Toxic-TOG curves using a trial value of TOG = 1.0 g/mi. Thus 100 estimated values of pollutant emission rate were obtained. Figures 2-19 to 2-23 show the cumulative probability plots for the predicted concentrations of Benzene, 1,3-Butadiene, MTBE, Formaldehyde and Acetaldehyde, respectively. These graphs are all positively skewed. The mean is higher than the median in all the cases as can be seen from Table 2-7. Figures 2-20 and 2-22 for 1,3-Butadiene and Formaldehyde have heavy tails. There is very high range of variation in predicted emission rates for Benzene and 1,3-Butadiene compared to the other pollutants. For example the values for Benzene emission rate range from 2.31 mg/mi to 71.2 mg/mi (variability factor of 31) while the values of predicted Acetaldehyde emission rate range from 4.37 to 10.9 (variability factor of 2).

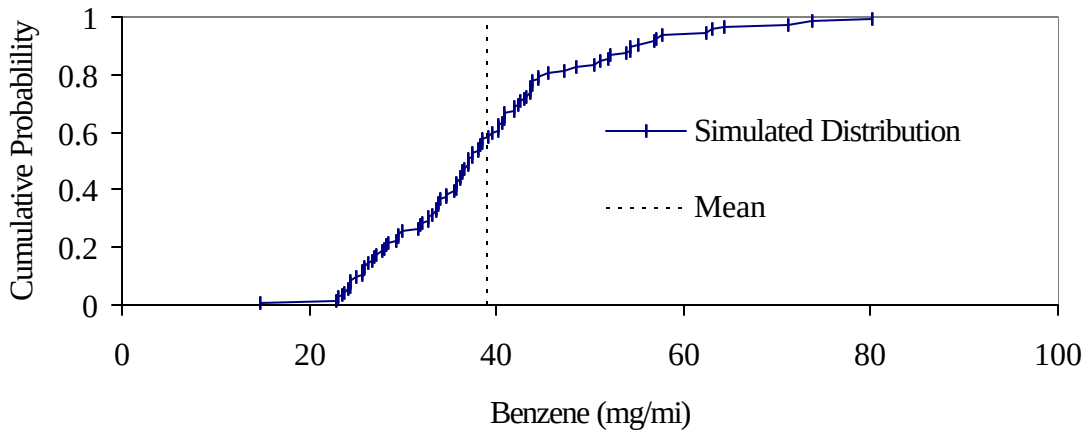

Figure 2-19. Variability in Predicted Target Fuel Benzene Emissions for Base Fuel TOG = 1 g/mi

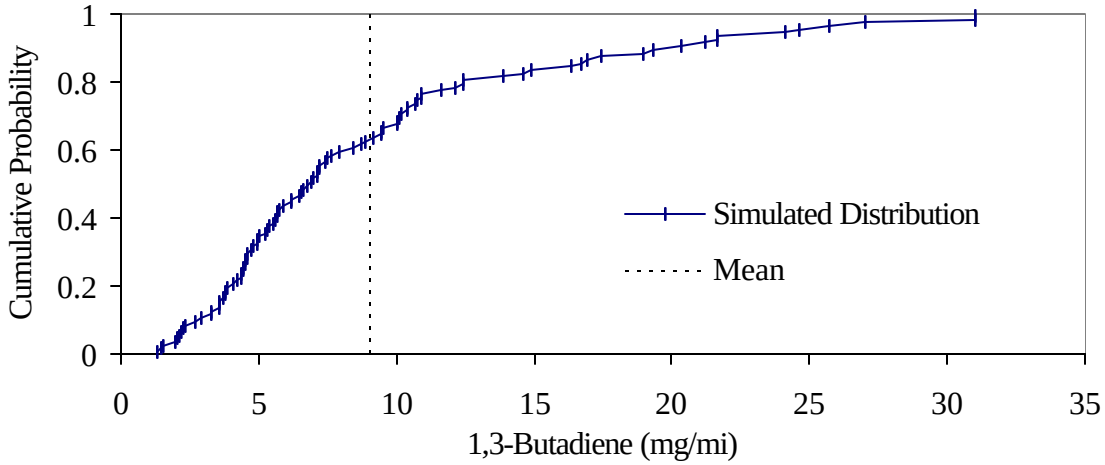

Figure 2-20. Variability in Predicted Target Fuel 1,3-Butadiene Emissions for Base Fuel TOG = 1 g/mi

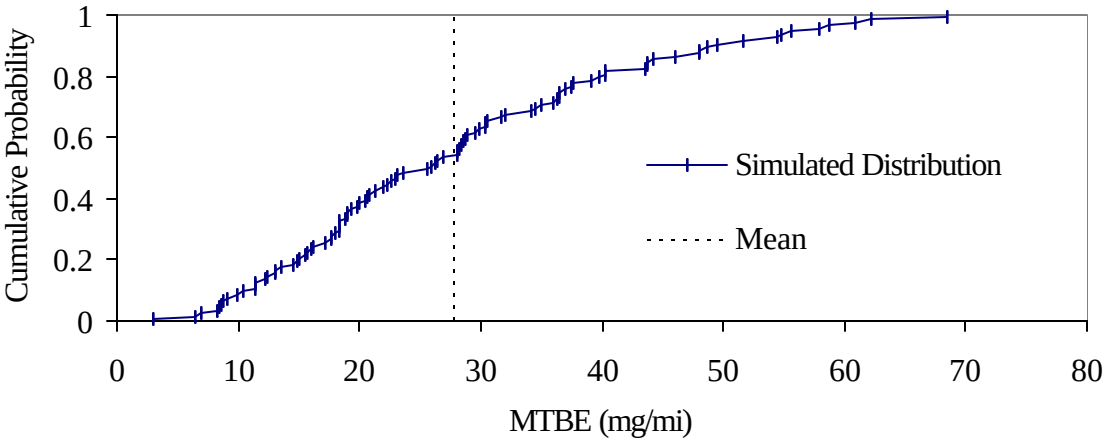

Figure 2-21. Variability in Predicted Target Fuel MTBE Emissions for Base Fuel TOG = 1 g/mi

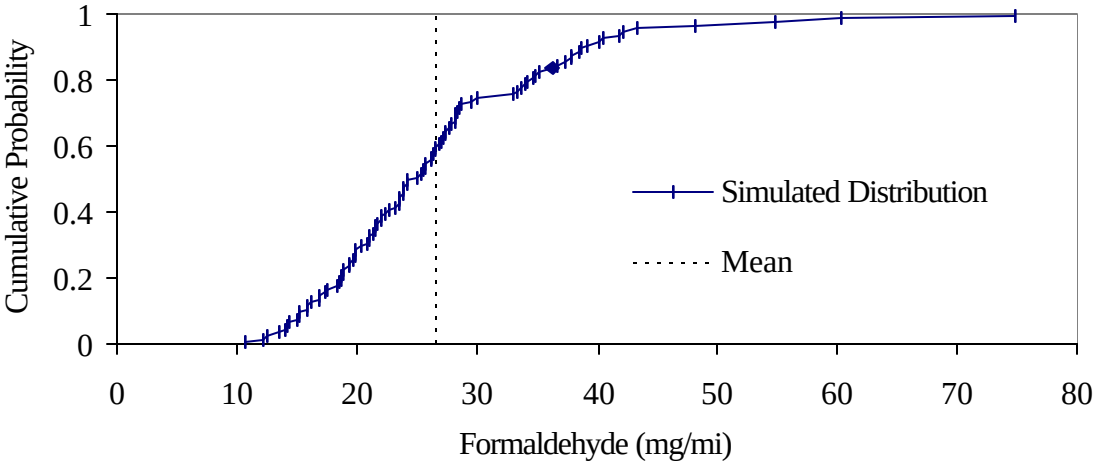

Figure 2-22. Variability in Predicted Target Fuel Formaldehyde Emissions for Base Fuel TOG = 1 g/mi

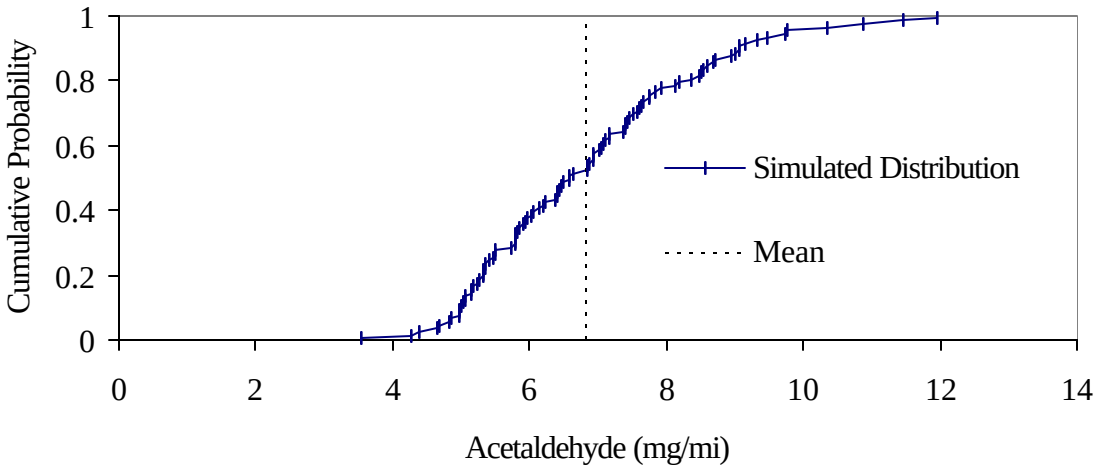

Figure 2-23. Variability in Predicted Target Fuel Acetaldehyde Emissions for Base Fuel TOG = 1 g/mi

The predicted air toxic concentrations were then analyzed for variability. The variability analysis of the 100 data points predicted from the probabilistic Toxic-TOG curves of each of the five pollutants is summarized in Table 2-7. Next the results from Table 2-4 and Table 2-7 are compared. It is seen that for all pollutants except Benzene and 1,3-Butadiene the measured variability in reported test data for target fuel (RFG) in units of mg/mi (Table 2-4) is many times higher than the measured variability in data in units of mg/mi, predicted from probabilistic Toxic-TOG curves (Table 2-7). For example the variability factor for predicted Formaldehyde emission rate for target fuel is 4 while that of reported data is 117, which is 30 times higher.

Table 2-8. Summary of the Variability Analysis of Predicted Air Toxic Emissions

Pollutants	Mean (mg/mi)	Median (mg/mi)	95% Prob. Range (mg/mi) [a]	Variability Factor [b]
Benzene	38.8	36.9	2.31 to 71.2	31
1,3-Butadienne	8.99	6.83	1.53 to 27.0	18
MTBE	27.7	25.7	6.91 to 60.8	9
Formaldehyde	26.6	24.6	12.5 to 54.8	4
Acetaldehyde	6.82	6.57	4.37 to 10.9	2

[a] Range between 2.5^{th} percentile and 97.5^{th} percentile.
[b] Ratio of the 97.5^{th} percentile to the 2.5^{th} percentile.

This section presented the methodology used to develop probabilistic Toxic-TOG curves, which were then used to predict the emission rates of the five pollutants. The results of the variability analysis of the predicted versus the reported emissions for the five pollutants were compared and in general the variation in the predicted emission rates for the Target fuel was found to be less than that for the reported Base fuel emission rates. This is because all the probabilistic toxic-TOG curves that were developed have a slope less than that of the line "y=x". This reduces the variability in the estimation of toxic emissions from the target fuel based on the known emissions from Baseline fuel. Hence this exercise demonstrates the effects of using this technique on the inter vehicular variability in emissions when they are linearly transformed from Baseline fuel to the target fuel.

2.2.4 Effect of Fuel Used

The purpose of this analysis is to evaluate whether there is a significant difference in pollutant emissions as percent of TOG for different fuels. The CARB database was sorted for data on the basis of fuel type (California Phase 2 Reformulated Gasoline or "RFG," Commercial Unleaded Gasoline or "UnL" and Indolene). Out of the 18 vehicles tested, 8 were RFG-fueled, 7 were UnL-fueled and 3 were Indolene-fueled. For MTBE

however data was available for only 8 RFG-fueled, 6 UnL-fueled and 1 Indolene-fueled vehicles. Then, 2-tailed *t* – tests for the differences in means at a 5 percent level of significance were done on the data to investigate significant differences in emission rates expressed in units of percent of TOG. It was found that there is no significant difference in pollutant % TOG by fuel type. The results of these tests are summarized in Tables 2-9, 2-10 and 2-11. Table 2-9 presents the results of the comparison between emissions from RFG-fueled vehicles versus UnL-fueled vehicles. Table 2-10 presents the results of the comparison between emissions from RFG-fueled vehicles versus Indolene-fueled vehicles. Table 2-11 presents the results of the comparison between emissions from Indolene-fueled vehicles versus UnL-fueled vehicles.

Table 2-9. Results of Comparison of Percent of TOG Using the Fuels RFG and UnL Based Upon *t*-Tests for the Difference of Two Means at a 5% Level of Significance.

Comparison	Air Toxic	Significant Difference between Data Sets?
RFG vs. UnL	Benzene	No
	1,3-Butadiene	No
	MTBE	No
	Formaldehyde	No
	Acetaldehyde	No

Table 2-10. Results of Comparison of Percent of TOG Using the Fuels RFG and Indolene Based Upon *t*-Tests for the Difference of Two Means at a 5% Level of Significance

Comparison	Air Toxic	Significant Difference between Data Sets?
RFG vs. Indolene	Benzene	No
	1,3-Butadiene	No
	MTBE	NA
	Formaldehyde	No
	Acetaldehyde	No

NA: Only one data point for Indolene, hence comparison not possible.

Table 2-11. Results of Comparison of Percent of TOG Using the Fuels Indolene and UnL Based Upon *t*-Tests for the Difference of Two Means at a 5% Level of Significance

Comparison	Air Toxic	Significant Difference between Data Sets?
Indolene vs. UnL	Benzene	No
	1,3-Butadiene	No
	MTBE	NA
	Formaldehyde	No
	Acetaldehyde	No

NA: Only one data point for Indolene, hence comparison not possible.

The final recommendations that are made after studying the CARB database are made in the next section.

2.3 Uncertainty in Toxic Emissions as Percent of TOG

The purpose of this research was to characterize variability and uncertainty in air toxic emissions. For this first a unit of measurement of toxic emission rates was found which had the least amount of variability associated with it. This unit was the emission rate of the air toxic as a percentage of TOG emission rate. This section presents the results of characterizing uncertainty in the mean toxic emission rates in units of percent of TOG.

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The first step involves the compilation and evaluation of the database. The database for this category had emission rates reported for Benzene, 1,3-Butadiene, MTBE, Formaldehyde, Acetaldehyde, THC and TOG. CARB developed these emission rates by testing a group of 18 vehicles using two test procedures namely, the UC and FTP cycles. The next step involved fitting parametric probability distribution to the data sets. The fitted distributions chosen were Normal, Lognormal, Gamma and Weibull. The Maximum Likelihood Estimation (MLE) approach was used to estimate the parameters

of the fitted distributions. This is discussed in detail in Section 1.2.3.2. The variability was characterized using the fitted probability distributions. For each pollutant data set and the corresponding fitted distribution, a ratio of the 2.5^{th} and 97.5^{th} percentile was calculated which served as a measure of variability in the data set under consideration. For example Table 2-3 and 2-4 present the results of the variability analysis of emission rates of the pollutants for the FTP and UC cycles. On comparing the results presented in the two tables it was found that for both the cycles the variability in toxic emission rates is an order of magnitude less when the unit of measurement is percent of TOG as opposed to mg/mi.

Finally, the uncertainty in the air toxic emissions expressed in units of percentage of TOG emission rates is characterized. This is done by using bootstrap simulation. Using this technique confidence intervals are calculated in the fitted CDF which are then used to evaluate the goodness of fit. From the sampling distribution the mean of the bootstrap samples is calculated. The 95 percent confidence interval over this mean is then inferred from the sampling distribution. Section 1.2.4 has more details on this.

Figures 2-24 to 2-26 show the Bootstrap simulation plots for MTBE for all the three cases considered: (1) normal and high emitters combined, (2) high emitters only, and (3) normal emitters only. The data were obtained from RFG-fueled, UnL-fueled and Indolene fueled vehicles. In Figure 2-24, results are shown for the MTBE emission data set in units of percent of TOG for both high and normal emitters. The variability in emissions among these engines is from approximately 0.25 percent of TOG to

approximately 4.6 percent of TOG for MTBE. A fitted Weibull distribution is shown in comparison to the data. The Weibull distribution captures the overall trends of the empirical distribution of the data. The fitted distribution appears to under-predict the data between the range of approximately 2 percent of TOG to 2.5 percent of TOG for MTBE. In order to evaluate whether the deviations of the data with respect to the fitted distribution imply a poor fit, confidence intervals obtained from bootstrap simulation for the fitted CDF of the Weibull distribution are shown. More than one half of the data (11 out of 15 data points) are enclosed by the 50 percent confidence interval, and almost all of the data are enclosed by the 90 percent confidence interval. This comparison suggests that the Weibull distribution is an adequate fit to the data set and, therefore, is a reasonable representation of inter-engine variability in emissions.

Results for MTBE emissions as percent fraction of TOG for only high emitters are shown in Figure 2-25. In this latter case, it is clear that the fitted distribution is heavily influenced by an extreme data point with an emission rate of approximately 4.6 percent of TOG as MTBE. In contrast, all of the other data have emission rates of approximately 1.3 percent of TOG as MTBE or less. However, we have no basis for discarding the extreme data point. Furthermore, if this large data point was ignored, the mean emission estimate would be biased to a lower value than if this data point is retained in the analysis. All of the data are enclosed by the 90 percent confidence interval of the bootstrap simulation. However, there seems to be a large amount of deviation of the fitted distribution from the mean emissions and this may be explained by the very small size of the data set (four). Also there were some limitations of the

Bootstrap simulation software that need to be overcome for sample sizes of 5 data points or less. Specifically, the bootstrap percentile method was used in this work. For very small data sets it may be better to use an alternative bootstrap method such as the bias corrected and accelerated (BCa) method (Efron and Tibshirani, 1993). However as an initial estimate, the bootstrap percentile method nonetheless indicates that there is a wide range of uncertainty in this case. Therefore, the fit though not perfect appears to be adequate.

Figures 2-26 illustrates probabilistic analysis results for MTBE emission factors, respectively, expressed as percent of TOG for only normal emitters. The inter-engine variability in MTBE emissions among the 11 data points ranges from approximately 0.2 percent of TOG as MTBE to over 3.5 percent of TOG as MTBE. There is one data point that lies outside the 95 percent confidence interval, which is a possibility attributable to random sampling. The fitted Weibull distribution agrees well with the upper portions of the distribution, although there is apparent disagreement near the central values of the distribution. However, all except one of the data are enclosed within the 95 percent confidence interval, indicating that the fit is adequate.

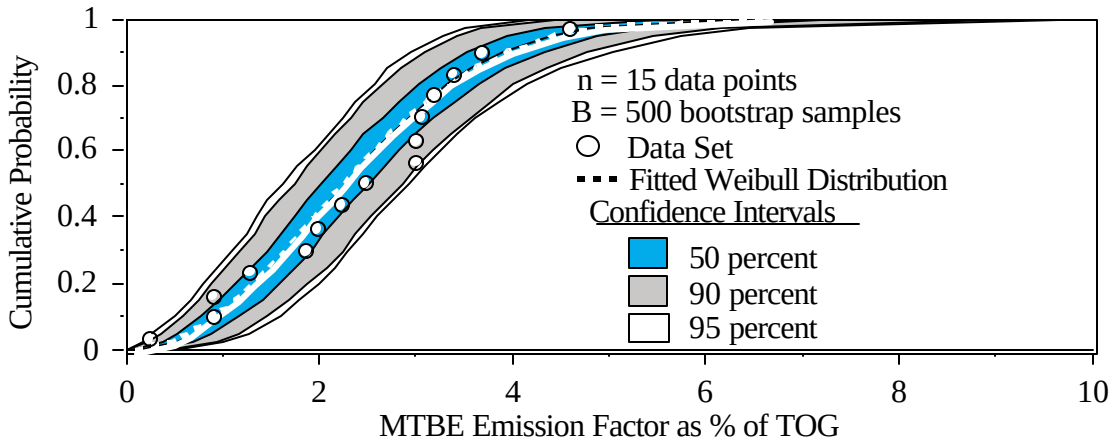


Figure 2-24. Bootstrap Simulation Results for MTBE Emissions as % of TOG for Both Normal and High Emitters (All Fuels).

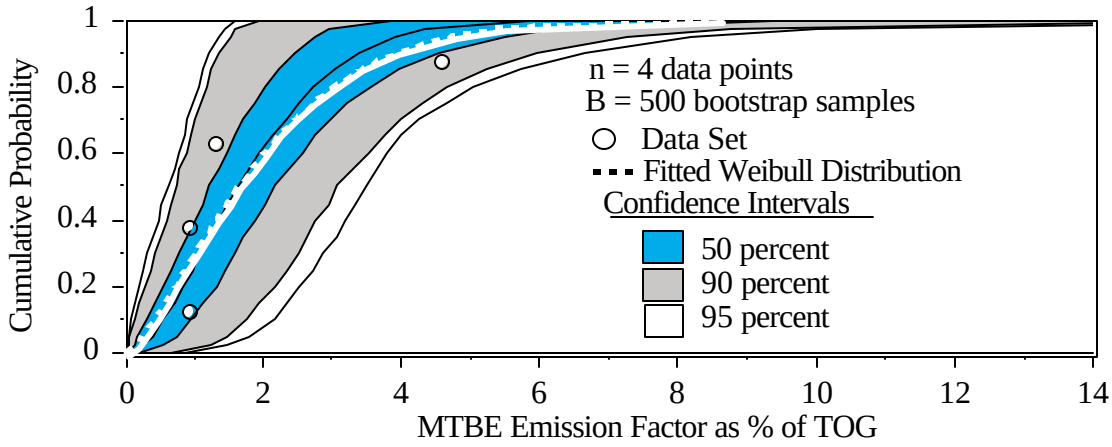


Figure 2-25. Bootstrap Simulation Results for MTBE Emissions as % of TOG for High Emitters only (All Fuels).

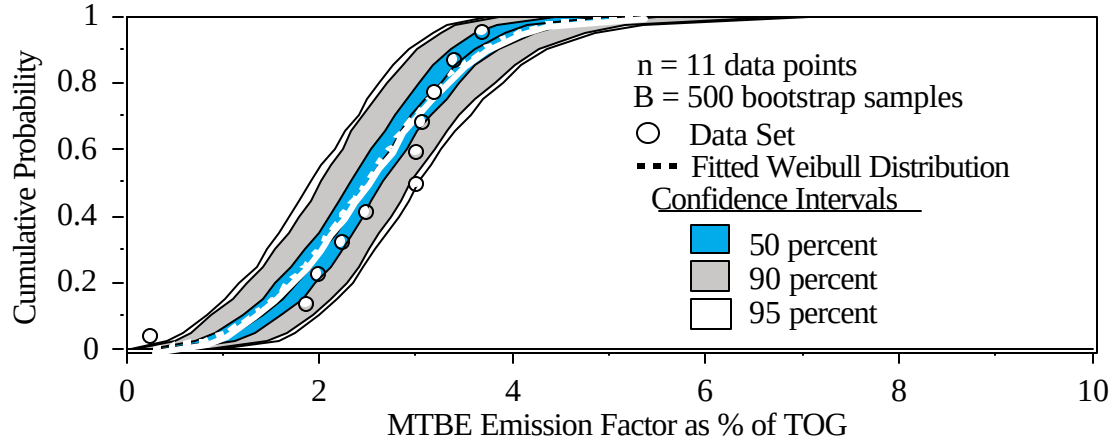


Figure 2-26. Bootstrap Simulation Results for Benzene Emissions as % of TOG for Normal Emitters only (All Fuels).

The bootstrap simulation plots for the other pollutants are presented in the Appendix A. For all the figures in Appendix A, the 95 percent confidence intervals of the fitted distribution enclose all of the data, indicating that the fitted distributions adequately describe the data. Tables 2-12 to 2-14 present a summary of the fitted distributions to the pollutant data sets for all the three cases considered.

Table 2-12. Summary of Fitted Distributions for all Five Pollutants: (High and Normal Emitters Both)

Pollutant	# of Data	Mean	Std. Dev.	Fitted Distribution	1st Parameter	2nd Parameter
Benzene	18	3.25	0.7	Lognormal	1.1562	0.2049
1,3-Butadiene	18	0.46	0.21	Lognormal	-0.8702	0.4160
MTBE	15	2.39	1.19	Weibull	2.1225	2.6779
Formaldehyde	18	1.9	1.2	Lognormal	0.4820	0.5495
Acetaldehyde	18	0.39	0.15	Lognormal	-1.0135	0.3734

Table 2-13. Summary of Fitted Distributions for all Five Pollutants: (Only High Emitters)

Pollutant	# of Data	Mean	Std. Dev.	Fitted Distribution	1st Parameter	2nd Parameter
Benzene	5	3.3	0.79	Lognormal	1.1674	0.2303
1,3-Butadiene	5	0.56	0.36	Lognormal	-0.7836	0.6438
MTBE	4	1.93	1.79	Weibull	1.3890	2.1436
Formaldehyde	5	1.89	0.94	Lognormal	0.5421	0.4227
Acetaldehyde	5	0.54	0.16	Lognormal	-0.6511	0.2768

Table 2-14. Summary of Fitted Distributions for all Five Pollutants: (Only Normal Emitters)

Pollutant	# of Data	Mean	Std. Dev.	Fitted Distribution	1st Parameter	2nd Parameter
Benzene	13	3.23	0.7	Lognormal	1.1519	0.1941
1,3-Butadiene	13	0.42	0.1	Lognormal	-0.9035	0.2760
MTBE	11	2.55	0.96	Weibull	2.9928	2.8075
Formaldehyde	13	1.91	1.32	Lognormal	0.4591	0.5893
Acetaldehyde	13	0.33	0.1	Lognormal	-1.1530	0.3058

The summary of the uncertainty analysis for the five pollutants for three different cases is shown below in Tables 2-15 to 2-17. From Table 2-15 it is seen that when all the data are combined, the uncertainty in the mean is approximately plus or minus 20 percent. In all cases except that of Formaldehyde the confidence intervals are approximately symmetric. For Formaldehyde the confidence interval is positively skewed which is attributable to the fitted lognormal distribution, which has a heavy tail.

In Table 2-16 the confidence intervals for the mean emission rate for all the pollutants are positively skewed. The relative uncertainty in the 1,3-Butadiene and MTBE mean emission rate is typically very high compared to other cases considered. This can be attributed to a larger range of variability for the 1,3-Butadiene and MTBE data sets compared to the other pollutants for that case. For example in case of 1,3-Butadiene and MTBE the ratio between the highest and the lowest emission rate in the data set is 0.95/0.19 (≈ 5) and 4.6/0.91 (≈ 5), while the similar ratio for others such as Benzene is 2.33/3.92 (≈ 1.7). This higher relative variability is understood to be a reason for this higher uncertainty in the mean emission rate for 1,3-Butadiene and MTBE. Figures 2-27 and 2-28 show the CDF graphs for distribution of mean emissions for 1,3-Butadiene and MTBE for the case of high emitters only as discussed above. In both these cases the mean of the fitted distribution is more than the median indicating the positive skewness of the fitted distribution.

Table 2-15. Mean and the 95% Confidence Intervals (CI) of the Mean of the Fitted Distributions for Five Pollutants (as %TOG) (High and Normal Emitters both): CASE 1

Pollutant	Number of Data	Fitted Distribution	Mean [a]	95% C.I. on Mean[b]	Relative Uncertainty[c]
Benzene	18	Lognormal	3.24	2.91 - 3.56	-10% to +10%
1,3-Butadiene	18	Lognormal	0.46	0.37 - 0.55	-20% to +20%
MTBE	15	Weibull	2.39	1.82 - 3.00	-24% to +26 %
Formaldehyde	18	Lognormal	1.87	1.42 - 2.43	-24% to +30%
Acetaldehyde	18	Lognormal	0.36	0.30 - 0.42	-17% to +17%

[a] Mean of the 500 bootstrap samples
[b] Numbers shown here are for the 95 percent confidence interval of the mean obtained from bootstrap simulation in terms of absolute emission rates
[c] Numbers shown here are for the 95 percent confidence interval of the mean obtained from bootstrap simulation in terms of relative deviation from the mean.

Table 2-16. Mean and the 95% Confidence Intervals (CI) of the Mean of the Fitted Distributions for Five Pollutants (as %TOG) (High Emitters): CASE 2

Pollutant	Number of Data	Fitted Distribution	Mean [a]	95% C.I. on Mean[b]	Relative Uncertainty[c]
Benzene	5	Lognormal	3.28	2.63 - 4.02	-20% to +23%
1,3-Butadiene	5	Lognormal	0.57	0.29 - 1.02	-49% to +79%
MTBE	4	Weibull	1.97	0.77 - 3.36	-61% to + 71%
Formaldehyde	5	Lognormal	1.87	1.24 - 2.72	-34% to +45%
Acetaldehyde	5	Lognormal	0.54	0.42 - 0.71	-22% to +31%

[a] Mean of the 500 bootstrap samples
[b] Numbers shown here are for the 95 percent confidence interval of the mean obtained from bootstrap simulation in terms of absolute emission rates
[c] Numbers shown here are for the 95 percent confidence interval of the mean obtained from bootstrap simulation in terms of relative deviation from the mean.

Table 2-17. Mean and the 95% Confidence Intervals (CI) of the Mean of the Fitted Distributions for Five Pollutants (as %TOG) (Normal Emitters): CASE 3

Pollutant	Number of Data	Fitted Distribution	Mean [a]	95% C.I. on Mean[b]	Relative Uncertainty[c]
Benzene	13	Lognormal	3.23	2.90 - 3.61	-10% to +12%
1,3-Butadiene	13	Lognormal	0.42	0.36 - 0.50	-14% to +19%
MTBE	11	Weibull	2.52	1.94 - 2.98	-23% to + 18 %
Formaldehyde	13	Lognormal	1.88	1.32 - 2.67	-30% to +42%
Acetaldehyde	13	Lognormal	0.33	0.28 - 0.40	-15% to +21%

[a] Mean of the 500 bootstrap samples
[b] Numbers shown here are for the 95 percent confidence interval of the mean obtained from bootstrap simulation in terms of absolute emission rates
[c] Numbers shown here are for the 95 percent confidence interval of the mean obtained from bootstrap simulation in terms of relative deviation from the mean.

In Table 2-17 the relative uncertainty in mean emission rates is approximately less than or equal to plus or minus 20 percent for all the pollutants except for Formaldehyde where it ranges from minus 30 percent to plus 42 percent. The confidence intervals for all the pollutants except MTBE were positively skewed. The emission rate for MTBE had negatively skewed interval, which is a possibility as the fitted distribution for this case is Weibull, which can be negatively skewed. Also as can be seen from Figure 2-29 the emission factor dataset for normal emitters for MTBE is very negatively skewed with one data point of value 0.25 percent of TOG being significantly less than the other data points which are all of values more than 1.5 percent of TOG. This negative skewness in the data set is reflected in the confidence intervals of the mean emission rate.

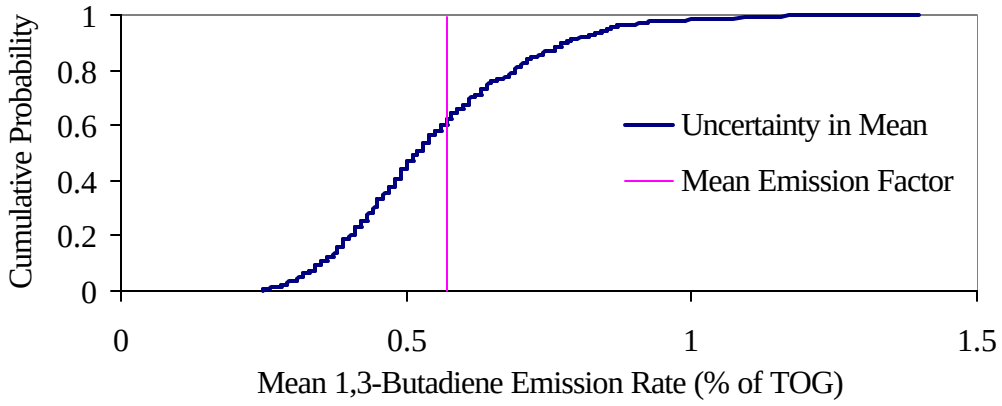


Figure 2-27. Uncertainty in 1,3-Butadiene Mean Emission Factor (% of TOG)

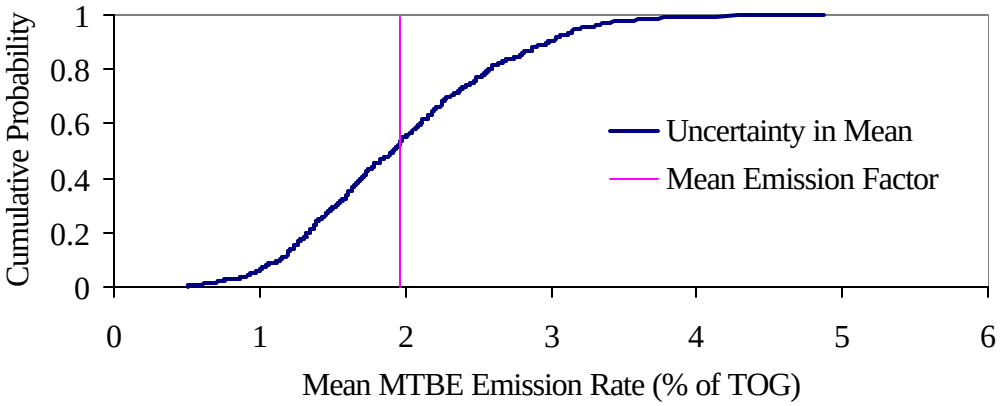


Figure 2-28. Uncertainty in MTBE Mean Emission Factor (% of TOG)

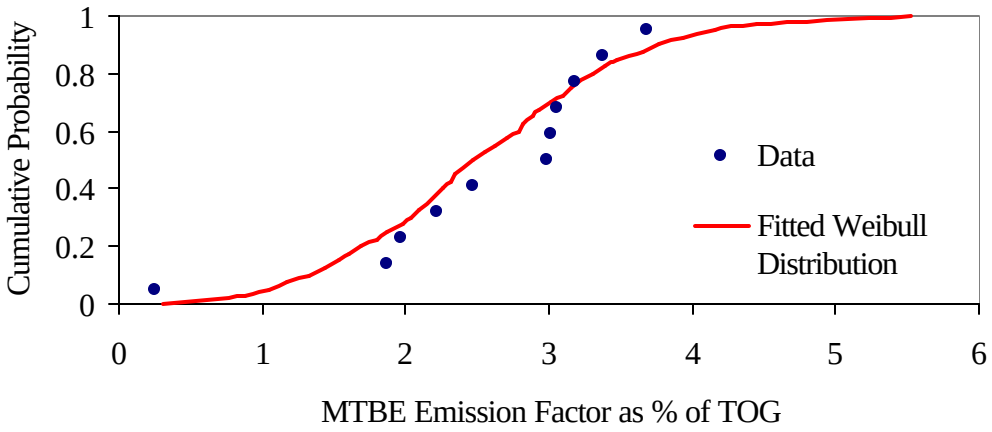


Figure 2-29. Fitted Weibull Distribution for MTBE Emission Factor Data for Normal Emitters Only in Units of % of TOG.

The results presented in Tables 2-15 to 2-17 show that the uncertainty in the mean of the fitted distribution is larger for the high emitters compared to the cases when we group high and low emitters together or when we consider only low emitters. This is in due to the small size of the data set for the case of high emitters. Table 2-18 summarizes the variability in the data sets for emission rates for only high emitters and only normal emitters. The variability analysis for the case when both high and normal emitters are considered together is presented in Table 2-3. It can be seen from these tables that the variability in emission rates for high emitters is generally less than or equal to the variability of the other two cases for all the pollutants. Hence only small size of the data sets was judged as the reason for high ranges of uncertainty in the mean for high emitters.

Table 2-18. Summary of Variability in Emission Factor Data for High and Normal Emitters for all the Five Pollutants in units of % of TOG.

Pollutants	High Emitters Only			Normal Emitters Only		
	Mean of data	95% Prob. Range [a]	Variability Factor [b]	Mean of data	95% Prob. Range [a]	Variability Factor [b]
Benzene	3.3	2.16 to 4.63	2	3.23	2.04 to 5.05	2
1,3-Butadiene	0.56	0.24 to 0.7	3	0.42	0.13 to 1.61	12
MTBE	1.93	0.82 to 4.34	5	2.55	0.15 to 5.49	36
Formaldehyde	1.89	0.5 to 5.02	10	1.91	0.75 to 3.94	5
Acetaldehyde	0.54	0.17 to 0.57	3	0.33	0.3 to 0.9	3

[a] Range between 2.5^{th} percentile and 97.5^{th} percentile.
[b] Ratio of the 97.5^{th} percentile to the 2.5^{th} percentile.
Note: Except for MTBE all the other pollutants have Lognormal as fitted distribution for variability analysis. For MTBE Weibull distribution was used.

The relative range of uncertainty for normal emitters is in some cases less than the relative range of uncertainty for both normal and high emitters together. For example the 95 percent confidence interval for 1,3-Butadiene and MTBE in CASE 3 is smaller compared to the 95 percent confidence interval for 1,3-Butadiene and MTBE in CASE 1. This can be explained on the basis of higher variability in 1,3-Butadiene and MTBE emissions for normal emitters even though size of 1,3-Butadiene and MTBE data sets for normal emitters is small compared to the 1,3-Butadiene and MTBE data sets for high and normal emitters combined. For example 1,3-Butadiene and MTBE in case of normal emitters have variability factors of 12 and 36 (see Table 2-18) while the corresponding values for the case when both high and normal emitters are considered are 5 and 11 (see Table 2-3).

When the mean emission rates for the three cases are considered together for each pollutant individually we find that for Benzene and Formaldehyde the mean emission rates are similar for all the three cases. For example the value of the mean emission rates

for Benzene and Formaldehyde for Cases 1, 2 and 3 are (3.24, 3.28 and 3.23) and (1.87, 1.87 and 1.88). However, this is not the case for the other pollutants namely 1,3-Butadiene, MTBE and Acetaldehyde. Therefore for these three pollutants a separate analysis of the high and the normal emitters is recommended.

2.4 Summary

In this chapter the inter vehicle variability in emission rates was quantified for the three cases by considering high emitters only, normal emitters only and high and normal emitters combined. Emission rates expressed as a percent of TOG were found out to be the most robust method of measuring toxic emissions from vehicles as this unit off measurement has the least amount of Uncertainty associated with it.

A methodology to develop probabilistic Toxic-TOG curves was presented and the variability in toxic emissions estimated from these probabilistic curves were then compared to that in the emissions reported by CARB. The estimated toxic emissions were found to have lesser variability compared to the reported ones.

The emissions data were also analyzed for the uncertainty in the mean of the fitted distribution. This was done for the three cases of high emitters, normal emitters and both high and normal emitters. The uncertainty ranges were in most cases in excess of plus or minus 20 percent and in some cases more than plus or minus 40 percent. The high emitters were found to have higher ranges of uncertainty in the mean compared to the cases when only normal emitters or both high and normal emitters were considered. This was due to the smaller data sets that were available for the high emitters.

Since the test vehicles ran on three different fuels, the emission data were tested to see whether there was a significant difference in emissions as percent of TOG from different vehicles based on the fuel they used. The three fuel used were RFG, UNL and Indolene. The emission rates were found out to be not significantly different for vehicles running on these three different fuels.

One of the limitations of the study was the small size of data sets used due to lack of data available. Hence it is recommended as future work to collect more data on toxic emissions from vehicles. In doing so, the types of vehicles from which the data was collected and the number of air toxics being measured can be increased. Future emissions testing programs can also look at collection diesel particulate matter emissions. The final recommendations of the study are summarized in Table 2-19 below:

Table 2-19. Final recommendations of the study

Pollutant	**Most Useful Measure of Emission**	**Consider High & Low Emitters Separately?**	**Is Fuel Type Important?**
Benzene	% of TOG	No	No
1,3-Butadiene	% of TOG	Yes	No
MTBE	% of TOG	Yes	No
Formaldehyde	% of TOG	No	No
Acetaldehyde	% of TOG	Yes	No

3.0 LAWN AND GARDEN ENGINE EMISSIONS

In this chapter, quantitative methods for characterizing both variability and uncertainty are demonstrated and these methods are applied to case studies of emission factors for gasoline-fueled Lawn and Garden (L&G) engines. L&G engines, which are primarily 2-stroke and 4-stroke gasoline engines of less than 25 hp, are used in a variety of applications including walk behind mowers, lawn tractors, shredders, grinders, blowers, vacuums, string trimmers, chainsaws, hedge trimmers, and others (CARB, 1990). Data were obtained from emissions testing conducted by others and were analyzed to quantify both variability and uncertainty. The variability in emissions was quantified using empirical and parametric distributions. Bootstrap simulation was used to characterize confidence intervals for the fitted distributions. The 95 percent confidence intervals for the mean emission factors associated with 2S total hydrocarbon (THC) and Nitrogen Oxides (NO_x) emissions in g/hp-hr units were -32% to +38% and -46% to +65%, respectively. The confidence intervals for mean emissions in g/hp-hr units for 4S engines were -38% to +45% for THC and -25% to +38% for NO_x. These quantitative measures of uncertainty convey information regarding the quality of the emission factors and serve as a basis for calculation of uncertainty in emission inventories. The method, example case studies, and benefits of the approach will be presented.

3.1 A Review of Technologies

The EPA defines lawn and garden category to be typically “small land based spark ignition” (SI) engines (EPA, 2000 a). These engines, which usually run on gasoline include, lawnmowers, string trimmers, leaf blowers, chain saws, commercial turf equipment, and lawn and garden tractors. Utility equipment is generally defined by

California Air Resources Board (CARB) as equipment used in a variety of L&G applications and in numerous "general utility" applications (CARB, 1990). Equipment in the L&G Category includes:

- Walk Behind Mowers
- Riding Mowers
- Lawn Tractors
- Fixed Blade Edgers
- Roto Tillers
- Shredders/Grinders
- Blower/Vacuums
- String Trimmers
- Snow Blowers
- Chainsaws
- Hedge Trimmers
- Other special purpose equipment

Equipment in "general utility" category includes (CARB, 1990):

- Pumps
- Generators
- Sprayers
- Special purpose saws (concrete, steel, etc.)
- Compressors
- Grinders
- Vibrators/Finishers
- Refrigeration equipment

A vast majority of this equipment is powered by internal combustion engines less than 25 HP (19 kW). EPA does not however include the above in the lawn and garden category. The types of engines used include diesel cycle, Otto cycle four-stroke, and Otto cycle two-stroke. Electric motors, powered by either battery or household line current, are also available and used in selected Lawn and Garden equipment; particularly in lower power hand-held equipment such as blowers, vacuums, string trimmers, and hedge

trimmers. Residential use edgers and chainsaws are also available in electric powered versions as are walk behind mowers.

Nonroad engine emission data is available in myriad forms in the different reports that were consulted during this study. Some of the most popular ways in which the data has been grouped are:

- By type of application as for the NEVES study by EPA (EPA, 1991)
- By power rating as for NONROAD model by EPA (Beardsley *et al*., 1998a)
- Type of cycle, two-stroke or four-stroke (EPA, 1991 and CARB, 1990)
- Type of design, overhead valve or side valve as used by CARB (CARB, 1990)
- Handheld or non-handheld as used by CARB (CARB, 1990)

The next four sections discuss alternative groups of L&G emission factor data.

3.1.1 Application vs. Power Rating

EPA, in the NEVES study, grouped emission factors for L&G engines by application (Beardsley *et al*., 1998a). EPA did not report any difference between emission factors for different sizes within the same application. On the other hand, there were other nonroad emissions models, such as CARB's OFFROAD Model, which had emission factors for L&G engines grouped by engine size (Beardsley *et al*., 1998a). In OFFROAD the emission factors were grouped by engine size using their horsepower rating. The latest NONROAD model that EPA is developing groups emission factors for L&G engines primarily by power level, but it also uses "application specific" emission

factors where there is "sufficient" information to justify their use (Beardsley *et al*., 1998a).

3.1.2 Two-Stroke vs. Four-Stroke

EPA and CARB have categorized emission factors with respect to two-stroke versus four-stroke classifications (EPA, 1991 and CARB, 1990). Two-stroke engines are used in equipment such as chainsaws, string trimmers, blowers, vacuums, small generators and pumps, and in walk behind mowers. Two-stroke engines dominate applications requiring a lightweight, high power engine. Four stoke engines dominate the "general utility" equipment category and are also used in the majority of L&G equipment including walk behind mowers, riding mowers and tractors, tillers, grinders, and other equipment where the implement is supported by wheels rather than hand-held.

3.1.3 Overhead Valve (OHV) Design vs. Side Valve (LHV) Design

Four stroke engines include two major design variations: (1) over head valve (OHV); and (2) side or L-Head valve (LHV). OHV and LHV are devices that open and close the combustion chamber of an internal-combustion engine to admit the fuel-air mixture or exhaust the gases. The intake and the exhaust ports, in the LHV design, are positioned on one side of the cylinder. In the case of the OHV design both valves are located directly over the piston. CARB has categorized 4-stroke engine emission factors as either OHV or LHV. Compared to similarly powered LHV engines, OHV engines have lower emissions, better fuel economy, and longer life (CARB, 1994).

3.1.4 Handheld vs. Non-Handheld

Handheld engines are those that need to be held in hand when being used, such as string trimmers or chainsaws. Non-handheld engines are those that are not held in hand while in use, such as walk behind mowers and garden tractors. Most of the handheld engines are two-stroke engines, with a few exceptions. Similarly most of the non-handheld engines are four-stroke engines. Hence the difference in the emissions between these two categories is similar to the difference in emissions between 2-stroke and 4-stroke engine categories. The CARB J1088 test procedure proposes different test cycles for handheld versus non-handheld applications for a given type of engine (e.g., 2-stroke).

3.2 Steady State Test Procedures for the Measurement of Exhaust Emissions from Small Utility Engines

Emission test procedures for small utility engines have changed little over the past 20 years. Current test work and research projects still employ raw exhaust measurements conducted according to SAE recommended Practice J1088 (White, 1990). Small changes have been made to J1088 over the years in details such as required operating modes, and more recently, exhaust system configuration and recommendation against inlet air flow measurements for 2-stroke engines (Hare and White, 1990). While raw exhaust measurements have the advantage of producing modal exhaust gas concentration data for design feedback, they are laborious, may influence both engine performance and emissions, and have no provision for concurrent particulate measurements. In this section, the various steady state test procedures that were used for estimating emissions from the small utility engines have been discussed with major emphasis on the SAE

J1088 test procedure. The data thus reported in various technical reports/studies that have used one or more of these procedures is compiled in the appendix B.

3.2.1 SAE 9-Mode Procedure

The Small Engine subcommittee of the Society of Automotive Engineers (SAE) Engine Committee developed the SAE 9-Mode test procedure. This test involves measuring emissions of hydrocarbons, CO, CO_2, O_2 and NO for 2-stroke engines only. The procedure requires a single operating speed which is the manufacturer's rated rpm, with different combinations of loads and fuel/air mixture settings as described in Table 3-1. Since many small engines operate at or near rated speed a majority of the time, the SAE-9-Mode procedure may be representative to some extent of real world operations. However, the procedure may not represent other real world applications. To represent a range of operating conditions, which might be encountered in the field, three-mixture settings have been included. The "lean best power" carburetor setting is defined as the leanest mixture the engine will tolerate at rated speed and full load without loss of power. The rich and lean conditions are arrived at by continuously changing the carburetor mixture setting in either the rich or the lean direction until a one percent drop in power is noted. These latter conditions are difficult to arrive at in a repeatable fashion because of the lack of accuracy of dynamometer systems and the effects of vibration (Hare and Springer, 1973a).

Table 3-1. Test conditions for SAE 9-mode Procedure

Mode	Speed	Fuel/Air Mixture	Load
1	Mfr. Rated	Lean Best Power	Full
2	Mfr. Rated	Lean Best Power	Half
3	Mfr. Rated	Lean Best Power	None
4	Mfr. Rated	Fuel Rich	Full
5	Mfr. Rated	Fuel Rich	Half
6	Mfr. Rated	Fuel Rich	None
7	Mfr. Rated	Fuel Lean	Full
8	Mfr. Rated	Fuel Lean	Half
9	Mfr. Rated	Fuel Lean	None

Source: (Hare and Springer, 1973a).

3.2.2 Modified EMA 13-Mode

The modified EMA 13-mode method has been adapted from the EMA – California procedure (Hare and Springer, 1973a). The major points common between the two are the speed load schedule and the weighting factors given to the modes. A summary of the test conditions is given in Table 3-2. There are three idle modes and the time the engine is tested in idle, i.e. 20 percent of the total time, is divided equally amongst all three of them. Similarly the time for other non-idle modes is 80 percent of the total and is divided equally amongst them. This procedure "maps" the emissions at two speeds as a function of load. For both the 13-mode procedure and the 9-mode procedure, the time spent in each mode is dictated by stability of emissions and batch sampling requirements. The stabilization period often consists of periodic variations around a central value of the measured emission rate rather than a gradual asymptotic approach to a constant. This is attributed to the inability of the engines to maintain a constant speed with precision (Hare and Springer, 1973a).

Table 3-2. Test conditions for "Modified EMA 13-mode" Procedure

Mode	Speed	Load	Mode Weight
1	Low Idle	None	0.20/3 = 0.0667
2	*Intermediate	None	0.08
3	Intermediate	25 %	0.08
4	Intermediate	50 %	0.08
5	Intermediate	75 %	0.08
6	Intermediate	Full	0.08
7	Low Idle	None	0.20/3 = 0.0667
8	Mfr's. Rated	Full	0.08
9	Mfr's. Rated	75 %	0.08
10	Mfr's. Rated	50 %	0.08
11	Mfr's. Rated	25 %	0.08
12	Mfr's. Rated	None	0.08
13	Low Idle	None	0.20/3 = 0.0667

* Peak torque speed or 60 % of rated speed, whichever is higher
Source: (Hare and Springer, 1973a).

3.2.3 6-Mode Method

The Federal small engine certification cycle is referred to as the 6-Mode test and is conducted by taking exhaust gas samples while the engine is operating at six different steady-state load points. Five of the load points are defined as 100, 75, 50, 25, 10 percent of rated torque at 85% of rated speed; the sixth point is at idle bad. The sample is taken for a 600-second period after all engine and sampling readings have stabilized (Gabele, 1997a).

3.2.4 C6M Method

The Composite 6 Mode (C6M) was developed by Southwest Research Institute (SwRI) from the certification test (6-Mode) for small (≤ 19 Kw) non-handheld engines. This test uses constant volume sampling. It is a combination of the six separate steady state modes of the certification procedure into one composite, six-mode test. The C6M test procedure is a quasi-steady-state test cycle since emission data are collected during

the transient that occurs when shifting from mode to mode. The engine is run through six modes, which are the same as those in 6-Mode test, while emissions are sampled continuously. The time spent in each mode is proportional to the weight given to the mode in the certification procedure. For example, if the weight of a mode is thrice that of a second mode in the test, the length of time spent in that mode is thrice that of the second mode. Instead of having twelve, six sample and six background, bags to analyze following test, the C6M has only two, a sample and a background, bags (Gabele, 1997a). This greatly reduces the cost and simplifies the analysis component. During the C6M test, engine speed is maintained at 85% of rated speed except at idle when it decreases to the lowest speed inside a smooth operating regime. Table 3-3 specifies the test parameters of the C6M.

Table 3-3. C6M Test Cycle Description

Mode Points	**1**	**2**	**3**	**4**	**5**	**6**
Speed	Intermediate (85% of Rated Speed)					Idle
Load Percent	100	75	50	25	10	0
Time in Mode (sec.)	106	240	348	360	84	60

Source: (Gabele, 1997a).

3.2.5 SAE J1088

The SAE J1088 test is a steady state raw gas procedure, which involves testing the engine in seven different operating modes. The purpose of developing this procedure is to specify a uniform procedure for measuring and evaluating exhaust emissions from small spark ignition engines of power rating ≤ 19 kW or 25 hp. A lot of flexibility has been provided in the physical reconstruction of the experimental apparatus. An engine test procedure including a test sequence is outlined such that it would cover the various applications in which the small engines can be used. An understanding of the levels of exhaust emissions is provided and depending upon the engine and/or its application, only those modes that are appropriate need be applied. Since the J1088 test procedure is used a standard for inter cycles comparisons in this study, it is discussed in more detail in the following sections. This information has been sourced from appendix (A) of the SwRI report by White (1990).

3.2.5.1 Engine Test Setup.

The engine under test is instrumented in such a way so that the following variables, in addition to exhaust levels, can be measured:

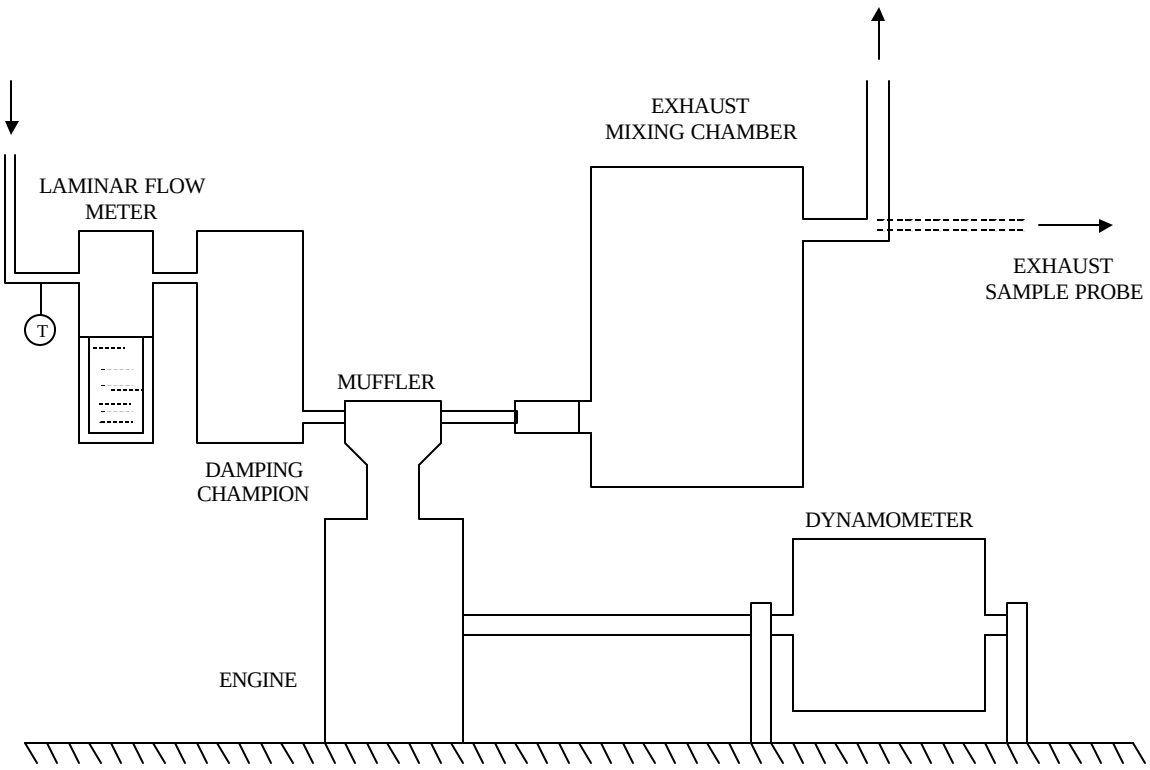
- Inlet Air mass flow rate
- Inlet air temperature
- Inlet air humidity
- Barometric pressure
- Fuel mass flow rate
- Engine speed

- Engine brake torque output

The exhaust composition is measured throughout the course of a test using an analytical train and instrumentation system.

3.2.5.1.1 Air and Fuel Measurement. Measurement of emissions is made on a molar basis, however results are given in terms of concentration. Conversions of molar measurements into concentrations may be based either on engine airflow or on fuel flow. The equations used for this on the principle of fuel flow are presented in Section 3.2.5.3.2.

Figure 3-1 pictorially describes the recommended inlet airflow measurement system. The measurement system uses a laminar flow meter in conjunction with a pressure wave-damping chamber. Any vessel having an internal volume not less than 100 times the displacement of the engine under the test can be used as the damping chamber. The damping chamber is placed between airflow metering element and the engine carburetor inlet. This is done to isolate the meter from the engine. An auxiliary blower is used to compensate for the effect of the air meter in an event when the airflow element reduces the engine airflow because of the excessive pressure drop. When the blower is used, engine inlet pressure is measured and controlled to $\pm$ 2in H_2O ($\pm$ 500 Pa) of barometer readings. If the mass calculations are based upon the airflow method, a device like rotometer is used to determine the fuel rate. But for mass calculations based upon fuel flow, a precision mass rate meter having an accuracy of $\pm$ 1% of the reading is used.



Source: (White, 1990)

Figure 3-1. Engine Setup for Emissions Tests

3.2.5.1.2 Exhaust Gas Sampling System. The exhaust sampling system consists of the exhaust system usually supplied with the engine, an exhaust mixing chamber, and the exhaust-sampling probe. The Exhaust Mixing Chamber is placed in the exhaust system between the muffler and the sampler probe. It ensures the complete mixing of the engine exhaust before a sample is extracted; thereby obtaining a truly representative average exhaust sample. The mixing chamber has approximately same dimensions as of the engine under test. Its internal volume is not less than 10 times the cylinder displacement of the test engine. Consistent with the 10 times cylinder displacement minimum size limitation, the tank is coupled as close to the engine as possible. This is done to minimize the dropout of heavy hydrocarbons fractions in the exhaust mixing tank

during part throttle, light load operation. To eliminate possible sampling errors due to strong exhaust pulsations, the exhaust line leaving the tank is extended at least 24 in (610 mm) beyond the sample probe location. The temperature of the inner surface of the mixing chamber is kept above the dew point of the exhaust gases. A minimum temperature of 150°F to 160°F (65°C to 70°C) is recommended by the SAE.

The exhaust sample probe consists of a length of ¼ in (6 mm) OD stainless steel tubing projecting into the exhaust line just downstream of the exhaust-mixing chamber. The sample probe inlet is centered in the exhaust line and face upstream as depicted in Figure 3-1.

3.2.5.2 Exhaust Gas Analysis.

In this section the analysis of exhaust gas is discussed. It includes discussions on analytical methods exhaust sample preparation, analysis of samples and instrument calibration.

3.2.5.2.1 Analytical Methods. This subsection provides information about the instruments that are used to measure the exhaust concentrations of the various species. For unburned hydrocarbons, a Heated Flame Ionization Detector (FID) is recommended for use. Operation of this analyzer conforms to the procedure specified in paragraph 3 of SAE J215. If SAE J215 is not applicable to the specific instrument, then manufacturer's recommendations are followed. An oven temperature in the range of 350-375°F (177-190°C) is recommended for both 2-stroke-cycles and 4-stroke-cycle engines.

For carbon monoxide, a Nondispersive Infrared Analyzer (NDIR) is usually used. Operation of the infrared analyzer conforms to the practice specified in SAE J254 and/or SAEJ177. The instrument is capable of accurate measurement of CO levels down to 0.1%.

To measure nitric oxide (NO), a Nondispersive Infrared analyzer (NDIR) or chemiluminescent analyzer is usually used. Operation of the infrared analyzer conforms to the practice specified in SAE J254 and/or SAEJ177. Recommendations for the operation of chemiluminescent analyzer are given in Federal Register, Vol. 42, September 8, 1977, Part III, Subpart D (42 FR 45154). If the recommendations of the Federal Register are not applicable to the particular make of chemiluminescent analyzer being used, then the manufacturer's recommendations are followed. The NDIR and chemiluminescent instruments are sensitive to NO only. They do not measure NO_2. But the above instruments can be modified to measure NO_2 also, as described in the Federal Register for the bag sample analytical technique by using a NO_2 to NO converter. Thus total NO_x is measured. Since the exhaust from 4-stroke-cycle engines contains little or no NO_2, and the residence time of this exhaust is short, NDIR or chemiluminescent analyzer for NO_x measurement can be used without incurring appreciable error. However, this is not the case with 2-stroke-cycle engines. Only a chemiluminescent analyzer equipped with a converter is used for 2-stroke engine work.

3.2.5.2.2 Exhaust Sample Preparation and Analysis. The SAE suggested an analytical system which provides for continuous measurement of emissions levels. This system is illustrated in Figure 3-2. The drawing does not represent the complete system

but just the essential systems. Two-stroke engines in their exhaust discharge a certain amount of lubricating oil. Some oil will be entrained in the sample, which may lead to the fouling of the sampling train. Hence to remove the oil in the sample from, 2-stroke-cycle engine tests, it is recommended that a heated low-restriction filter be installed between the sample probe and sample lines. A successfully used filter system, consists of flip-top type of filter assembly normally used with emissions instrumentation, which has been wrapped with heating tape to maintain the filter assembly temperature above the dew point of the exhaust gas. The filter housing is made of stainless steel and 11 cm glass fiber discs are used as filter media. Depending upon sampling requirements, exhaust gases from the sample probe are split into two or three streams. One sample line leads to the heated FID. This line should be heated to the same temperature as the detector oven. A temperature of 350 ^{o}F to 375^{o}F (177 ^{o}C -190^{o}C) is recommended for both 2-stroke and 4-stroke engines. The second sample line leads to the NDIR analyzers. The sample passes through a cold trap (to remove the water) and then through to the analytical instruments. In case of a NDIR NO analyzer being used, a dessicator is provided in the sample line branch to this analyzer to remove all traces of moisture.

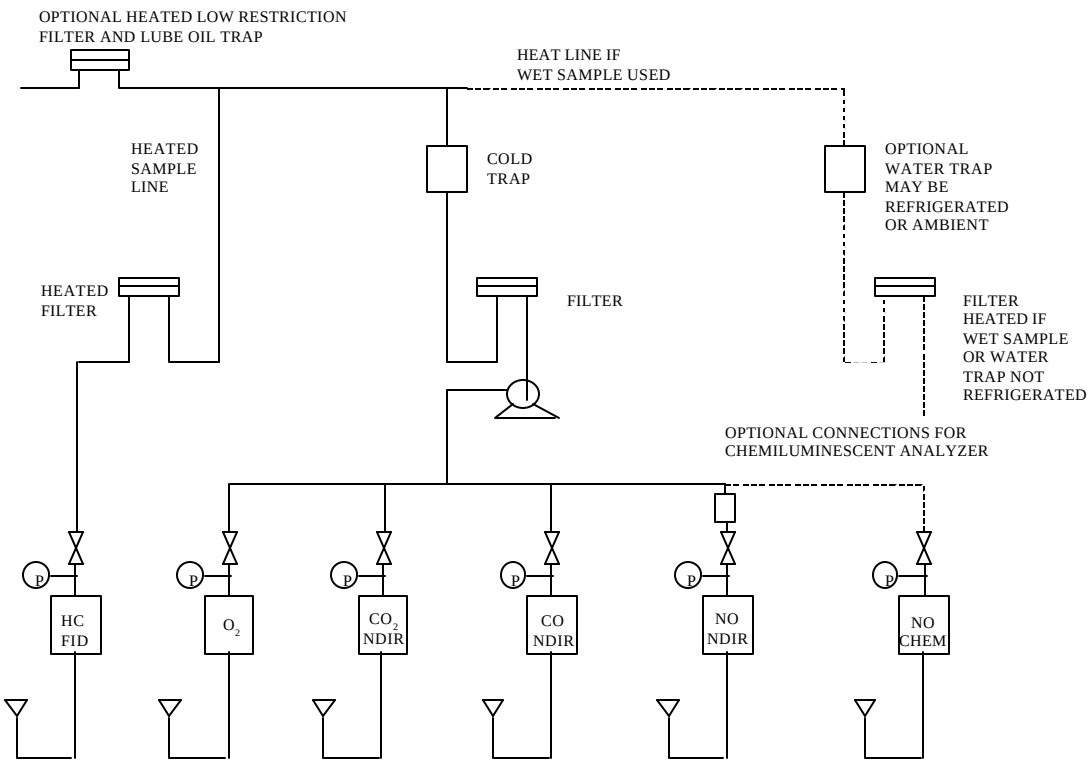


Figure 3-2. Exhaust Gas Analysis System
Source: (White, 1990)

If a chemiluminescent analyzer is used for NO analysis, alternate sample line connections are provided. The exact details of the analysis system and its layout as shown in Figure 3-2 would depend upon the requirements of the particular instrument being used.

3.2.5.2.3 Instrument Checkout and Calibration. Periodic calibration and adjustment is performed as specified by the instrument manufacturer and as dictated by experience with each individual analyzer. A minimum warm-up time of 2 hours is recommended for the NDIR analyzers before beginning to record data. At least ½hour

warm-up is allowed for the FID and chemiluminescent analyzers to permit these instruments to stabilize.

3.2.5.3 Engine Test Procedure

This section presents discussion on test preparation of the engine; exhaust emission measurement procedure, data reduction and presentation of results.

3.2.5.3.1 Engine Preparation. Test fuel that is representative of the commercially available gasolines is desirable to use. It is recommended that the test fuel specifications remain consistent from batch to batch. For the aforesaid reasons, the fuel to be used for emission tests is typically Indolene HO Motor Fuel III (less than 0.03 cm^3 tetraethyl lead per gallon (0.008 cm^3/L) and approximately 97 percent Research octane). For engines requiring a higher-octane fuel, the Indolene 30 is recommended.

For all engine tests, lubricating oil consistent with the engine manufacturer's specifications is employed. For 2-stroke engines, the oil-fuel mixture ratio conforms to the engine manufacturer's recommendations. Prior to beginning engine exhaust emission tests, it is recommended that the engine should run-in in accordance with the manufacturer's instructions for an operating period of not less than 10 hours. During the run-in period, the fuel and lubricants as specified previously are employed. Prior to starting the emissions tests, the engine is allowed to warm up in accordance to manufacturer's instructions. Before proceeding with the tests, the carburetor idling adjustments and the rated load fuel flow are set according to the recommendations of the manufacturer.

3.2.5.3.2 Exhaust Emission Measurement Procedure. When a comprehensive mapping of exhaust emissions from a given engine is desired, a sequence of 16 engine-operating modes is employed in the SAE J1088 test procedure as shown in Table 3-4. Once an engine is coupled to a specific end product, it would not operate in all the modes shown in the Table 3-4. Several engine applications are shown in Table 3-5 as a guideline along with the modes of the SAE J1088 procedure that might typically correspond to the real world use of the engine for the given application. For example, lawn mowers typically operate, though not always, at or close to rated engine speed but at different loads. Therefore, the high speed modes of the J1088 procedures are perhaps most likely to correspond to real world lawn mower applications compared to lower speed modes. Emissions are recorded in each mode. The engine is run in a given mode for a stabilization period so that the three consecutive readings agree with ± 5% of the central value. Rather than running under a governed throttle condition, the throttle is locked in place for each specified throttle setting.

Table 3-4. 16 Engine Operating Modes of the SAE J1088 Procedure

Mode No.	Throttle	Speed ± 2%	Boom Load ± 2%
1	Closed	Recommended low idle	Minimum
2	Full	Rated speed	Full Load at rated speed
3	Full	Max governed or 85 % rated speed	Full load at 85% rated speed
4	Part	Max governed or 85 % rated speed	85% of load obtained at mode 3
5	Part	Max governed or 85 % rated speed	75% of load obtained at mode 3
6	Part	Max governed or 85 % rated speed	50% of load obtained at mode 3
7	Part	Max governed or 85 % rated speed	25% of load obtained at mode 3
8	Part	Max governed or 85 % rated speed	Minimum
9	Full	Speed at peak torque or 60% rated speed	Full at corresponding speed
10	Part	Speed at peak torque or 60% rated speed	85% at corresponding speed
11	Part	Speed at peak torque or 60% rated speed	75% at corresponding speed
12	Part	Speed at peak torque or 60% rated speed	50% at corresponding speed
13	Part	Speed at peak torque or 60% rated speed	25% at corresponding speed
14	Part	Speed at peak torque or 60% rated speed	Minimum at corresponding speed
15	Part	30 % Rated	20% at corresponding speed
16	Closed	Recommended low idle	Minimum

Source: (White, 1990)

Table 3-5. Utility Engine Applications – Typical Operating Modes Compared to the SAE J1088 Procedure

Application	Mode number from Table 3-4									
	1	2	3	4	5	6	7	8	9	13
Walk Behind Mower	*	-	*	*	*	*	*	-	-	-
Riding Mower	*	-	*	*	*	*	*	-	-	-
Garden Tractor	*	-	*	*	*	*	*	*	-	-
Edger – Trimmer	*	-	-	-	-	*	*	*	-	-
Roto – Tiller	*	-	*	-	-	-	*	-	-	-
Reafer	-	-	-	-	-	-	*	*	-	*
Generator Utility	-	*	-	-	*	*	*	*	-	-
Pumps	-	-	-	-	-	*	-	*	-	-
Tamper	*	-	-	-	-	-	*	-	-	-
Shredder	-	-	-	-	-	*	*	-	-	-
Splitter	-	-	-	-	-	*	*	-	-	-
Snow Blower	*	-	*	*	*	*	*	-	-	-
Chain Saw	*	*	-	-	-	-	-	-	*	-

(*) Denotes major nodes of operation.
(-) Denotes modes in which engine seldom operates
Source: (White, 1990)

3.2.5.4 Data Reduction And Presentation Of Results

The engine operating and performance parameters that should be presented for each test are shown in Table 3-6. The table also shows the units in which these should be reported. The concentrations of each of the exhaust species are recommended to be measured in the units as shown in the Table 3-7.

Table 3-6. Engine Operating/Performance Parameters to be Reported in the SAE J1088 Procedure

Parameter	Units	
	English	**SI**
Airflow rate (dry)	lb/h	g/h
Fuel flow rate	lb/h	g/h
Engine speed	rpm	rpm
Engine torque output	lb-ft	N – m
Power output	hp	kW
Air inlet temperature	^{o}F	^{o}C
Air humidity	grains/lb dry air	mg/kg
Coolant temperature (water cooled)	^{o}F	^{o}C
Exhaust mixing chamber surface temperature	^{o}F	^{o}C
Exhaust mixing chamber surface temperature	^{o}F	^{o}C
Total accumulated hours of engine operation	H	h

Source: (White, 1990)

Table 3-7. Units of Measured Initial Molar Concentrations

Exhaust Species	Concentrations
Unburned hydrocarbons (HC)	Molar ppm C (in wet exhaust)
CO_2	Mole percent (in dry exhaust)
CO	Mole percent (in dry exhaust)
NO	Molar ppm (in dry exhaust if measured by NDIR or chemiluminescent analyzer requiring dry sample, in wet exhaust if chemiluminescent analyzer uses wet exhaust
O_2	Mole percent (in dry exhaust)

Source: (White, 1990)

Conversion of measured quantities to mass terms can be done using either wet or dry specie concentration data. Since engine emissions are discharged to the atmosphere in the wet state, it is considered reasonable to report the emissions on a wet basis. Hence, the conversion equations given below are written for use with wet concentration data. Two methods may be used to calculate the mass rate of discharge. One makes use of both fuel and airflow data while the other uses just fuel flow alone. The fuel flow method is discussed below as it appears to be used most often (White, 1990; Carroll, 1991; Carroll and White, 1993;and Carroll and White, 1994).

The following equations may be used when fuel flow is selected as a basis for mass calculations. These equations are based on the assumptions that are listed below (White, 1990):

- The exhaust unburned HC is assumed to have an average hydrogen-to-carbon ratio of 1.85/1 and a molecular weight of 13.85 g HC per mole HC.
- NO_x mass determinations are made in terms of NO_2.
- At fuel/air ratios leaner than 0.068 g fuel/g air, the molecular weight of the exhaust gas may be assumed to be 29 g/mol. As mixtures become progressively richer above 0.068, however, molecular weight of the exhaust gas decreases significantly. The following empirical equation can be used to estimate the molecular weight of the exhaust for mixtures richer than 0.068 g fuel/g air:

$$\text{Mol. Wt. Exh.} = (34.67 - 83.3\ F/A)\ \text{g per mol.} \qquad (3\text{-}1)$$

The equations are:

$$\text{HC, g/h (wet basis)} = 4.536 \times 10^{-2}\ (\text{HC, ppm C})\ \frac{\textit{fuel consumption, lb/h}}{TC}$$

$$\text{or,} = 10^{-4}\ (\text{HC, ppm C})\ \frac{\textit{fuel consumption, g/h}}{TC} \qquad (3\text{-}2)$$

$$\text{CO, g/h (wet basis)} = 916.27(\text{CO, \% wet})\ \frac{\textit{fuel consumption, lb/h}}{TC}$$

$$\text{or,} = 2.02(\text{CO, \% wet})\ \frac{\textit{fuel consumption, g/h}}{TC} \qquad (3\text{-}3)$$

$$\text{NO}_2\text{, g/h (wet basis)} = 15.06 \times 10^{-2}(\text{NO, ppm wet})\ KH \times \frac{\textit{fuel consumption, lb/h}}{TC}$$

$$\text{or,} = 3.32 \times 10^{-4}\ (\text{NO, ppm wet})KH \times \frac{\textit{fuel consumption, g/h}}{TC} \qquad (3\text{-}4)$$

where,

TC = total carbon = vol % CO_2 wet + vol % CO wet + vol % HC wet (3-5)

KH = federal factor for correcting for the effect of humidity on NO_x formation.

$$= \frac{1}{[1-0.0047(H-75)]}$$, where, H = specific humidity, grains/lb of dry air at test conditions (For 4-stroke Engines)

= 1 (For 2 – stroke Engines) (3-6)

Although not explicitly stated by White (1990), it appears that only one mole of carbon per mole of HC is assumed. However, as long as the HC emissions are relatively small this assumption does not introduce much error. The humidity correction factor (*KH*) given above has been taken from the Code of Federal Register, 40 CFR 86. 144-78. This correction factor has not been verified for small engines. Also, NO_x emissions for small engines are low, and the *KH* factor, as an option, may therefore be set to one (White, 1990).

3.2.6 CARB J1088 Procedure

The California Air Resources Board (CARB) modified the method proposed by SAE by treating handheld and non-handheld equipment separately, having different modes for both, and attaching different weighting factors to them. The CARB modification of the SAE J1088 procedure, referenced to here as CARB J1088, is a steady state modal procedure based on raw exhaust gas analysis. The CARB procedure will govern small engine emission certification in California (Carroll, 1991). Table 3-8 shows the proposed CARB J1088 modes and weighting factors for both handheld and non-handheld equipment.

Table 3-8. Proposed CARBJ1088 Modes and Weighting Factors

J1088 Mode	1	2	3	4	5	6	7
Speed	Idle	Rated	85 % of Rated	85 % of Rated	85 % of Rated	85 % of Rated	85 % of Rated
Load	0	Full	Full	75 % of Full	50 % of Full	25 % of Full	Minimum
Handheld	10 %	90 %	----	----	----	----	----
Non-Handheld	5 %	----	9 %	20 %	29 %	30 %	7 %

Source: (Carroll, 1991)

Analysis of the engine exhaust including hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), carbon dioxide (CO_2) and oxygen (O_2) is required by this procedure. The fuel flow to the engine must be measured and used to calculate total exhaust flow. A full discussion of the emissions calculations is given by White *et al.*, (1991). The procedure calculates exhaust emissions by balancing carbon-containing compounds in the exhaust with carbon in fuel (Carroll, 1991).

3.2.7 SAE J1088 "A" Procedure

Some investigators report variations of the SAE J1088 procedure using different nomenclature. For example *Sun et. al*. (1995) report that the SAE J1088 "A" cycle is comprised of six modes: 100%, 75%, 50%, 25%, 10%, and 0% torque. Mode 6 (0% torque) is run at idle speed. All the other modes are at 85% rated speed. The mode weightings (in time) are 9%, 20%, 29%, 30%, 7%, and 5%, respectively. This is same cycle as proposed by the CARB for non-handheld intermediate speed applications such as walk behind rotary or reel lawn mowers, front or rear engine riding lawn mowers, rotary tillers, edger trimmers, waste disposers, lawn sweepers, sprayers, and snow removal

equipments. Thus, the so called SAE J1088 "A" procedure is merely a specific application of the SAE J1088 procedure.

3.2.8 SAE J1088 "C" (90:10 & 70:30) Procedure

One subset of the SAE J1088 procedure is referred to by Sun *et al*. (1995) as the SAE J1088 "C" procedure. EPA refers to the SAE J1088 "C" (70:30) cycle as the "Chainsaw Cycle". This cycle is developed for hand-held rated speed applications such as chainsaws, edge trimmers, string trimmers, blowers, and vacuums. It is composed of 2 modes with one at 100% torque and at rated speed and with other one at 0% torque and at idle speed. There are two different mode-weightings for this cycle. One is a 90%/10% split between the two modes, which has been used by the CARB for handheld engines in their modified version of the SAE J1088 procedure (i.e. CARB J1088). The other is a 70%/30% split between the modes, which is designed from experience and used exclusively for chainsaw engines (Sun *et al.*, 1995).

3.2.9 Lawn Mower Cycle

The Lawn Mower cycle was developed by University of Michigan from the analysis of the transient GGRASS cycle and is designed specifically for steady state test of lawnmower engines (Sun *et al.*, 1995). The GGRASS cycle, is a transient cycle designed from the average of a large amount of records of practical lawnmower engine operations. It is an 18-minute cycle with 2 additional minutes of warm-up time. The GGRASS cycle was first recommended by Southwest Research Institute and tested in Tecumseh Co. and the University of Michigan. It is operated under governor control. The lawn mower cycle is a steady-state test procedure comprising of 5 modes; 90%, 70%,

50%, 30%, and 10% torque. All the modes are run at 85% rated speed. The mode-weightings are 6%, 10%, 20%, 47%, and 17%, respectively (Sun *et al.*, 1995).

3.2.10 Generator Set Cycle

The generator set cycle is specifically designed for integrated generator sets and has been accepted by the CARB. The generator set cycle is a steady-state test procedure comprising of five modes: 100%, 75%, 50%, 25%, and 0% torque. All modes are run at rated speed. The mode weightings are 9%, 21%, 31%, 32% and 7%, respectively. The engine is integrated with the generator, which is very convenient for end use. However it does not permit the engine to be tested separately. Since the governor and control systems are designed only for rated speed operations, the integrated sets can only be run at rated speed. Therefore the set cannot be run at 85% intermediate speed or idle speed (Sun *et al.*, 1995).

3.3 Data Analysis

While working on the nonroad mobile source category, the original objective of the data collection activity was to collect all of the test data that was used by the EPA in coming up with the emission factors for the Lawn and Garden (L&G) and Construction, Farm and Industrial (CFI), presented in Chapter 4, source categories and then reproduce those emission factors. However, the data to do this was not easily available. EPA uses these emission factors in the NONROAD emission inventory model. Information regarding the specific data and algorithms used by the model to come up with the emission factors are not readily available. In particular, the emissions data are from a variety of reports, a number of which are not available in the open literature and could

not be obtained after several months of searching. Moe details about the reports that could not be found are presented in Appendix G. Given the unavailability of a complete data set and the incomplete documentation of the current version of the NONROAD model, it was decided instead to focus on obtaining a reasonable data set and analyzing these data to develop relative measures of uncertainty. Relative measures of uncertainty, such as plus or minus percentage ranges on the estimated mean value, provide insight into the level of uncertainty anticipated in any emission factor calculated based upon a similar dataset in the NONROAD model.

Data collected from the literature review were analyzed for possible groupings among the emission factors. First, the reproduction of the reported emission factors is discussed followed by comparisons between the various test procedures that were used to develop the reported emission factors. Finally, the results of statistical analysis of the data to ascertain statistically significant groupings among the emission factors are presented.

3.3.1 Reproducing Reported Emission Factors

To better understand the emission factor development process, the emission factors for THC and NO_x that were reported for the J1088 test procedures in the SwRI reports were recalculated from the modal engine test data given in these reports. This was possible with the SwRI reports because they contained the actual test mode data and not just the weighted averages of all modes. There were no humidity correction factors that needed to be applied to the L&G emission factors as none of the reports that were consulted for this study did so. It was possible to recalculate the reported average emission factors for each test to within three or four significant digits. The units with

emission factors were reported varied among the data sources. For example, g/hp-hr units are reported by CARB, whereas this and other units are reported in the reviewed SAE papers. The emission factors were reproduced exactly in almost all the cases barring a few where the recalculated emission factors were off by just one significant digit. For example, in one case the reported emission factor was 65.0 g/h and the value calculated was 64.9 g/hp-h. The recalculation of emission factors served as a quality assurance step. However, it was the reported emission factors and not the recalculated emission factors that were used in the database.

The emission factors were usually reported in gram/hour and gram/hp-hour units in the reports that had used the SAE J1088 or the CARB J1088 testing procedure. In the other reports the emission factors were usually reported in gram/hp-hour units. For such reports, if the power output data of the engine was given as measured during the testing then, for them emission factors in gram/hour units were also calculated. Also for all the reports where the fuel flow rate was given as measured during the testing, emission factors in gram/gallon units were also calculated. The fuel used for gasoline engine testing was an emissions grade, unleaded, certification fuel. The specific gravity of the fuel was taken to be 0.75 (Frey and Eichenberger, 1997) and using the fuel flow rate and the specific gravity emission factors in gram/gallon units were calculated. The conversion can be done as shown in the following simple steps:

1. Specific Gravity of gasoline = 0.75, implies $\rho_{Gasoline}$ = 6.26 lb/gallon
2. [(Gram of pollutant/hour)/(lb of fuel/hour)] x $\rho_{Gasoline}$ = Gram of pollutant/ gallon of fuel. OR,
3. [(Gram of pollutant/hp-hour)/(lb of fuel/hp-hour)] x $\rho_{Gasoline}$ = Gram of pollutant/ gallon of fuel.

A sample calculation is given here for converting from g/hr to g/gallon of fuel using actual test data. Suppose the gram/hour emission factor is 126.6 for HC and the fuel flow rate in lb/hour is 2.62 lb/hour, then the emission factor for HC in gram/gallon is computed as:

[(126.6 g of HC/hr)/(2.62 lb fuel/hr)] x 6.26 lb fuel/gallon of fuel

= 303 g of HC/gallon of fuel

A sample calculation is given here for converting from g/hp-hr to g/gallon of fuel using actual test data. Suppose an emission factor is 69.44 g/hp-hr for HC and the fuel flow rate is 1.44 lb/hp-hour, then the emission factor for HC in gram/gallon is computed using the above method as:

[(69.44 g of HC/hp-hr)/(1.44 lb fuel/hp-hr)] x 6.26 lb fuel/gallon of fuel

= 302 g of HC/gallon of fuel

Both methods yield the same emission factor for grams/gallon of HC irrespective of the method we chose for calculating the emission factor. Besides the above methods,

there was another one that was employed to get g/gallon emission factors from the known concentrations of CO_2, CO and HC emission rates, given that all are measures on the same basis and a reasonable fuel composition is assumed (Frey and Eichenberger, 1997). The combustion reaction of the fuel is as shown in Equation 3-7.

$$CH_y + m\,[0.21\,O_2 + 0.79\,N_2] \rightarrow a\,CO + b\,H_2O + c\,C_3H_6 + d\,CO_2 + e\,N_2 \quad (3\text{-}7)$$

where a, b, c, d, e and m are unknown stoichiometric coefficients as defined below:

a = moles of CO formed per mole of fuel consumed

b = moles of H_2O formed per mole of fuel consumed

c = moles of C_3H_6 formed per mole of fuel consumed

d = moles of CO_2 formed per mole of fuel consumed

e = moles of N_2 formed per mole of fuel consumed

m = moles of "air" (Mixture of O_2 and N_2) formed per mole of fuel consumed

y = 1.84 for Diesel and 1.95 for gasoline (Frey and Eichenberger, 1997)

writing mass balance equations based on the conservation of atoms for each elemental species:

Element	**Reactants**	**=**	**Products**	
Carbon (C)	1	=	a + 3c + d	(3-8)
Hydrogen (H)	y	=	2b + 6c	(3-9)
Oxygen (O)	0.42 m	=	a + b + 2d	(3-10)
Nitrogen (N)	1.58 m	=	2e	(3-11)

Since the emission factors of CO, CO_2, and HC are known following additional equations are obtained:

$$R_{CO} = \frac{\text{CO Emission Factor / Mol. Wt. Of CO}}{\text{CO}_2\text{ Emission Factor / Mol. Wt. of CO}_2} = a / d \quad (3\text{-}12)$$

$$R_{HC} = \frac{\text{HC Emission Factor / Mol. Wt. Of HC}}{\text{CO}_2\text{ Emission Factor / Mol. Wt. of CO}_2} = c / d \quad (3\text{-}13)$$

From equations (3-12) and (3-13), the stoichiometric coefficients for CO and C_3H_6 can be expressed in terms of stoichiometric coefficients for CO_2 and the ration of CO to CO_2 and HC to CO_2.

$$a = R_{CO}\, d \quad (3\text{-}14)$$

$$c = R_{HC}\, d \quad (3\text{-}15)$$

Based on Equation (3-14) and (3-15), Equation (3-8) can be written as:

$$d = \frac{1}{R_{CO} + 3R_{HC} + 1} \quad (3\text{-}16)$$

Thus assuming that the closure on carbon mass balance can be obtained by considering CO_2, CO, and C_3H_6, the moles of CO_2 produced per mole of fuel can be estimated based upon the emission factor ratios. Equations (3-14) and (3-15) can then be used to calculate the moles of CO and C_3H_6, using the value of d, formed per mole of fuel combusted. Next for calculating the emission factors on g/gallon basis the molecular weight of the gasoline fuel and the estimated density of gasoline in units of gmol/gallon, were taken to be 13.976 grams of fuel and 201 gmol/gallon respectively, as reported by Frey and Eichenberger, (1997). Using this information the HC and CO_2 emission factors on basis of g/gallon can be calculated by the following equations:

$$EF_{HC} = 201 \text{ gmol/gallon}*(c)*(\text{Mol. Wt of HC as } C_3H_6) \quad (3\text{-}17)$$

$$EF_{CO2} = 201 \text{ gmol/gallon}*(d)*(\text{Mol. Wt of } CO_2) \quad (3\text{-}18)$$

For calculating the NO_x emission factor the ratio of NO_x emissions to CO_2 emissions is needed:

$$R_{NOx} = \frac{NO_x \text{ Emission Factor / Mol. Wt. Of } NO_x}{CO_2 \text{ Emission Factor / Mol. Wt. of } CO_2} \quad (3\text{-}19)$$

The emission factor for NO_x on gm/gallon basis is given by:

$$EF_{NOx} = \left(EFCO_2 \ \frac{g\,CO_2}{gallon}\right)\left(\frac{M\,Wt.\,of\ NO_2}{M\,Wt.\,of\ CO_2}\right)\left(RNO_x \ \frac{gmol\ NO_x}{gmol\ CO_2}\right) \quad (3\text{-}20)$$

As an example let's assume that the HC emission factor is 112 g/kW-hr, CO emission factor is 182 g/kW-hr, CO_2 emission factor is 1081 g/kW-hr and NO_x emission factor is 1.1 g/kW-hr. Then the values of R_{CO}, R_{HC}, and R_{NOx} are :

R_{CO} = (182 g/kW-hr /28 g/gmol) / (1081 g/kW-hr / 44 g/gmol)

= 0.27 gmol CO/gmol CO_2

R_{HC} = (112 g/kW-hr /42 g/gmol) / (1081 g/kW-hr /44 g/gmol)

= 0.11 gmol HC/gmol CO_2

R_{NOx} = (1.1 g/kW-hr /46 g/gmol) / (1081 g/kW-hr /44 g/gmol)

= 0.001 gmol NO_x/gmol CO_2

After this, the values of d and c are calculated as follows:

d = 1 / [0.27(gmol CO/gmol CO_2) + 3*0.11(gmol HC/gmol CO_2) + 1]

= 0.63 gmol CO_2/gmol fuel

c = [0.11 (gmol HC/gmol CO_2)]*[0.63 (gmol CO_2/gmol fuel)]

= 0.07 gmol HC as C_3H_6/gmol fuel

Calculating the HC, CO_2 and NO_x emission factors:

EF_{HC} = [201(gmol/gal)]*[0.07(gmol HC as C_3H_6/gmol fuel)]*[42g HC/gmol]

= 575 g/gallon

EF_{CO2} = [201(gmol/gal)]*[0.63(gmol CO_2/gmol fuel)]*[44g CO_2/gmol]

= 5560 g/gallon

EF_{NOx} = [5560 (g CO_2/gal)]*[0.001(gmol NO_x/gmol CO_2)]*

[(46 g NO_x/gmol)/(44g CO_2/gmol)]

= 5.66 g/gallon

3.3.2 Comparing the Test Cycles

Emission factors were reported in the literature based upon a variety of test procedures. Before grouping data from multiple test procedures into a single database for statistical analysis, it is important to first identify whether the data from two or more different types of tests are comparable. Therefore, an initial task in data analysis was to identify each test procedure and to determine whether emissions from different test procedures could be converted to a consistent basis. The various cycles were compared on the basis of how their modes are defined. In all of the comparisons, the CARB J1088 test cycle was taken to be a standard with which all the others were compared. This is because most of the engine test data that are well documented used the CARB J1088 test procedure. Table 3-9 gives a brief description of the various test cycles.

Table 3-9. Comparison of Selected L&G Equipment Test Cycles Based on the Number of Modes and Type of Engine Load

No.	Cycle	No. of Modes	Number of Modes by Type of Engine Load		
			Low Idle	Intermediate	Rated
1	SAE J1088	16	2	13	1
2	CARB J1088 (handheld)	2	1	-	1
3	CARB J1088 (non-handheld)	6	1	5	-
4	EMA 13-Mode	13	3	5	5
5	C6M	6	1	5	-
6	6-Mode	6	1	5	-
7	Lawn Mower Cycle	5	-	5	-
8	Generator Set Cycle	5	-	-	5

Each test cycle is characterized by a number of steady-state "modes." Each steady-state mode typically involves operation at a specified engine speed or type of speed and load (i.e. idle, low, intermediate or rated) for a given length of time. The intermediate speed varies from one test cycle to another. For example, in the CARB J1088, C6M and 6-Mode test procedures the intermediate speed is 85 percent of the rated speed (Carroll, 1991; Gabele, 1997a) but for the EMA 13 mode test it is 60 percent of the rated speed (Hare and Springer, 1973a). The SAE J1088 test procedure has equal number of modes with intermediate speeds of 60 percent and 85 percent of the rated speed (White, 1990)

The CARB J1088 procedure proposes two test cycles for measuring emissions: one for engines used in hand held applications and the other for engines used in non-handheld applications. For handheld applications only the first two modes are used in testing, whereas for non-handheld applications modes 1, 3, 4, 5, 6, and 7 are used (Carroll, 1991).

There were a number of conclusions drawn from the comparison of test cycles. The EMA 13 Mode procedure is not the same as the CARB J1088. The EMA procedure has 9 steady state modes that are not the same compared to any of the modes used in the CARB J1088 procedure. Also there were no test results available, so that further statistical comparisons be done, where the same engine was tested using these two test cycles. The C6M test procedure is the same as the CARB J1088 procedure for non-handheld engines because it uses the same steady state modes and the same weights. The Generator Set Cycle and the Lawn Mower Cycle use different steady state modes compared to the CARB J1088 procedure. The Lawn Mower Cycle has modes with different loads and the Generator Set Cycle has modes with different speeds. The 6-Mode test cycle has the same modes as those defined in the CARB J1088 test cycle for non-handheld engines but the weightings used were not available. The engines which were tested using the 6 Mode test cycle were also tested using the C6M procedure. For such engines the data from C6M test procedure were used in the database. This was done because more information was available for the C6M procedure such as modal weightings. Also, the emission factors reported did not differ by more than six percent between the C6M and 6-Mode test cycles. Emission factor data developed using the SAE J1088 “A” and “C” (90:10) cycles was also included in the database as they were found similar to the CARB J1088 test procedure.

The SAE J1088 procedure from which the CARB J1088 procedure was derived has more modes than the CARB J1088 procedure. However not all of these are used to test a particular L&G engine. All steady state modes in the CARB J1088 procedure are in the SAE J1088, and it is mostly these modes that are recommended by the SAE J1088

procedure for testing L&G engines. For these reasons the emission factor data from L&G engines using these two test procedures were combined in the database. In general, there were no data available where the same engine had been tested using two different cycles so that those two cycles could be compared statistically using that emission factor data. In light of this fact, cycles had to be compared with the standard J1088 procedure by comparing their modes with it. Hence emission factor data from five test procedures was finally included in the database namely: SAE J1088, CARB J1088, C6M, SAE J1088 "A", and SAE J1088 "C" (90:10).

3.3.3 Summary of Database

In Table 3-10, a summary of the database is presented which shows the number of engines for which emission factor data could be obtained with respect to possible emission factor categories, pollutants, and emission factor units. The complete database is given in the appendix. The database includes data only from J1088 (CARB, SAE, SAE "A" and SAE "C" 90:10) and C6M test procedures. Data for a total of 51 engines are included. The numbers shown for the 2-stroke and the 4-stroke categories include both handheld and non-handheld engines. Please note that numbers in any given row or column do not add up to the total number of engines in the database because many engines can be included in more than one category (e.g., as 4-stroke, OHV, and Non-handheld) and may include data for more than one emission factor unit (e.g., g/hr, g/hp-hr, and g/gal).

Table 3-10. Summary of the L&G Engine Emission Factor Database

Category	Number of Engines					
	THC (g/hr)	**THC (g/hp-hr)**	**THC (g/gal)**	**NO_x (g/hr)**	**NO_x (g/hp-hr)**	**NO_x (g/gal)**
2 – Stroke	18	16	16	18	16	16
4 – Stroke	19	22	19	19	27	19
OHV	9	9	9	9	10	9
LHV	6	9	6	6	13	6
Handheld	16	14	14	16	14	14
Non Handheld	21	24	20	21	29	20

Emission factor data were not available for all the three emission factor units (i.e. g/hr, g/hp-hr, and g/gal) for all cases. For example, some reports had THC and NO_x data in g/hp-hr units only, while some had enough additional information provided so that emission factors could be calculated in other units. Also in one of the reports, instead of THC, the emission factors reported were in terms of Non-Methane Organic Gas (NMOG) and were not used in the database (Gabele, 1997b). THC is defined as total hydrocarbon, which contains methane and other non oxygenated hydrocarbons. NMOG on the other hand contains both oxygenated hydrocarbons (e.g. alcohols and aldehydes) and non oxygenated hydrocarbons (except methane). Thus, for the 4-stroke L&G category there are 27 data points for NO_x (g/hp-h) and only 22 data points for THC (g/hp-h).

Each data point in the database represents a separate make and model of L&G engine. However, there were three cases (2-stroke NO_x g/h, 2-stroke THC g/h and 4-stroke NO_x g/hp-h) when there were multiple emission factors reported for a particular engine measured by the same test procedure but under different test conditions or fuels. The value considered most representative of typical measurements was included in the

database. In all of these cases the chosen value was not different from the other measurements by more than 11 percent.

3.3.4 Grouping the Test Data

The database compiled from the available literature was analyzed statistically to identify whether there are any significant differences in emissions that justify categorization of the data with respect to the type of engine application, the engine technology, and/or the engine size.

3.3.4.1 Categorizing Emission Factors By Application.

The L&G data set compiled from available literature was evaluated to determine whether there is a statistically significant difference in the mean emission factor estimate when comparing engines used in handheld applications versus those used in non-handheld applications. For this, 2-tailed *t* – tests for the differences in means at a 5 percent level of significance were done on the data for these two categories. The comparison between handheld and non-handheld applications was made for six groups of data: for each of the two pollutants (NO_x and THC), three different emission factor units were considered separately (g/hr, g/hp-hr, and g/gallon). The *t* – Test results are described in Table 3-11. Except for NO_x emissions when measured in g/gallon units and THC emissions when measured in g/hp-h units, for all of the other cases considered there was a significant difference in the mean emission rates when comparing handheld and non-handheld datasets. Thus, it would be reasonable to separately calculate emission factors with respect to these two types of applications.

Table 3-11. Results of Comparison of Non-Handheld versus Handheld Emissions Data Based Upon *t*-Tests for the Difference of Two Means at a 5% Level of Significance.

Comparison	Pollutant	Units	Significant Difference between Data Sets?
Non-Handheld Engines Versus Handheld Engines	THC	g/h	Yes
		g/hp-h	No
		g/gallon	Yes
	NO_x	g/h	Yes
		g/hp-h	Yes
		g/gallon	Yes

Table 3-12. Results of Comparison of 2-Stroke versus 4-Stroke Engine Emissions Data, and of OHV versus LHV 4-Stroke Engines, Based Upon *t*-Tests for the Difference of Two Means at a 5% Level of Significance**.**

Comparison	Pollutant	Units	Significant Difference between Data Sets?
2-Stroke Engines versus 4-Stroke Engines	THC	g/h	Yes
		g/hp-h	Yes
		g/gallon	Yes
	NO_x	g/h	Yes
		g/hp-h	Yes
		g/gallon	Yes
4-Stroke Engines: Over Head Valve versus Side Head Valve	THC	g/h	Yes
		g/hp-h	No
		g/gallon	No
	NO_x	g/h	No
		g/hp-h	No
		g/gallon	No

3.3.4.2 Categorizing Emission Factors By Technology.

The L&G data set compiled from available literature was evaluated to determine whether there is a statistically significant difference in the mean emission factor estimates when comparing 2-stroke versus 4-stroke engines. In addition, a comparison was made between OHV and LHV 4-stroke engines. To make the comparisons, 2-tailed *t* – tests for the difference in means at a five percent significance level were done. Both comparison were made for six groups of data: for each of the two pollutants (NO_x and THC), three different emission factor units were considered separately (g/hr, g/hp-hr, and g/gallon). The *t*-test results are described in Table 3-12. The analysis showed that there is a significant difference in the means of the 2-stroke versus 4-stroke engine data sets. Also except for THC emissions when measured in units of g/h, there was not a significant difference in the mean OHV versus LHV emissions. Thus, it is reasonable to develop emission factors separately for 2-stroke and 4-stroke engines. However, it is not necessary to subdivide 4-stroke engines into categories of OHV and LHV technologies.

3.3.4.3 Categorizing Emission Factors By Engine Size.

Although in the NEVES report EPA has not categorized L&G engines of less than 25 hp by size, EPA plans to do so in its new NONROAD model. Within these size categories emission factors would be divided on the basis of application also if there were sufficient information to justify their use. Specifically, EPA reports that two stroke engines will be divided into a category of less than 3 hp and a category of greater than 3 hp. Both of these categories are assumed by EPA to correspond to non-handheld applications of the 2-Stroke engines. EPA does not report plans to categorize L&G four stroke engines by size (Beardsley *et al*., 1998)

In the database, there are only 2 data points in the category of 2-stroke engines, non handheld (≤ 3hp) and only one data point in the category of 2-stroke engines, general non handheld (≥ 3hp). This is not sufficient data to perform a statistical analysis of uncertainty, nor is it a sound basis for subdividing the emissions database. Because 2-stroke engines are primarily used in handheld applications, and because 4-stroke engines are primarily used in non-handheld applications, there are few data available for non-handheld 2-stroke engines and for handheld 4-stroke engines. Therefore, on the basis of lack of data, the analysis of emissions with respect to size focuses on the type of engine, rather than on the type of application. For 2-stroke engines, the emissions measurements for the three non-handheld engines in the database fall within the range of measurements for the 16 handheld engines included in the database. Therefore, it was judged acceptable to combine the non-handheld 2-stroke engine data with the larger amount of handheld 2-stroke engine data to create a database with measurements for a total of 19 engines. Similarly, for 4-stroke engines, the emissions measurement for one handheld engine was within the range of values for 31 non-handheld 4-stroke engines. Therefore, it was judged acceptable to include the data for the handheld 4-stroke engine as part of the 4-stroke engine database of 32 total measurements.

To evaluate whether there is a possible dependence of emissions with respect to size for the 2-stroke and for the 4-stroke engines, scatter plots of emissions versus measures of size were created for each type of engine. Examples of these scatter plots are shown in Figures 3-3 and 3-4 for 4-stroke and 2-stroke engines, respectively. The example scatter plot for 4-stroke engine THC emissions versus engine horsepower

indicate a possible difference in emission rates for engines of less than approximately eight horsepower compared to those in the 8 to 25 hp range. The differences are two-fold: (1) there appears to be substantially more variability in emissions for the smaller size range, with emissions varying from approximately 10 g/hp-hr to as much as nearly 100 g/hp-hr, versus values close to 10 g/hp-hr in the upper size range; and (2) the average emissions appear to be greater for the smaller size range.

The example scatter plot for 2-stroke engine THC emissions versus engine rated horsepower does not provide any strong indication of a dependence of emissions with respect to engine size. There is more variability in the emissions for engines of less than 3 hp compared to engines of greater than 3 hp. However, the average values of emissions appear to be approximately similar for both size ranges. Therefore, it is less clear in this case as to whether engine emissions differ significantly with respect to size.

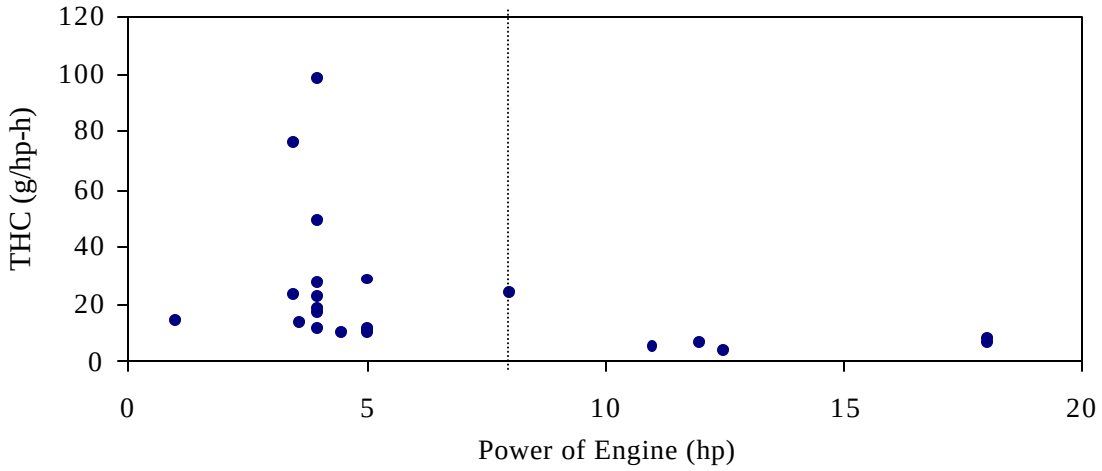


Figure 3-3. Scatter Plot of THC (g/hp-h) Emission Factors for 4-Stroke L&G Engines Versus the Size of the Engine (Rated Horsepower)

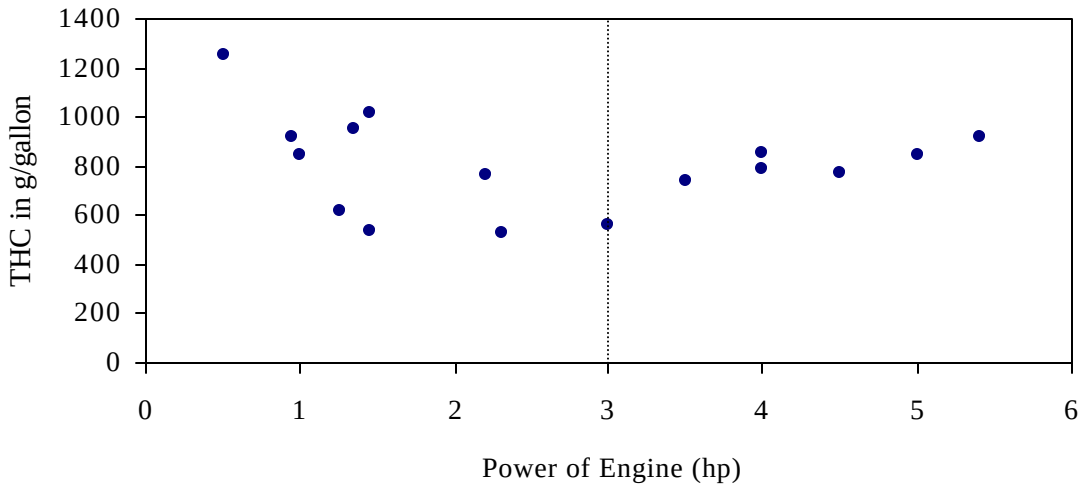


Figure 3-4. Scatter Plot of THC (g/gallon) Emission Factors for 2-Stroke L&G Engines Versus the Size of the Engine (Rated Horsepower).

To identify whether apparent differences in the scatter plots are statistically significant, two-tailed t-tests, at a five percent significance level, for differences in the mean values of emissions for different size ranges were conducted. For the 4-stroke engines, emissions data were divided into two size ranges of less than eight horsepower and greater than eight horsepower. Six comparisons were made inclusive of both pollutants and of all three units used for emission factors. Similarly, for 2-stroke engines, six pair-wise comparisons were made for engines sizes of less than three horsepower versus those greater than three horsepower. The results of the statistical tests are given in Table 3-12.

The statistical test results depend on which emission factor unit is used. For example, for 2-stroke engines there is not a statistically significant difference in mean values if g/gallon emission factors are used. For 2-stroke engines, the 95 percent confidence interval for the mean of the small size range is 670 g/gallon to 984 g/gallon, compared to a 95 percent confidence interval for the larger size range of 688 g/gallon to 862 g/gallon. The confidence interval for the larger size range is enclosed by the confidence interval for the smaller size range, indicating substantial overlap between the two intervals. As indicated in Table 3-13, the mean emissions for these two size ranges are not statistically significantly different from each other.

Table 3-13. Results of Comparison of Size Ranges for 4-Stroke and for 2-Stroke Engines Based Upon *t*-Tests for the Difference in Mean Emissions at a 5% Level of Significance.

Comparison	Pollutant	Units	Significant Difference between Data Sets?
4 Stroke Engines: Size Range ≥ 8hp vs. Size Range < 8hp	THC	g/h	No
		g/hp-h	Yes
		g/gallon	Yes
	NO_x	g/h	Yes
		g/hp-h	No
		g/gallon	No
2 Stroke Engines: Size Range ≥ 3hp vs. Size Range < 3hp	THC	g/h	Yes
		g/hp-h	No
		g/gallon	No
	NO_x	g/h	No
		g/hp-h	No
		g/gallon	No

Source: (Bammi and Frey, 2001).

Based upon the results in Table 3-13, it appears that, for 2-stroke engines, there is little evidence to suggest that the mean emissions are significantly different between the two size ranges considered. The only exception to this is for g/hr units for the THC emission factor. However, because g/hr emissions are not normalized to any measure of engine size (e.g., hp-hr produced or gallons of fuel consumed) it is expected that this measure of emissions would be size dependent. Furthermore, g/hr emission factors are not particularly useful as an emission factor because they are size dependent. Thus, for practical purposes, there is not a demonstrated need, based upon the data, to divide 2-stroke engines into size categories. For 4-stroke engines, there is more evidence that there are differences in emissions for different size ranges. For example, average g/gallon emissions differ significantly between the two size ranges. However, as noted, mean g/hp-hr emissions do not differ significantly.

The findings from comparison of different possible categories of data are as follows: (1) there are significant differences in mean emissions between 2-stroke engines and 4-stroke engines; (2) there are significant differences in mean emissions between handheld and non-handheld engines; (3) there are not significant differences in mean emissions between 4-stroke OHV engines and 4-stroke LHV engines; and (4) there are mixed indications regarding differences in mean emissions with respect to engine size. Because there is strong concordance between 2-stroke engines and handheld engines, and between 4-stroke engines and non-handheld engines, and lack of sufficient data for 2-stroke non-handheld engines and 4-stroke handheld engines, classifications with respect to engine design (2-stroke versus 4-stroke) or application (handheld versus non-handheld) are approximately equivalent. In this work, classification by engine design is selected for 2-stroke engines but the 4-stroke engines are classified on the basis of both design and size. The analysis also suggests no need to classify 4-stroke engines with respect to OHV versus LHV design.

3.4 Analysis of Variability and Uncertainty

The previous sections focused upon development and exploration of an L&G engine emission factor database. In this section, variability in the emission factor data are quantified using parametric probability distribution models. Uncertainty in the mean emission factors, and regarding the fitted distributions, is quantified using bootstrap simulation. Estimates of uncertainty in mean emission factors are presented for both 2-stroke and 4-stroke engines for two pollutants (THC and NO_x) and for three emission factor units (g/hr, g/hp-hr, and g/gallon).

3.4.1 Quantification of Inter-Engine Variability and Uncertainty in Mean of Emissions

Measured emissions vary from one engine to another in the database. The variability in emissions can be described as an empirical cumulative distribution function (CDF) or by a parametric probability distribution function. Parametric distributions offer advantages of enabling interpolation within the range of the observed data and for extrapolation to the tails of the distribution beyond the range of observed data (Cullen and Frey, 1999). The latter is important because it is unlikely, with a finite sample of data, that the true minimum or maximum values are represented by the sample minimum and maximum values. In this work, alternative parametric probability distribution models were fit to the data and evaluated for goodness-of-fit based upon visualization of the fitted distribution compared with the data and based upon the results of bootstrap simulations of the fitted distribution. Statistical goodness-of-fit tests were not used because the data sample sizes are too small. The parametric distributions considered were Normal, Lognormal, Gamma and Weibull. Maximum likelihood estimation was used to estimate the parameters of the fitted distributions. To characterize the uncertainty in the mean emissions the technique of bootstrap simulation was used. Using this technique 95 percent confidence intervals were determined for the mean emissions for each of the different emission factor groupings.

3.4.2 Results of Quantitative Analysis of Variability and Uncertainty in L&G Engine Emission Factors

The probabilistic techniques were applied to each of the emission factor data groups identified as having statistically significant differences in mean emissions with respect to each other. To illustrate the application of the probabilistic methods, example results are presented for selected cases.

In Figure 3-5, results are shown for the 2-stroke engine NO_x emission data set in units of g/hp-hr. The variability in emissions among these engines is from approximately 0.1 g/hp-hr to approximately 2.4 g/hp-hr, with most of the data having emission values of less than 1.0 g/hp-hr. A fitted Lognormal distribution is shown in comparison to the data. The Lognormal distribution captures the overall trends of the empirical distribution of the data. There is some scatter of the data above and below the fitted distribution. In order to evaluate whether the deviations of the data with respect to the fitted distribution imply a poor fit, confidence intervals for the fitted CDF of the Lognormal distribution are shown. These confidence intervals were obtained based upon bootstrap simulation. Approximately one half of the data (7 out of 16 data points) are enclosed by the 50 percent confidence interval, and all of the data are enclosed by the 95 percent confidence interval. This comparison suggests that the Lognormal distribution is an adequate fit to the data set and, therefore, is a reasonable representation of inter-engine variability in emissions.

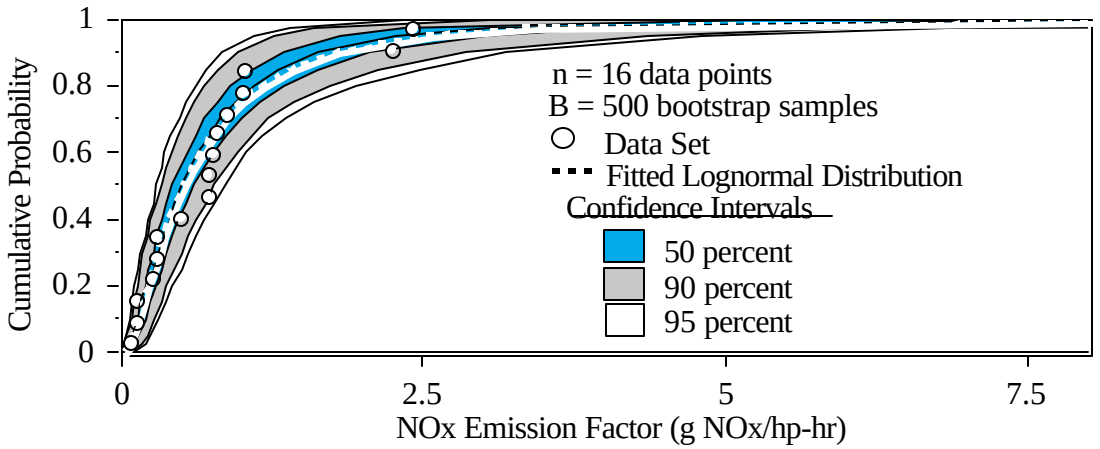


Figure 3-5. Fitted Lognormal Distribution and Bootstrap Simulation Results for 2-Stroke L&G Engine NO_x Emission Data in Units of g/hp-hr.

Results are shown for 2-stroke engines with respect to THC emissions in Figure 3-6. In this latter case, it is clear that the fitted distribution is heavily influenced by an extreme data point with an emission rate of approximately 1,300 g/hp-hr. In contrast, all of the other data have emission rates of approximately 300 g/hp-hr or less. However, we have no basis for discarding the extreme data point. Furthermore, if this large data point were ignored, the mean emission estimate would be biased to a lower value than if this data point is retained in the analysis. Although there appear to be some systematic deviations between the data and the fitted distribution in a cumulative probability range between approximately 0.6 and 0.9, almost all of the data are enclosed by the 90 percent confidence interval of the bootstrap simulation. Therefore, the fit appears to be adequate even though it is not perfect.

Figures 3-7 and 3-8 illustrate probabilistic analysis results for 4-stroke engines for NO_x and THC emission factors, respectively, in units of g/hp-hr. The inter-engine variability in NO_x emissions among the 27 data points ranges from approximately 0.4 g/hp-hr to over 5.0 g/hp-hr. There are no obvious outliers in the data set; the highest value differs from the second highest value by only approximately 35 percent. The fitted Lognormal distribution agrees well with the lower and upper portions of the distribution, although there is apparent disagreement near the central values of the distribution. However, all of the data are enclosed within the 95 percent confidence interval, indicating that the fit is adequate.

In the case of the THC data, the inter-engine variability in emission ranges from approximately 5 g/hp-hr to nearly 100 g/hp-hr. There are three data points above 30 g/hp-hr. The fitted Lognormal distribution appears to slightly overestimate the emission values systematically in a range of cumulative probability from 0.3 to 0.9. However, all of the data in this range are enclosed by the 90 percent confidence interval. Thus, the fit appears to be adequate.

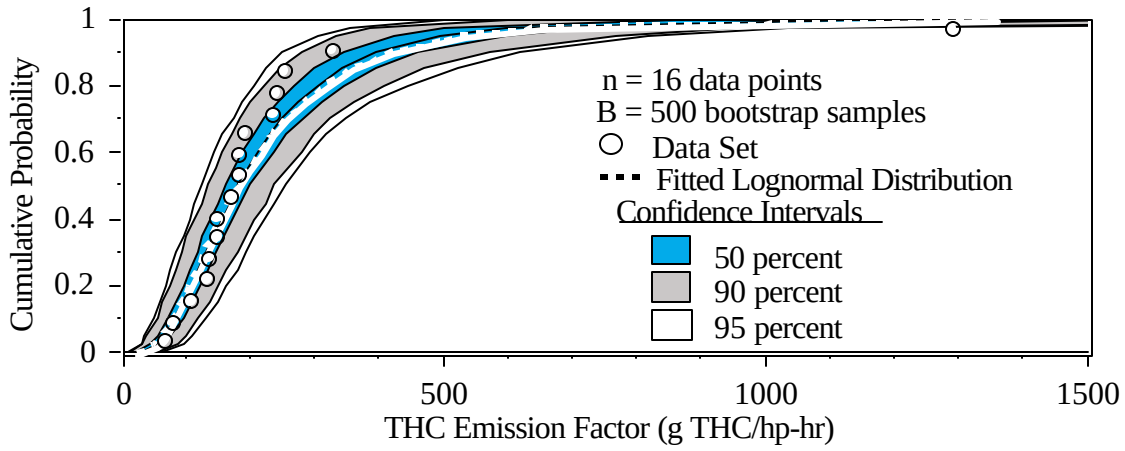


Figure 3-6. Fitted Lognormal Distribution and Bootstrap Simulation Results for 2-Stroke L&G Engine THC Emission Data in Units of g/hp-hr.

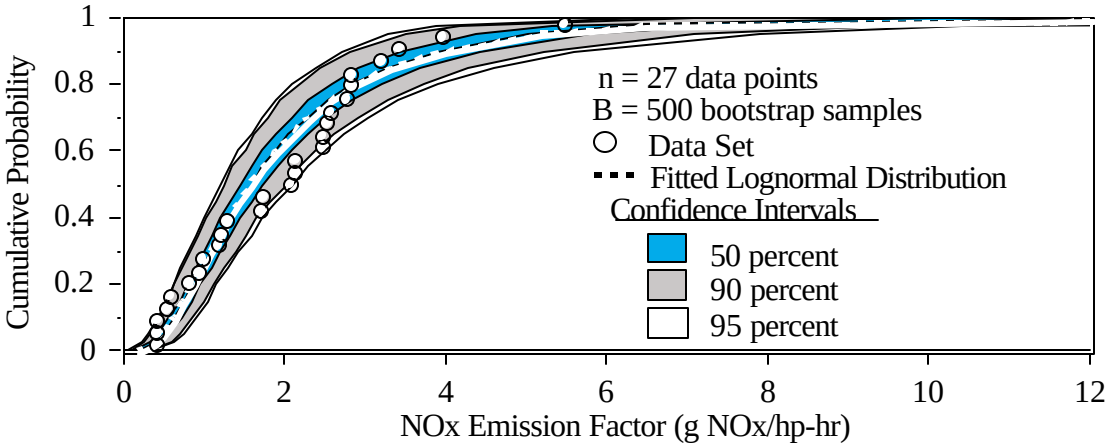


Figure 3-7. Fitted Lognormal Distribution and Bootstrap Simulation Results for 4-Stroke L&G Engine NO_x Emission Data in Units of g/hp-hr.

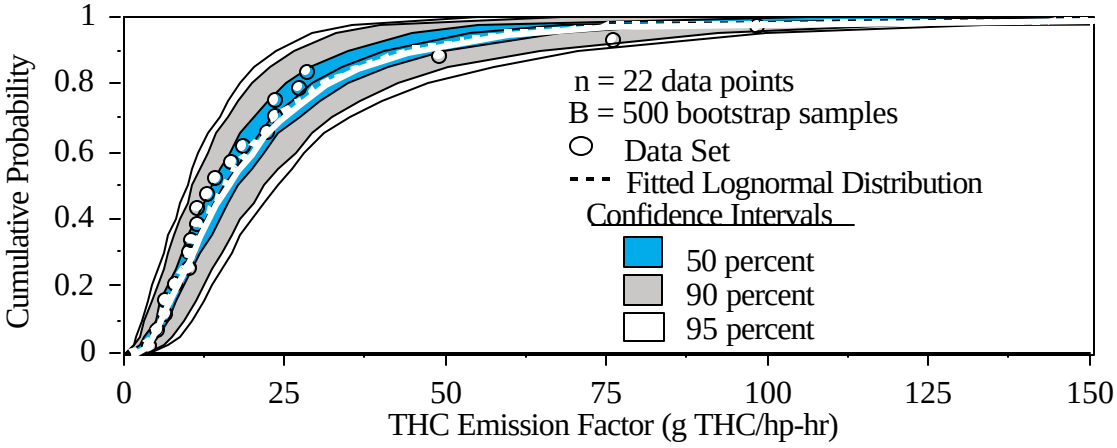


Figure 3-8. Fitted Lognormal Distribution and Bootstrap Simulation Results for 4-Stroke L&G Engine THC Emission Data in Units of g/hp-hr.

The figures showing the bootstrap simulation results for other categories are presented in Appendix B. They all generally indicate good agreement of the fitted distribution with the emission factor data. However there is one case of THC emission factors, for 4-stroke engines > 8 hp size range, where one of the emission factor data point appears like an outlier with a value of approximately 25 g THC/hp-hr compared to the rest which are all less than 10 g THC.hp-hr. There was no reason to discard it and it was included in the analysis. Also not having included it would have affect the mean emissions for this category.

Results of the analysis of uncertainty in mean emission factors for all cases considered are given in Table 3-14. For example, for the 2-stroke engine NO_x emissions in units of g/hp-hr depicted in Figure 5, the mean emission rate is 0.81 g/hp-hr. This corresponds to the approximately 65^{th} percentile of the fitted distribution. The mean occurs at a cumulative probability above the median (50^{th} percentile) because the data and the distribution are positively skewed. The 95 percent confidence interval for the mean is 0.44 g/hp-hr to 1.34 g/hp-hr, which is a range of minus 46 percent to plus 65 percent of the mean value. The relatively wide range of uncertainty in the mean emission factor in this case is a result of both the relatively small sample size of this data set (n=16) and the wide range of variability in the data.

Of the 24 cases shown in Table 3-14, all but one have uncertainty ranges of greater than approximately plus or minus 20 percent, and eleven have uncertainty ranges of greater than approximately plus or minus 40 percent. Thus, there is substantial

quantified uncertainty in the mean emission factors. For the same type of engine and pollutant, the range of uncertainty in emission factors varies depending on the unit used, at least in part because differing numbers of data points are available depending on the unit of measure employed.

Table 3-14. Results of the Uncertainty Analysis of Mean NO_x and THC Emission Rates for 2-Stroke and 4-Stroke Lawn and Garden Engines for Three Emission Factor Units (g/gal, g/h, and g/hp-h)

Engine Type	Pollutant	Units	Number Of Data	Fitted Dist.	Mean [a]	95% C.I. on Mean [b]	Relative Uncertainty [c]
2-Stroke	NO_x	g/gal	16	Gamma	3.62	2.09 – 5.42	-42% to +50%
		g/h	18	Lognormal	0.92	0.53 - 1.43	-42% to +55%
		g/hp-h	16	Lognormal	0.81	0.44 - 1.34	-46% to +65%
	THC	g/gal	16	Lognormal	808	715 – 902	-12% to +12%
		g/h	18	Lognormal	235	175 – 303	-26% to +29%
		g/hp-h	16	Lognormal	222	152 – 306	-32% to +38%
4-Stroke	NO_x	g/gal	19	Weibull	12.6	9.41 – 16.8	-25% to +33%
		g/h	19	Lognormal	5.48	2.69 – 10	-51% to +82%
		g/hp-h	27	Lognormal	2.05	1.54 - 2.82	-25% to +38%
	THC	g/gal	19	Gamma	114	86.4 – 149	-24% to +31%
		g/h	19	Lognormal	34.2	24.8 – 47.2	-27% to +38%
		g/hp-h	22	Lognormal	21.5	13.3 – 31.1	-38% to +45%
	$NO_x \geq 8$ hp	g/gal	6	Weibull	19.6	11.7 – 28.1	-40% to +43%
		g/h	6	Weibull	14.0	8.16 – 21.7	-42% to +55%
		g/hp-h	6	Lognormal	2.99	1.52 – 5.65	-49% to +89%
	$NO_x < 8$ hp	g/gal	13	Weibull	9.29	6.6 – 12.1	-29% to +30%
		g/h	13	Weibull	1.82	1.26 – 2.44	-31% to +25%
		g/hp-h	21	Weibull	1.77	1.39 – 2.28	-21% to +29%
	THC ≥ 8 hp	g/gal	6	Weibull	66.3	35.6 – 106	-46% to +60%
		g/h	6	Lognormal	39.7	25.0 – 57.0	-37% to +44%
		g/hp-h	6	Gamma	9.02	5.34 – 13.7	-41% to +52%
	THC< 8 hp	g/gal	13	Gamma	136	103 – 177	-24% to +30%
		g/h	13	Lognormal	30.8	20.3 – 43.8	-34% to +42%
		g/hp-h	16	Lognormal	26.3	17.9 – 37.1	-32% to +41%

[a] Mean of the 500 Bootstrap Samples

[b] Numbers shown here are for the 95 percent confidence interval of the mean obtained from bootstrap simulation in terms of absolute emission rates

[c] Numbers shown here are for the 95 percent confidence interval of the mean obtained from bootstrap simulation in terms of relative deviation from the mean

The mean emissions from 2-stroke engines for NO_x are considerably less than those of the THC emissions. There is a similar trend in the 4-stroke engines but the difference is much greater in case of 2-stroke engines. For example the THC emissions in from 2-stroke engines are approximately 200 times more than the corresponding NO_x emissions. But in case of 4-stroke engines the THC emissions at the most are only 11 times more than the NO_x emissions.

The general trend of THC emissions being more than NO_x in gasoline-fueled engines is observed in Table 3-14, as has been reported in other studies (CARB, 1990; Sun *et al*., 1995). This adds validity to the database that was assembled for this study. Similarly the trend that the THC emissions of the 2-stoke engines are much higher than those of the 4-stroke engines has also been previously reported by Sun *et al.* (1995). The reason for such high THC emissions has mainly been attributed to the scavenging losses of the 2-stroke engines and the direct in-cylinder fuel injection system has been proposed as a remedy for this (Sun *et al.*, 1995). The NO_x emissions of the 2-stroke engines are much lower than those of the 4-stroke engine. This is also in accordance with the test results published by CARB (1990) and Sun *et al.* (1995). These low NO_x emissions can be attributed to greater fuel-rich combustion that takes place in the 2-stroke engines compared to the 4-stroke ones.

Amongst the 4-stroke engines the larger ones (≥ 8 hp size range) have higher mean NO_x emissions compared to the smaller ones (< 8 hp size range) for all the different units of emission factors considered. However this was not the case with the THC

emissions where for g/gal and g/hp-hr units the smaller 4-stroke engines had higher mean THC emissions compared to the larger ones.

There are other issues that the assembled database does not address with respect to the engines in it, both 2-stroke and 4-stroke. These issues deal with engine age, hours of operation, maintenance, etc. There was not much information available in the reports consulted during this study that could warrant the consideration of the aforementioned issues. Hence as one of the recommendations of this study to the various testing agencies it is emphasized here that such information be made available whenever engines are tested to support regulatory work.

Table 3-15 compares the mean of the dataset with the mean of the fitted distribution for all the categories of emission factors shown in Table 3-14. The means of the data set are generally not differ by more than 8 percent from the means of the fitted distribution. For the case of THC emissions in units of g/hp-hr from 2-stroke engines the mean of the data set is higher than the mean of the fitted distribution by 8 percent. This can be explained by the fact that in Figure 3-6, there is one data point which has a value of approximately 1300 g/hp-hr while all the other 15 data points are less than 400 g/hp-hr. Also this data point lies below the fitted lognormal distribution. Thus in this case the data set is more positively skewed than the fitted distribution.

Table 3-15. Comparison of the Mean of Data Sets with the Mean of the Fitted Distribution for All the Emission Factor Categories

Engine Type	Pollutant	Units	Number Of Data	Mean of Data Set	Fitted Dist.	Mean of Bootstrap Samples
2-Stroke	NO_x	g/gal	16	3.61	Gamma	3.62
		g/h	18	1.05	Lognormal	0.92
		g/hp-h	16	0.77	Lognormal	0.81
	THC	g/gal	16	808	Lognormal	808
		g/h	18	238	Lognormal	235
		g/hp-h	16	242	Lognormal	222
4-Stroke	NO_x	g/gal	19	12.6	Weibull	12.6
		g/h	19	5.68	Lognormal	5.48
		g/hp-h	27	1.97	Lognormal	2.05
	THC	g/gal	19	114	Gamma	114
		g/h	19	34.2	Lognormal	34.2
		g/hp-h	22	22.6	Lognormal	21.5
	$NO_x \geq 8$ hp	g/gal	6	19.7	Weibull	19.6
		g/h	6	14.1	Weibull	14.0
		g/hp-h	6	2.71	Lognormal	2.99
	$NO_x < 8$ hp	g/gal	13	9.35	Weibull	9.29
		g/h	13	1.82	Weibull	1.82
		g/hp-h	21	1.76	Weibull	1.77
	THC ≥ 8 hp	g/gal	6	64.3	Weibull	66.3
		g/h	6	40.2	Lognormal	39.7
		g/hp-h	6	9.04	Gamma	9.02
	THC< 8 hp	g/gal	13	136	Gamma	136
		g/h	13	31.4	Lognormal	30.8
		g/hp-h	16	27.6	Lognormal	26.3

4.0 CONSTRUCTION, FARM AND INDUSTRIAL ENGINE EMISSIONS

In this chapter, quantitative methods for characterizing both variability and uncertainty are demonstrated and these methods are applied to case studies of emission factors for diesel-fueled Construction, Farm and Industrial (CFI) engines. Examples of CFI engines include agricultural equipment such as tractors, construction equipment like backhoes, material handling equipment like heavy fork lifts and utility equipment like generators and pumps.

Emission factor data were obtained from emissions testing conducted by others and were analyzed to quantify both variability and uncertainty. The variability in emissions was quantified using empirical and parametric distributions. Bootstrap simulation was used to characterize confidence intervals for the fitted distributions. The 95 % confidence intervals for the mean emission factors associated with 4-stroke diesel-fueled-engines for THC and NO_x emissions in g/hp-h units were -26% to +26% and -10% to +11%. The corresponding ranges for gasoline-fueled engines were -22% to +17% for THC and -32% to +38% for NO_x. These quantitative measures of uncertainty convey information regarding the quality of the emission factors and serve as a basis for calculation of uncertainty in emission inventories.

The chapter initially presents information about the various test procedures used to test the CFI engines followed by a discussion comparing these test procedures with each other. After this statistical analysis done to group the emission factors on the basis

of technology, application and engine size is presented. Finally the variability and uncertainty in the emission factors was quantified.

4.1 Emission Test Procedures

Most of the gaseous emission tests conducted on CFI engines and that are included in this report were composed of a number of steady-state conditions run in a prescribed sequence. A large portion of the data that forms the database made for gaseous emissions from CFI engines comes from a 1973 SwRI report (Hare and Springer, 1973b). Prior to 1973 during the steady-state procedures that were used to test engines, no attempt was made to compute emissions during transients (while engine load and/or speed were changing). The test procedures are mostly based on the EMA-California Air Resources Board (CARB) 13-mode procedure. However, in the 1973 study by SwRI, a few additional runs were made with continuous readouts of engine rpm, HC, CO, and NO_x, to determine if transient emissions were significantly different from steady-state operation emissions. This was done to justify their inclusion in calculations leading to development of emission factors. Although it was found that the exceedances of the emission values beyond the accepted normal limits did occur in some cases, however these exceedences did not combine in magnitude and duration to make any significant change in the overall emission factor calculation. (Hare and Springer, 1973b).

The other sources from which emission factor data were collected and studied for the purposes of this project came from contract reports prepared by Southwest Research Institute (SwRI) (Martin, 1981; Ullman, 1988; Fritz, 1991; Smith, 1992), a Society of Automotive Engineers (SAE) technical paper (Hare and Bradow, 1979) and

documentation of EPA's most recent NONROAD model (Beardsley and Lindhjem, 1998). Units in which emission factor data were reported were either: (1) grams per hour (g/hr); (2) grams per brake horsepower-hour (g/hp-hr); and/or (3) grams per kilowatt-hour (g/kw-hr).

In addition to references that contained emissions testing data, the Nonroad Engine and Vehicle Emissions Study (EPA, 1991) was also reviewed. This report provides general information regarding the types of data and categories used by EPA to calculate emission factors. However, the emission factor data needed for purposes of statistical analysis were not available in this report. Instead, emissions measurements databases had to be developed based upon the emission test reports described above.

In the following sections the steady state procedures, including the 13-Mode, 21-Mode, 8-Mode, 23-Mode, 23-Mode, S-1, S-2, and S-3 tests, and the transient test procedures, including the Agricultural Tractor, Backhoe Loader and Crawler Dozer, are discussed.

4.1.1 CARB 13-Mode Procedure

The CARB 13-mode test procedure is one of the most common procedures used to test gaseous emissions from CFI engines. Table 4-1 describes the procedure by giving engine speed and percent of full load at that speed for each of the13 modes. Twenty percent of the test is in idle, but idle is measured three times in three separate modes.

In a 1973 SwRI study, 12 CFI engines were tested for gaseous emissions (Hare and Springer, 1973b). Eight of them were diesel-fueled and four were gasoline-fueled. The steady-state gaseous emissions test procedures used for diesel engines had either 21 or 13 modes, and those used for gasoline engines had either 23 or 13 modes. The data were collected, recorded and reported separately for each mode. The 13 mode tests were identical for diesel and gasoline engines. The 21-mode and 23-mode procedures are described later in this section. The 13-mode procedure was run to provide a better basis for "mapping" emissions from the test engines according to speed and load. For this procedure there are two types of speeds used, namely the intermediate and the manufacturer's rated speed. The intermediate speed is defined as either peak torque speed or 60% of rated speed whichever was higher. The modal data for this test procedure is collected and reported separately in only one of the reports that were consulted for this study (Hare and Springer, 1973b).

4.1.2 21-Mode Procedure

The 21-mode procedure is derived from the 13-mode procedure described in Section 4.1.1. This procedure is used to test gaseous emissions from only diesel-fueled CFI engines. The 21-mode procedure includes the same modes as the 13-mode procedure. The eight additional modes in the 21-mode versus 13-mode procedure are at additional engine loads for both intermediate and rated speed. Table 4-1 summarizes the various modes in this procedure and compares the 13-mode and 21-mode procedures. Similar to the 13-mode procedure, for the 21-mode procedure 20 percent of the test is in idle, but idle is measured three times in three separate modes. The modal data for this test

procedure is collected and reported separately in only one of the reports that were consulted for this study (Hare and Springer, 1973b).

Table 4-1. Test conditions for 13-Mode and 21-Mode Test Procedures

13-mode test				21-mode test			
Mode	**Engine Speed (rpm)**	**Load**	**Mode Weight**	**Mode**	**Engine Speed (rpm)**	**Load**	**Mode Weight**
1	Low Idle	None	0.0667	1	Low Idle	None	0.0667
2	*Intermediate	None	0.08	2	*Intermediate	None	0.0444
				3	Intermediate	12.5%	0.0444
3	Intermediate	25 %	0.08	4	Intermediate	25 %	0.0444
				5	Intermediate	37.5%	0.0444
4	Intermediate	50 %	0.08	6	Intermediate	50 %	0.0444
				7	Intermediate	62.5%	0.0444
5	Intermediate	75 %	0.08	8	Intermediate	75 %	0.0444
				9	Intermediate	87.5%	0.0444
6	Intermediate	Full	0.08	10	Intermediate	Full	0.0444
7	Low Idle	None	0.0667	11	Low Idle	None	0.0667
8	Mfr's. Rated	Full	0.08	12	Mfr's. Rated	Full	0.0444
				13	Mfr's. Rated	87.5%	0.0444
9	Mfr's. Rated	75 %	0.08	14	Mfr's. Rated	75 %	0.0444
				15	Mfr's. Rated	62.5%	0.0444
10	Mfr's. Rated	50 %	0.08	16	Mfr's. Rated	50 %	0.0444
				17	Mfr's. Rated	37.5%	0.0444
11	Mfr's. Rated	25 %	0.08	18	Mfr's. Rated	25 %	0.0444
				19	Mfr's. Rated	12.5%	0.0444
12	Mfr's. Rated	None	0.08	20	Mfr's. Rated	None	0.0444
13	Low Idle	None	0.0667	21	Low Idle	None	0.0667

* Peak torque speed or 60 % of rated speed, whichever is higher
Source: (Hare and Springer, 1973b).

4.1.3 23-Mode Procedure

The 23-mode procedure, like the 21-mode procedure, is derived from the 13-mode procedure. This procedure was used in the 1973 SwRI study on nonroad engines (Hare and Springer, 1973b). The 23-mode procedure includes the same modes that are in the 21-mode procedure and it also has two more modes that represent "closed throttle" or

"motored" conditions. This procedure has been used to test only the gasoline fueled CFI engines. Table 4-2 summarizes the various modes in this procedure. What is shown in the table is order of conditions in which the engines were tested. Twenty percent of the test is in idle, but idle is measured three times in three separate modes. The modal data for this test procedure is collected and reported separately in only one of the reports that were consulted for this study (Hare and Springer, 1973b).

Table 4-2. Test Conditions for 23-Mode Procedure

Mode	Engine Speed (rpm)	Load	Mode Weight
1	Low Idle	None	0.20/3 = 0.0667
2	*Intermediate	None	0.04
3	Intermediate	12.5%	0.04
4	Intermediate	25 %	0.04
5	Intermediate	37.5%	0.04
6	Intermediate	50 %	0.04
7	Intermediate	62.5%	0.04
8	Intermediate	75 %	0.04
9	Intermediate	87.5%	0.04
10	Intermediate	Full	0.04
11	Low Idle	None	0.20/3 = 0.0667
12	Mfr's. Rated	Full	0.04
13	Mfr's. Rated	87.5%	0.04
14	Mfr's. Rated	75 %	0.04
15	Mfr's. Rated	62.5%	0.04
16	Mfr's. Rated	50 %	0.04
17	Mfr's. Rated	37.5%	0.04
18	Mfr's. Rated	25 %	0.04
19	Mfr's. Rated	12.5%	0.04
20	Mfr's. Rated	None	0.04
21	Low Idle	None	0.20/3 = 0.0667
22	Intermediate	CT **	0.04
23	Mfr's. Rated	CT **	0.04

* Peak torque speed or 60 % of rated speed, whichever is higher
** Means "Closed Throttle" or "motored" conditions
Source: (Hare and Springer, 1973b).

4.1.4 8-Mode Procedure

The 8-mode procedure is a steady state test used to develop emission factors for CFI engines. The procedure has been used to test gaseous emissions from diesel-fueled nonroad CFI engines only (Smith, 1992; Beardsley and Lindhjem, 1998b). All of the modes of this procedure can be found in the modes of the other test procedures discussed so far to test the diesel-fueled engines (i.e. 13-mode and 21-mode test procedures). SwRI has used this procedure in one of its studies involving dynamometer testing of nonroad CFI engines to support nonroad regulations. Table 4-3 summarizes the various modes of this procedure. There is no information in available as to whether modes are measured separately or whether transients between modes are measured.

Table 4-3. Test Conditions for 8-Mode Procedure

Mode	Engine Speed (rpm)	Load	Mode Weight
1	*Intermediate	25 %	0.1
2	Intermediate	50 %	0.1
3	Intermediate	75 %	0.1
4	Intermediate	Full	0.15
5	Mfr's. Rated	Full	0.15
6	Mfr's. Rated	75 %	0.15
7	Mfr's. Rated	50 %	0.1
8	Low Idle	None	0.15

* Peak torque speed or 60 % of rated speed, whichever is higher
Source: (Smith, 1992).

4.1.5 S-1, S-2 and S-3 Test Procedures

The S-1, S-2 and S-3 test procedures were developed by the SwRI in 1987 for one of their contract projects for CARB involving evaluation of two heavy-duty diesel engines on two low-sulfur fuels with variation in aromatics (Ullman, 1988). Table 4-4 gives modal information on these single mode test procedures. The single modes of all

these three tests can be found in the modes of the previously discussed test procedures for diesel fueled CFI engines.

Table 4-4. Test Conditions for S-1, S-2 and S-3 Test Procedures

Test Procedure	Mode	Engine Speed (rpm)	Load	Mode Weight
S-1	1	Intermediate	25%	1
S-2	1	Rated	25%	1
S-3	1	Rated	75%	1

Source: (Ullman, 1988)

In Section 4.1.1 through 4.1.5, a total of five different steady state tests have been reviewed. Of these, the 13-mode, 21-mode, 8-mode 23-mode, and S-1, S-2 and S-3 procedures have been used to develop emission factors from diesel fueled CFI engines. The S-1, S-2, and S-3 tests are considered here to be complementary variants of essentially one test procedure, in addition to 13-mode, 21-mode, 23-mode and 8-mode procedures. These tests share common modes with each other, while there are some having certain modes that are not found in others. For example, the 21-mode test has all of the modes that are in the 13-mode test, the 8-mode test and the S-1, S-2 and S-3 tests. It also has some more modes in it that are not in any of the others. For gasoline fueled CFI engines, there have been only two steady state tests used to develop emission factors. These are the 23-mode and the 13-mode test procedures. The 23-mode test includes all of the modes present in the 13-mode test while having some additional modes. A more quantitative comparison of these test cycles will be presented later in this chapter. In the next section, transient tests are reviewed.

4.1.6 Agricultural Tractor Cycle, Backhoe Loader Cycle and Crawler Dozer Cycle

The Agricultural Tractor Cycle, Backhoe Loader Cycle and the Crawler Dozer Cycle are all transient cycles developed jointly by the Engine Manufacturers Association (EMA) and EPA to more realistically represent typical operation of an agricultural tractor, a crawler dozer and a backhoe loader (Beardsley and Lindhjem, 1998b). These cycles have been used along with the 8-mode steady state test procedure to develop emission factors for CFI engines. The tests revealed that the transient Agricultural Tractor Cycle and the Crawler Dozer Cycle produced emission factors that were similar to those developed using the 8-mode steady state test procedure. A more quantitative comparison of these cycles is presented later in the chapter. Figures 4-1, 4-2 and 4-3 present the variation of speed and load, in terms of torque, during the Agricultural Tractor, Backhoe Loader and Crawler Dozer cycles.

4.2 Reproducing Reported Emission Factors

To better understand the emission factor development process, the emission factors for THC and NO_x that were developed using the 13-mode, 21-mode and 23-mode test procedures in the SwRI reports were recalculated from the given modal engine test data. This was possible with the SwRI reports because they contained the actual test mode data and not just the weighted averages of all modes. However there was no modal test data available for the 8-mode, S-1, S-2 and S-3 and the transient test procedures. It was possible to recalculate the reported average emission factors for each test to within three or four significant digits. The units with emission factors were reported varied among the data sources.

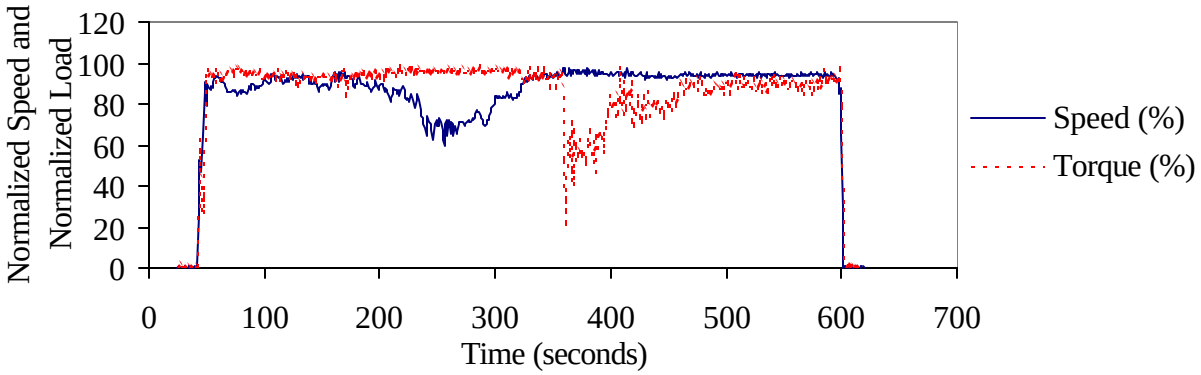


Figure 4-1. Variation of Speed and Torque During the Agricultural Tractor Cycle. Source: (EPA, 2001 c)

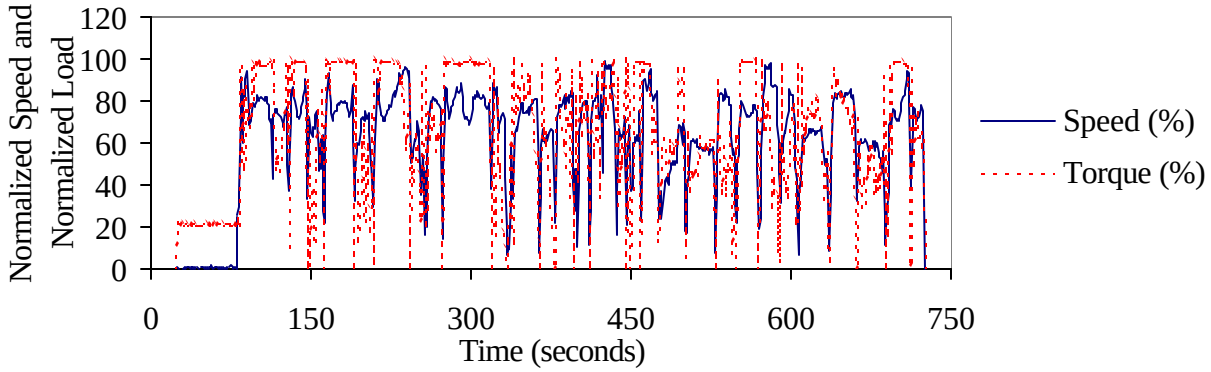


Figure 4-2. Variation of Speed and Torque during the Crawler Dozer Cycle. Source: (EPA, 2001 c)

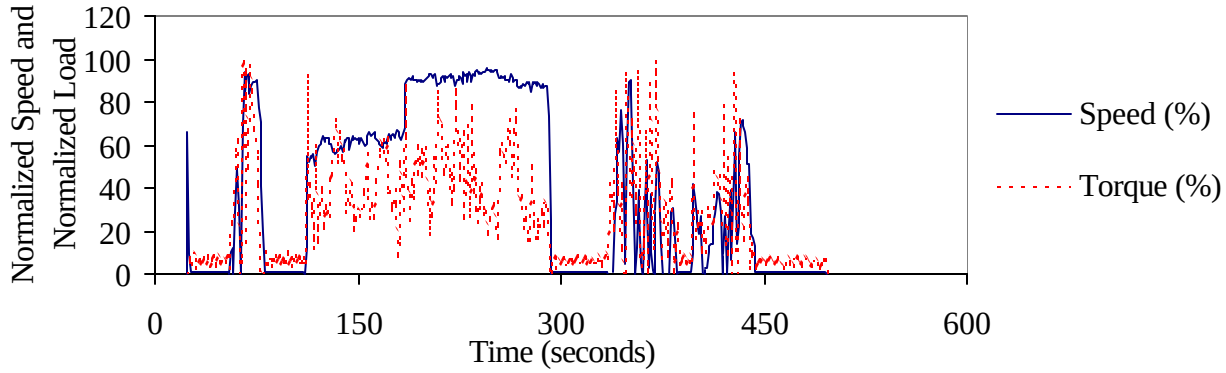


Figure 4-3. Variation of Speed and Torque during the Backhoe Loader Cycle. Source: (EPA, 2001 c)

For example, g/hp-hr units are reported by CARB, whereas this and other units are reported in the reviewed SAE papers and SwRI reports. The recalculated emission factors were off by not more than two significant digits in most of the cases considered. The recalculation of emission factors served as a quality assurance step.

There are two methods for computation of mass-based emissions by mode from concentration data, fuel flow, and (in some cases) airflow. The first method is to use the exhaust flow in computations and the second is to use the fuel flow. It was the second method that was used for recalculating the emission factors developed using the 13-mode, 21-mode and 23-mode test cycles. SwRI also used this method for calculating the emission factors from the modal data. This fuel-based technique is also called the "carbon balance" method. The main advantage of this method is that no airflow measurement is required. This helps to assure that the measurement process (especially from gasoline engines) is not upsetting the emissions estimates because a probe inserted in the exhaust pipe for measurements could disrupt the exhaust flow. The equation used to convert hydrocarbon concentrations to mass emissions is the same for gasoline and diesel engine emissions. For NO_x, the equation is same but the value of the constant (K_{NOx}) is different for diesel-fueled and gasoline-fueled engines. The following general equations apply to both gasoline and diesel emissions (Hare and Springer, 1973b).

$$G_{HC} = 0.0454(ppmC)\ (F) / TC \quad (4\text{-}1)$$

$$G_{NOx} = K_{NOx}\ (ppm\ NOx)\ (F) / TC \quad (4\text{-}2)$$

where,

G_{HC} = grams HC per hour

G_{NOx} = grams NO_x (as NO_2) per hour

F = fuel flow rate, lb_m/hr

TC = total carbon, which is the sum of %HC (as C), %CO and $\%CO_2$

K_{NOx} = a constant whose value depends on the type of fuel (diesel/gasoline), for gasoline it is 0.15 and for diesel it is 0.149

Although not explicitly stated by Hare and Springer (1973b), it appears that only one mole of carbon per mole of HC is assumed. However as long as the HC emissions are relatively small this assumption does not introduce much error. The principal assumption in this method of computing gaseous emission factors is that exhaust hydrocarbons have the same atomic hydrogen/carbon ratio as fuel hydrocarbons (1.85 for gasoline and 2.00 for diesel fuel). Another assumption made was that the molecular weight of exhaust was the same as that of air. All the species concentrations used in the "carbon balance" equations were on a wet basis (Hare and Springer, 1973b). The initial computation of composite brake specific emissions on the CFI engines was performed using mode-weighting factors as shown in the Table 4-1 and 4-2.

Once mass emissions by mode had been determined by the fuel flow method outlined above, the definitions and equations below were used to calculate cycle

composite emissions based on weighting factors for the test procedure used to measure gaseous emissions (Hare and Springer, 1973b).

$$\text{Cycle composite g/hr} = \sum_{i=1}^{n} M_i W_i \quad (4\text{-}3)$$

$$\text{Cycle composite g/bhp hr} = \frac{\sum_{i=1}^{n} M_i W_i}{\sum_{i=1}^{n} hp_i W_i} \quad (4\text{-}4)$$

where,

M_i = individual mode emissions, g/hr

W_i = individual time-based mode weighting factor

hp_i = individual mode power, hp

n = number of modes (13, 21, or 23)

After the composite emissions were calculated for diesels, a “correction factor” taken from Federal regulations (Fed. Reg. Vol. 37, No. 221) was applied to the NO_x results, and it is shown in Equation 4-5. The equation is designed to revise NO_x emissions to the value which would have occurred had the humidity during the test been 75 grains of water per pound of dry air (Hare and Springer, 1973b).

$$\text{Diesel } NO_x \text{ correction factor} = \frac{1}{1 - 0.0025\,(H - 75)} \quad (4\text{-}5)$$

where,

H = Humidity of intake air in grains water per pound dry air

Federal emissions regulations for gasoline engines include different correction factors for light-duty and heavy-duty engines. The SwRI report also acknowledges that it was not clear from federal regulations how to apply the correction, and states that an arbitrary decision had to be made for this. Hence SwRI did not apply the gasoline NO_x correction factor to the individual modal data that are reported. Only the cycle composite gasoline NO_x emission factors were corrected to 75 grains humidity using Equation 4-6 (Hare and Springer, 1973b).

$$\text{Gasoline } NO_x \text{ correction factor} = 0.634 = 0.00654H - 0.0000222H^2 \quad (4\text{-}6)$$

where,

H = Humidity of intake air in grains water per pound dry air

Equation 4-6 reproduces the gasoline NO_x correction factor exactly as it is given in the SwRI report. There seems to be a typo in it, the equality sign after the quantity 0.634 is probably an operator of some type i.e. "+" or "-". On testing these two possibilities in Equation 4-6 it was found that the sign after the quantity 0.634 should be "+" since for a negative sign the correction factor takes on negative values for higher values of humidity. Hence in the recalculation of gasoline NO_x emission factors this correction factor was applied to the composite emission factors. The emission factors that were reported by SwRI were the ones that were included in the database for analysis.

Fuels used in performing the 21, 23 and 13-mode tests on CFI engines in the 1973 study of the SwRI met the requirements for emission test fuels as listed in Federal Regulations (Fed. Reg. Vol. 37, No. 221). The diesel fuel was number 2 grade, and the gasoline was a leaded type. The hydrogen/carbon ratios of the fuels were not measured, but rather they were assumed when necessary to be 2.00 for diesel fuel and 1.85 for gasoline. These assumptions were in accordance with the practice used in formulating Federal calculation procedures (Hare and Springer, 1973b).

4.3 Comparing the Test Cycles

Emission factors were reported in the literature based upon a variety of test procedures. Before grouping data from multiple test procedures into a single database for statistical analysis, it is important to first identify whether the data from two or more different types of tests are comparable. Therefore, an initial task in data analysis was to identify each test procedure and to determine whether emissions from different test procedures could be converted to a consistent basis.

Table 4-5. Comparison of Steady-State CFI Equipment Test Procedures Based on the Number of Modes and Type of Engine Load

No.	Cycle	No. of Modes	Number of Modes by Type of Engine Load		
			Low Idle	Intermediate	Rated
1	13-Mode	13	3	5	5
2	21-Mode	21	3	9	9
3	23-Mode	23	3	10	10
4	ISO-C1 (8-Mode)	8	1	3	4
5	S-1	1	-	1	-
6	S-2	1	-	-	1
7	S-3	1	-	-	1

Source: (Hare and Springer, 1973b; Ullman, 1988; Fritz, 1991; Smith, 1992, Beardsley and Lindhjem, 1998)

For most of the test cycles identified, each test cycle is characterized by a number of steady-state "modes." Each steady-state mode typically involves operation at a specified engine speed or type of speed and load (i.e. idle, low, intermediate or rated) for a given length of time. In the 8-mode, 13-mode, 21-mode and 23-mode procedures, the intermediate speed was the peak torque speed or 60 percent of rated speed whichever was higher. For the other test cycles namely the S-1, S-2 and S-3 this information was not available. The individual modes of the S-2 and S-3 test cycles differ from each other on the basis of the load applied on the engine while it is running at the rated speed. The Agricultural Tractor, Crawler Dozer and Backhoe/Loader cycles are transient in nature. The engines which were tested using these cycles were also tested using the 8-mode test cycle. Table 4-5 gives a brief description of the various steady state test cycles.

The cycles were first compared on the basis of how their modes are defined. Most of the test data that was used for this analysis was taken from what is reported in the 1973 SwRI study of CFI engines (Hare and Springer, 1973b). This is because it contained detailed model test emissions data for the 21-mode, 13-mode and 23-mode test cycles.

Hence it provided an ideal basis for comparing these test cycles with each other, as different test cycles were used to test the same engines. Among the test cycles used to test diesel-fueled engines, the 21-mode test cycle was chosen to be the benchmark because it had well documented modal test data, was used widely and its modes contained all of the modes of the 13-mode and 8-mode test procedures. For the same reasons as above, the 23-mode test procedure was used as a benchmark for cycles used to test the gasoline-fueled CFI engines. The 13-mode test cycle was used to test both types of CFI engines i.e. diesel-fueled and gasoline-fueled. Besides the 21-mode and 13-mode test procedures, the 8-mode test procedure was also used extensively to test the diesel-fueled engines in other reports that were reviewed. The 8-mode, 13-mode, 21-mode and 23-mode test procedures were used to test more than 95 percent (54 out of 55) of the CFI engines in the assembled database.

4.3.1 Comparison of 21-Mode and 13-Mode Test Procedures

To compare the 21-mode and 13-mode procedures, data were compared for engines that were tested with both procedures. For this comparison the linear regression technique was used and the corresponding coefficient of determination R^2 values studied to judge the comparison. Figure 4-4 and Figure 4-5 present the comparison between the two test procedures. When used on the same engines, the calculated emission factors using the 13-mode test compared well to the reported emission factors developed using the 21-mode test procedure with R^2 values of 0.9717 for THC and 0.9667 for NO_x.

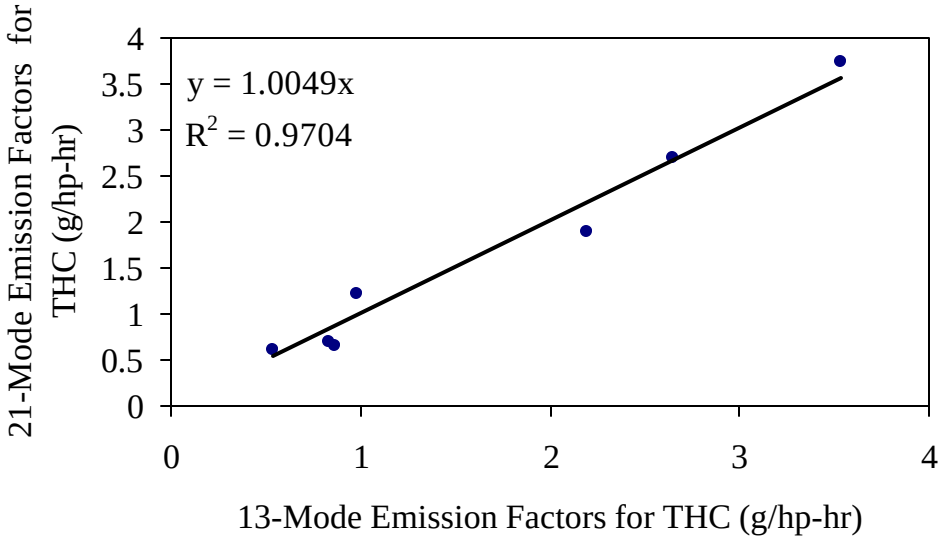


Figure 4-4. Comparison Between THC Emission Factors Measured with the 21-Mode Test and Those Developed from 13-Mode Test Data

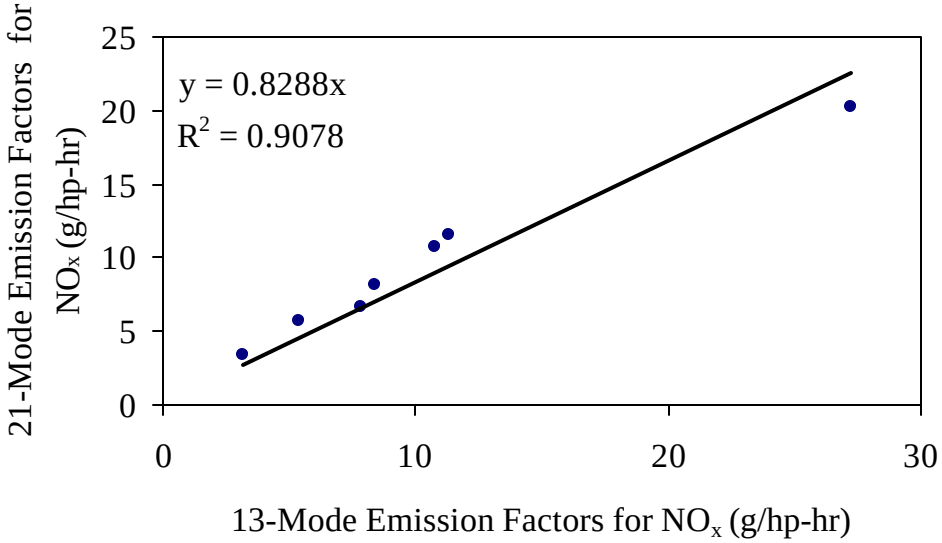


Figure 4-5.. Comparison Between NO_x Emission Factors Measured with the 21-Mode Test and Those Developed from 13-Mode Test Data.

The high R^2 values indicate that the variability observed in the 21-mode tests can be nearly fully explained by the 13-mode test. Essentially, the 13-mode and 21-mode tests provide the same information regarding the emissions: if an engine has a high emission rate on the 13-mode test then it also has a high emission rate on the 21-mode test and vice versa. Another measure of comparison between the 21-mode and 13-mode tests is the slope of the regression line in Figures 4-4 and 4-5. For THC, the slope is essentially equal to one, indicating that both tests give quantitatively equivalent emission results. For NO_x, as shown in Figure 4-5, the slope is 0.83, indicating that the NO_x emissions measured in the 21-mode test are approximately 17 percent lower than the emissions measured in the 13-mode test. However, although the results differ somewhat, the relative ordering of the engines with respect to emission rate is the same, and knowledge of emissions on one test can be used, with this regression result on the other test with reasonable precision.

Because the 13 modes of the 13-mode test are contained in the 21-modes of the 21-mode test, a comparison can be made just for the 13 modes that are common to both tests. Data from the 21-mode test for only the 13 common modes was "extracted" and used to calculate an average emission factor rate using the weighting factors of the 13-mode test. This so called "21 to 13 mode extracted" average emission value can then be compared with either the 21-mode test results or the separately measured 13-mode test results.

A comparison of an average emission rate estimates from the 13 common modes, based on the 21-mode test data, is shown in Figures 4-6 and 4-7 for THC and NO_x, respectively. In both cases, the R^2 values exceed 0.99 and the slopes are essentially equal to one. This comparison suggests that the 13 common modes between the 13-mode and 21-mode tests provide essentially the same information. Therefore, in a sense, these two procedures appear to be redundant with each other. One does not learn anything new by running both tests.

The average emission rate estimated from the 21-mode test data, based only upon 13 modes common with the 13-mode test, and using the same weightings as the 13-mode test are compared to the actual 13-mode test results in Figures 4-8 and 4-9 for THC and NO_x, respectively. For THC, the R^2 value is greater than 0.98 and the slope is essentially equal to one. This implies that the 13 common modes provide equivalent results in both the 21-mode and the 13-mode tests. For NO_x the R^2 is reasonably high at a value of 0.94. However the slope is 0.86, implying that the 13 common modes produced a slightly lower NO_x emission value in the 21-mode test than the 13-mode test. This might be explained due to the additional modes that the engine is being made to run through while collecting the data for the “21 to 13 mode Extracted” modes.

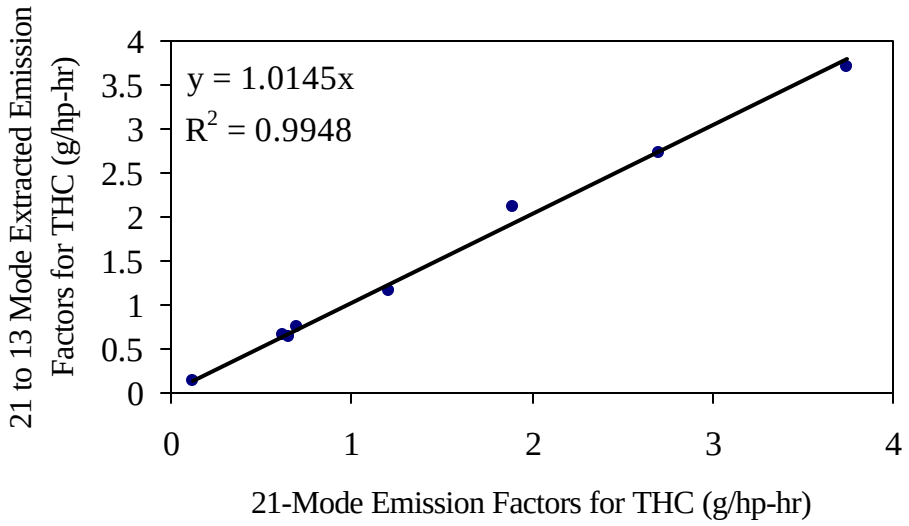


Figure 4-6. Comparison Between THC Emission Factors Developed from 13-Mode Test Data Extracted from 21-Mode Test and those Measured with 21-Mode Test.

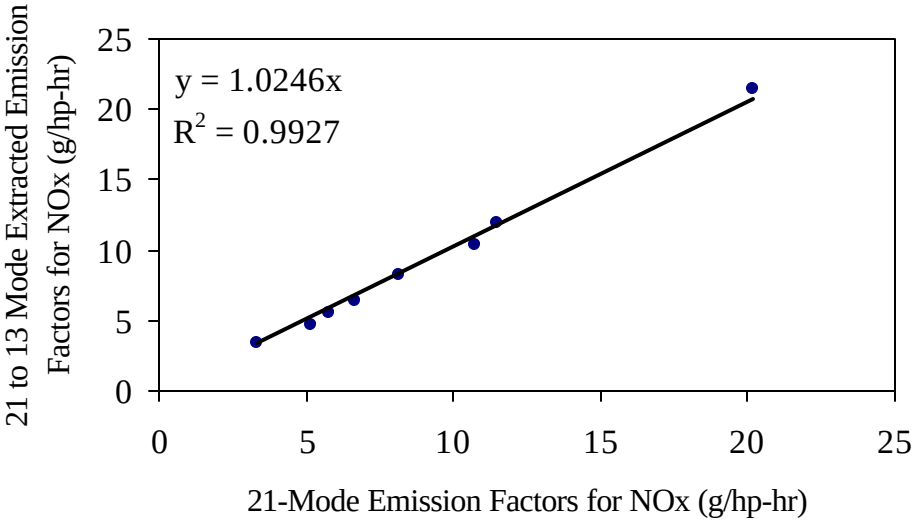


Figure 4-7. Comparison Between NO_x Emission Factors Developed from 13-Mode Test Data Extracted from 21-Mode Test and those Measured with 21-Mode Test.

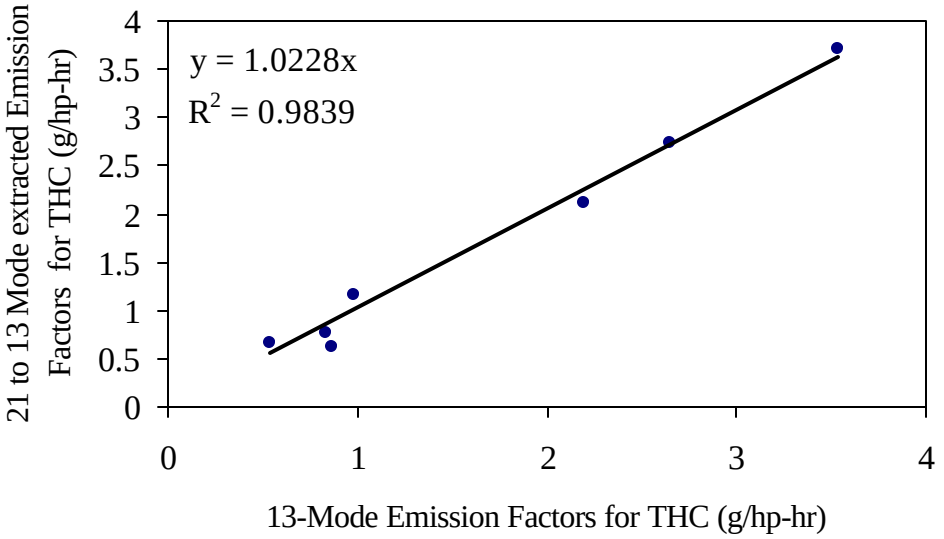


Figure 4-8. Comparison Between THC Emission Factors Developed from 13-Mode Test Data Extracted from 21-Mode Test and those Developed from 13-Mode Test Data.

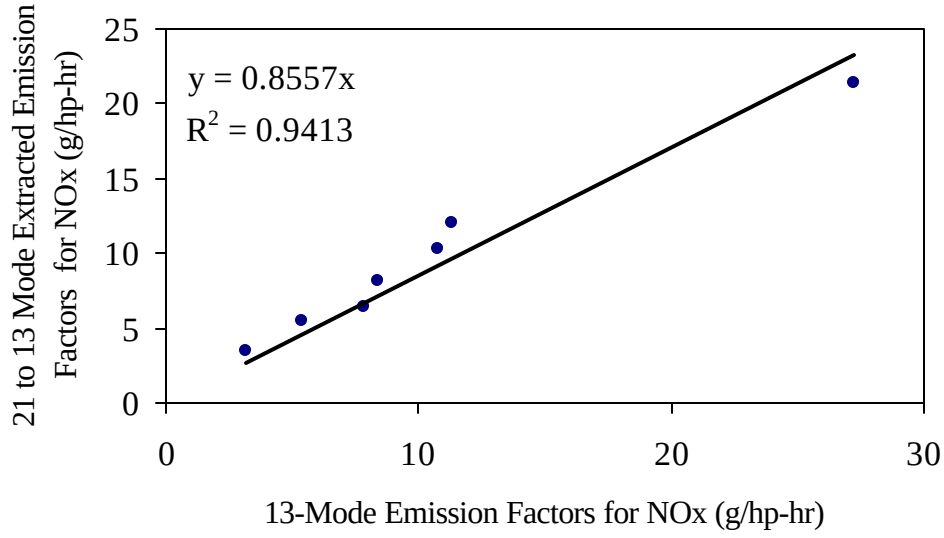


Figure 4-9. Comparison Between NO_x Emission Factors Developed from 13-Mode Test Data Extracted from 21-Mode Test and those Developed from 13-Mode Test Data.

Table 4-6. Summary of the Results of the Inter-Cycle Comparisons

Pair for Comparison	Pollutants	R^2	Slope			Slope Sig. Diff. From 1
			Value	t-stat value	Standard Error	
21-Mode vs. 13-Mode	THC	0.9704	1.0049	25.26	0.039	No
	NO_x	0.9078	0.8288	16.85	0.049	Yes
21 to 13 Mode Extracted vs. 21-Mode	THC	0.9948	1.0145	59.32	0.017	No
	NO_x	0.9927	1.0246	60.17	0.017	No
21 to 13 Mode Extracted vs. 13-Mode	THC	0.9839	1.0228	34.92	0.029	No
	NO_x	0.9413	0.8557	20.18	0.042	Yes
21 to 8 Mode Extracted vs. 21-Mode	THC	0.9866	0.7253	36.61	0.019	Yes
	NO_x	0.9826	0.9882	41.12	0.024	No
13-Mode vs. 23-Mode	THC	0.9647	0.7508	52.21	0.014	Yes
	NO_x	0.9092	1.2474	20.43	0.061	Yes

The values of the slope, its t-stat value, the R^2 value and the standard error of the aforementioned comparisons can be found in the Table 4-6. The t-stat value is calculated as a ratio of the value of the slope to the standard error. Thus a higher t-stat value implies lower standard error. The 95 percent confidence interval range on the slope can be roughly estimated as the value of the slope minus two times the standard error to value of the slope plus two times the standard error. As expected the slope of the line is significantly different from zero. It is clear that the 13-mode and 21-mode tests give the same results for THC. For NO_x there is some difference but the difference is judged not to be large since the 95 percent confidence interval on the slope is 0.731 to 0.927. The upper end of this range is within 8 percent of a value of one, so the slope is not substantially different from one. On the basis of these results it was decided that the

emission factors developed using the 21-mode and the 13-mode test procedures could be combined in to a single database.

4.3.2 Comparison of 21-Mode and 8-Mode Test Procedures

There were no data available for diesel-fueled CFI engines that were tested using both the 21-mode and the 8-mode test procedure. Because a direct comparison of separate measurements from the 8-modes and the 21-mode procedures is not possible, instead a comparison was made based on the 8-mode common to both tests, using the weights of the 8-mode procedure, and the reported 21-mode emission results. This comparison can be used to judge whether the 8-modes provide essentially the same information as the 21-modes.

The results of the comparison of the estimated equivalent 8-mode results and the actual 21-mode results are given in Figures 4-10 and 4-11 for THC and NO_x, respectively. In both cases the R^2 values are larger than 0.98, indicating that there is a strong linear relationship between the two types of tests. For NO_x, the slope is essentially equal to one, indicating that both procedures are expected to yield essentially identical results for NO_x emissions. This can be inferred by calculating the 95 percent confidence interval on the slope as shown in Section 4.3.1, which in case of the comparison between NO_x emissions reported from the 21-mode and the 8-mode extracted emissions is 0.94 to 1.04. This confidence interval includes the value of one and hence the slope is not significantly different from one for this case.

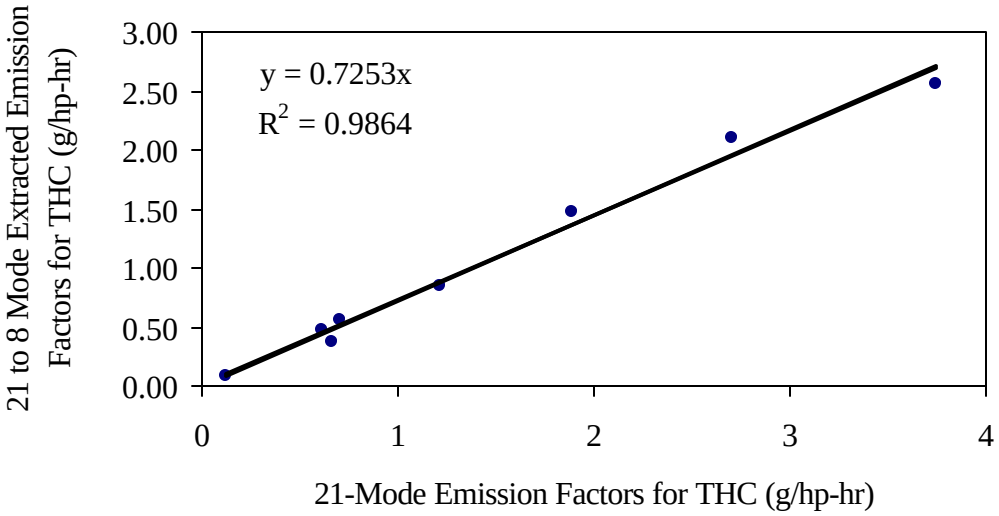


Figure 4-10. Comparison Between THC Emission Factors Measured with the 21-Mode Test and those Developed from 8-Mode Test Data Extracted from 21-Mode Test Data.

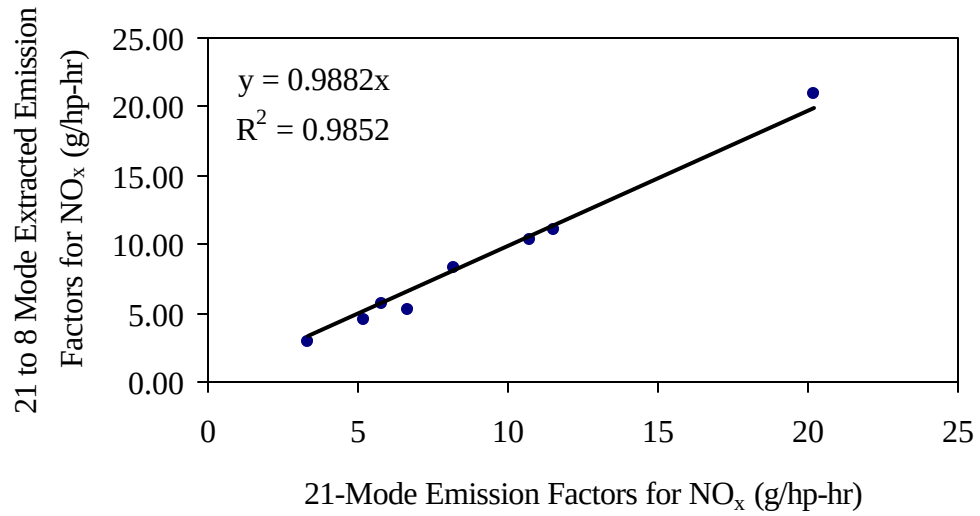


Figure 4-11. Comparison Between NO_x Emission Factors Measured with the 21-Mode Test and those Developed from 8-Mode Test Data Extracted from 21-Mode Test Data.

For THC, the slope is 0.73, indicating that the estimated 8-mode results are approximately 27 percent less than those of the 21-mode test results. The 95 percent confidence interval on the slope is 0.69 to 0.77. The upper end of this range is within 23 percent of the value of one, so the slope was not judged to be substantially different from one. Nonetheless, knowledge of the results of one test procedure could be used to predict the results on the other procedure, and both tests give similar, if not identical results. The *t*-stat values for the significance of the slope and the standard error associated with those can be found in the Table 4-6. It is clear that the 21-mode test and the 8-mode test give the same results for NO_x. For THC, there is some difference but the difference was judged not to be large. On the basis of these results it was decided to group emission factors developed using the 8-mode and 21-mode procedures into a single database.

4.3.3 Comparison of 21-Mode and S-1, S-2 and S-3 Test Procedures

There were no emission factors developed by testing the 21-mode and the S-1, S-2 and S-3 test procedures on the same engine. Also, S-1, S-2 and S-3 were all single mode test procedures, while the 21-mode test procedure had 21-modes. It was thus decided not to include emission factors developed using the S-1, S-2 and S-3 test procedures in the emission factor database.

4.3.4 Comparison of 23-Mode and 13-Mode Test Procedures

The 23-mode and the 13-mode procedures were the only ones used to test gasoline-fueled engines in the assembled database. There were only four data with which to compare the 13-mode and 23-mode test cycles. Both of these test procedures were used to test the same engines to produce THC and NO_x emission factors. The 23-mode

test procedure contains all of the modes that are in the 13-mode test procedure. Figure 4-12 and Figure 4-13 present the comparison between the two test procedures. The test data from the two compared favorably with each other for both THC and NO_x emission factors with R^2 value of 0.96 for THC and 0.91 for NO_x. For both THC and NO_x the value of R^2 is high. In case of NO_x emissions the slope of the regression line is not equal to one, but the emission results from the 23-mode test and the 13-mode test agree within less than 25 percent of each other. That is the THC emissions from 13-mode procedure are approximately 25 percent less than those from the 23-mode procedure and the NO_x emissions from 13-mode procedure average 25 percent more than those from 23-mode procedure. The NO_x emission factors that were compared were corrected using the gasoline NO_x correction factor as reported by SwRI (Hare and Springer, 1973b).

Thus the two tests give comparable results and data from one test can be used to predict results of the other with reasonable precision. However, it was only the 23-mode test data that was used in the database and in the analysis as SwRI reported the emission test results of only the 23-mode test, while only giving the modal test data for 13-mode test. *T*-stat values of the significance of the slope can be found in the Table 4-6. The slope was statistically significantly different from one for the case of both THC and NO_x emission factors. The 95 percent confidence interval on slope for THC is 0.72 to 0.78 and for NO_x it is 1.12 to 1.36. For NO_x the lower end of the 95 percent confidence interval range is about 10 percent more than the value of one. Similarly for THC the upper end of the 95 percent confidence interval on slope is about 22 percent less than the value of one. These differences are not judged to be large. However in the database only emission

factors developed using the 23-mode test procedure used as the 23-mode test procedure was chosen as the standard for gasoline fuel CFI engines.

4.3.5 Comparison of 8-mode and Agricultural Tractor, Crawler Dozer and Backhoe Loader Test Procedures

In one of the EPA reports there were several engines that were tested to develop emission factors using 8-mode, Agricultural Tractor, Crawler Dozer and Backhoe Loader test procedures. Even though the Agricultural Tractor, Crawler Dozer and Backhoe Loader cycles are transient test procedures while 8-mode is a steady state test procedure, it was decided to compare the results obtained from these. Figure 4-14, 4-15 and 4-16 present some of the typical results of this analysis for THC emission factors. The remaining scatter plots for this analysis can be found in the appendix.

The analysis showed that the emission factors for both NO_x and THC developed using the agricultural tractor and crawler dozer cycles were similar to those developed using the 8-mode test procedure. In Figure 4-14, more than half (6 out of 9) of the data points lie on the line y=x, while the remaining are close to it. The variability in the emission test results for the three data points which are off the line y=x is not judged to be large. Thus it was deduced that the emission test results of the 8-mode and the agricultural tractor cycle are similar.

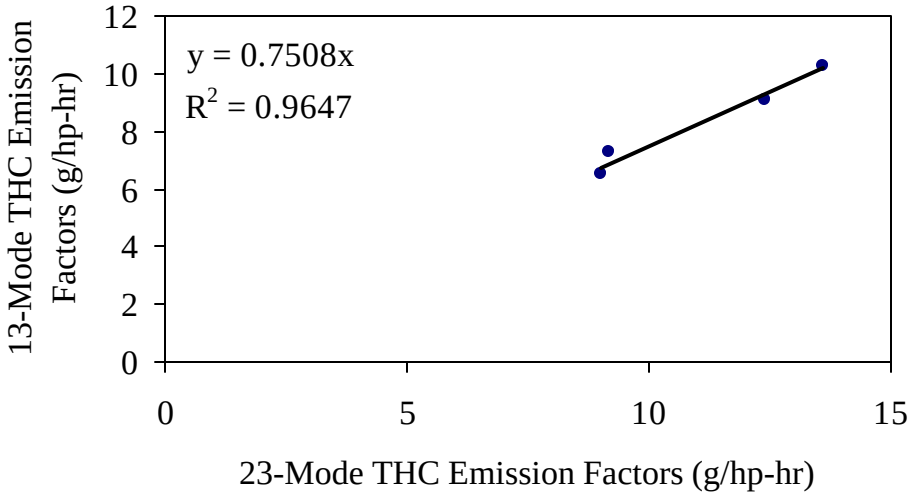


Figure 4-12. Comparison Between THC Emission Factors Measured with the 13-Mode Test and those Measured With the 23-Mode Test Data

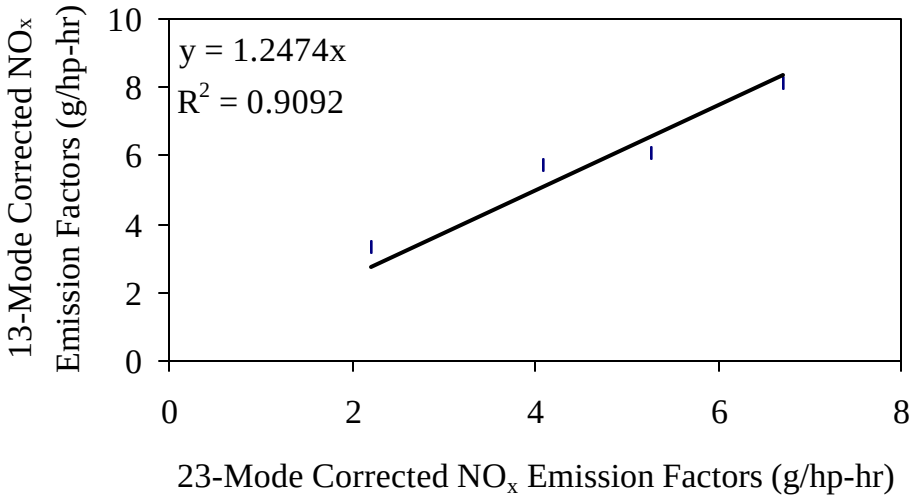


Figure 4-13. Comparison Between Corrected NO_x Emission Factors Measured with the 13-Mode Test and those Measured With the 23-Mode Test Data

Similarly in Figure 4-15, more than half (6 out of 9) data points are lying on the line y=x, while the remaining are very close to it. The deviation from the line y=x, for the remaining 4 data points is less compared to similar deviations noticed in the scatter plot of emission test results of 8-mode versus the agricultural tractor test procedure. Also the variability among the emission results from the 8-mode and the crawler dozer cycle is less compared to that between the emission results of the 8-mode versus the agricultural tractor cycle. On the basis of these observations it was deduced that the emission test results of the 8-mode and the crawler dozer cycle are similar.

In Figure 4-16, there is a linear relationship between THC emission factors developed using the Backhoe Loader cycle and the 8-mode procedure. This trend is not reflected in the NO_x emission factors developed using the Backhoe Loader cycle as shown in Figure 4-17. In Figure 4-17 the data points are evenly distributed closely on either side of the line y=x except for one point which is off by a large amount. But there was no information available to discard that point. The variability in the data points is not judged to be large and hence the NO_x emission test results from 8-mode procedure and the Backhoe Loader cycle are judged to be similar.

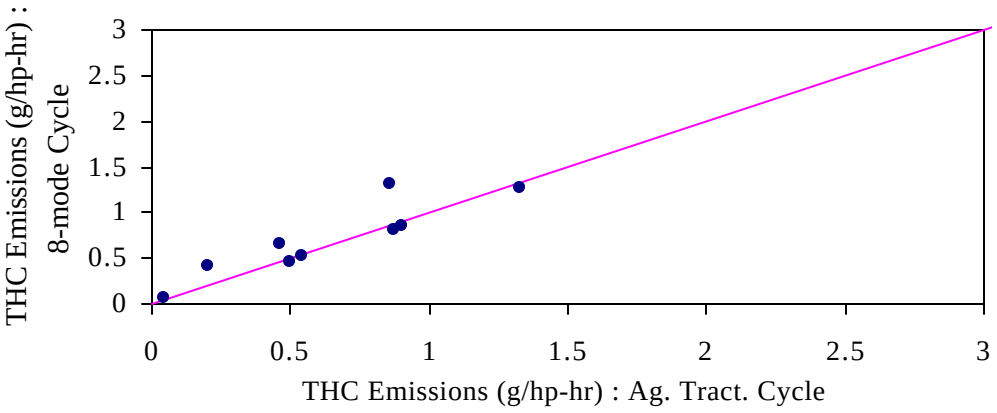


Figure 4-14. Scatter Plot to Compare the THC Emission Factors Developed Using the 8-Mode Steady State Cycle and the Agricultural Tractor Transient Cycle.

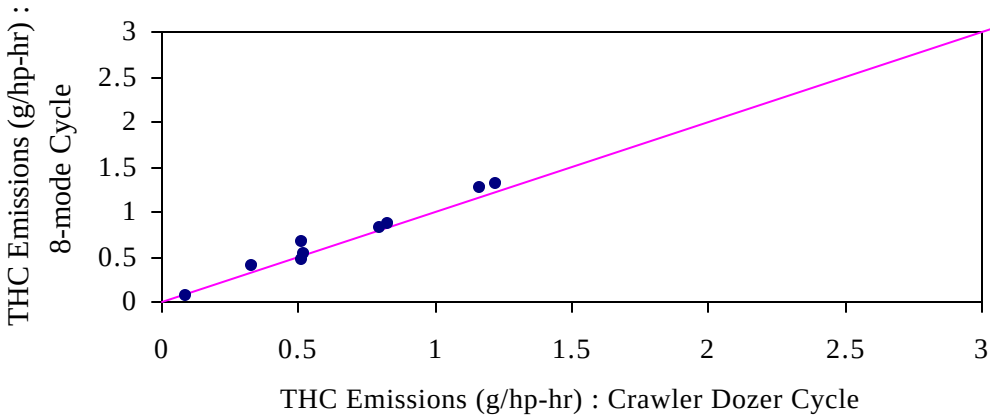


Figure 4-15. Scatter Plot to Compare the THC Emission Factors Developed Using the 8-Mode Steady State Cycle and the Crawler Dozer Transient Cycle.

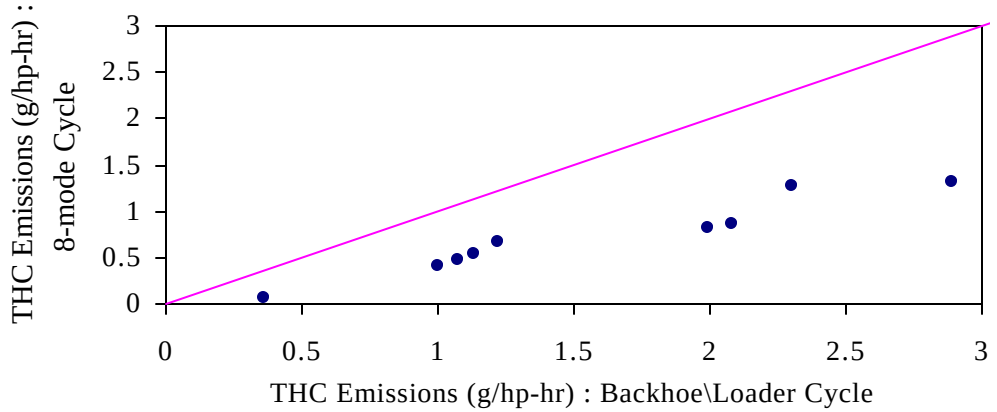


Figure 4-16. Scatter Plot to Compare the THC Emission Factors Developed Using the 8-Mode Steady State Cycle and the Backhoe Loader Transient Cycle.

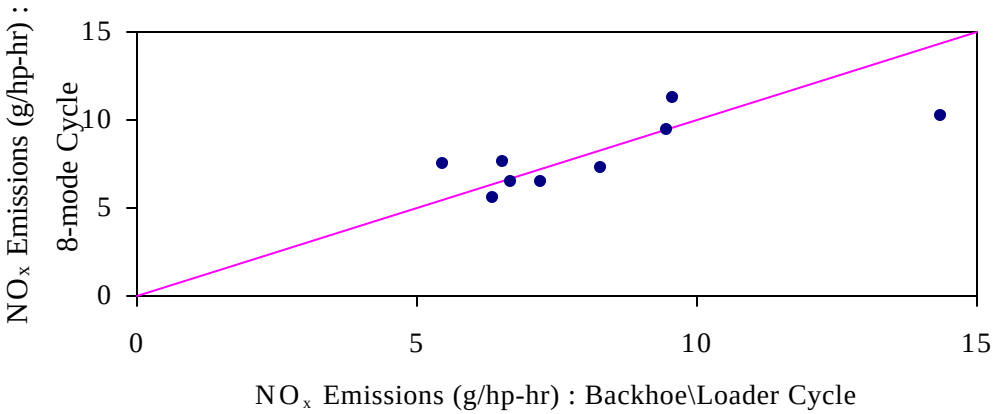


Figure 4-17. Scatter Plot to Compare the NO_x Emission Factors Developed Using the 8-Mode Steady State Cycle and the Backhoe Loader Transient Cycle.

The linear relation between the Backhoe Loader and the 8-mode tests indicate that we can calculate THC emission results of one test from the results of the other with reasonable precision. In Figures 4-14 and 4-15, the data points are reasonably close to the straight line, y=x indicating that the emission factors calculated form the Agricultural Tractor and Crawler Dozer cycles are essentially same as the ones developed using the 8-mode test. Emission factors developed from these transient cycles were not included in the emission factor database but the corresponding ones using the 8-mode procedure were.

Amongst the transient cycles the emission test results for THC from agricultural tractor and crawler dozer cycle were found to be comparable while there was a linear relationship between the THC emission results from agricultural tractor and backhoe loader and crawler dozer and backhoe loader cycles. For the case of NO emissions the emission test results from all the three cycles were found to be comparable.

4.4 Summary of the Database

In Table 4-7, a summary of the database is presented which shows the number of engines for which emission factor data could be obtained with respect to possible emission factor categories, pollutants, and emission factor units. Data for a total of 55 engines are included. All the reports reported emission factors in g/hp-hr units. Emission factors in other units were calculated wherever possible based on the information available in the report about fuel flow, size of the engine in hp or the availability of emission factors for CO, CO_2 and HC.

Emission factor data were not available for all the three emission factor units (i.e. g/hr, g/hp-hr, and g/gal) for all cases. For example, almost all the reports had THC and NO_x data in g/hp-hr units only, while not all had enough additional information provided so that emission factors could be calculated in other units i.e. g/hr and g/gal. To calculate emission factors in g/gal units either the fuel flow rate is needed or the emissions of CO_2, CO and HC all on the same basis, wet or dry (Frey and Eichenberger, 1997). An explanation of this method is presented in Section 3.3.1 in Chapter 3. To calculate the g/hr emission factors in units the horsepower rating of the engines was needed. Appendix F summarizes the information that was available to calculate the emission factors for the fifty five CFI engines in different units. Table 4-8 gives a summary of the tests done on each engine in the database and information about the fuel used.

Table 4-7. Summary of the L&G Engine Emission Factor Database

Category	Number of Engines					
	THC (g/hr)	**THC (g/hp-hr)**	**THC (g/gal)**	**NO_x (g/hr)**	**NO_x (g/hp-h)**	**NO_x (g/gal)**
Diesel	26	49	23	26	49	23
Gasoline	-	4	-	-	4	-
Pre 1988 (diesel) Old	7	33	3	7	33	3
Post 1988 (diesel) New	19	20	20	19	20	20
2-Stroke (diesel)	-	4	-	-	4	-
4-Stroke New (diesel)	20	37	15	20	37	15
4SNA (diesel)	8	17	3	8	17	3
4STC (diesel)	8	15	7	8	15	7

Each data point in the database represents a separate make/model of CFI engine. However, there were some reports when there were multiple emission factors reported for a particular engine. In one such report, a pair of tests (21-mode and 13-mode) were done on a set of eight diesel-fueled engines and another pair of tests (23-mode and 13 mode) were done on a set of four gasoline-fueled engines (Hare and Springer, 1973b). In this case the emission factors developed using the 21-mode and 23-mode test procedures were included in the database as these test procedures were chosen as benchmarks for diesel and gasoline fueled engines.

Table 4-8. Summary of the Information About the Type of Tests done on each Engine in the Database

Engine No.	Fuel	Available Test Results For					
		8-Mode	13-Mode	21-Mode	23-Mode	S-1, S-2, S-3	Transient Cycles
1	D		√				
2	D		√				
3	D		√				
4	D	√					
5	D	√					
6	D	√					
7	D	√					
8	D		√	√			
9	D		√	√			
10	D		√	√			
11	D		√	√			
12	D		√	√			
13	D		√	√			
14	D		√	√			
15	D		√	√			
16	G		√		√		
17	G		√		√		
18	G		√		√		
19	G		√		√		
20	D		√				
21	D		√				
22	D					√	
23	D					√	
24*	D		√	√			
25*	D		√	√			
26*	D		√	√			
27*	D		√	√			
28*	D		√	√			
29*	D		√	√			
30*	D		√	√			
31*	D		√	√			
32*	D		√	√			
33*	D		√	√			
34*	D		√	√			
35*	D		√	√			
36*	D		√	√			
37*	D		√	√			
38*	D		√	√			

39*	D		√	√			
40	D	√					
41	D	√					
42	D	√					
43	D	√					
44	D	√					
45	D	√					
46	D	√					
47	D	√					√
48	D	√					√
49	D	√					√
50	D	√					√
51	D	√					√
52	D	√					√
53	D	√					√
54	D	√					√
55	D	√					√

D ≡ Diesel, G ≡ Gasoline

* For these Engines it was not clear exactly which of the 21-mode or the 13-mode test was done. However these engines were included in the database as both the 21-mode and 13-mode tests have been found to be comparable.

The second report presented emission factors for two CFI engines measured by the same test procedure (13-mode) but using different test fuels (Hare and Bradow, 1979). The different test fuels were named as EM-238-F, EM-339-F, EM-240-F, EM-241-F and EM-242-F. For this case, the value that was least different from the others that were also reported was included in the database. It belonged to the EM-241-F fuel. It did not differ from others by more than 41% for THC and 18% for NO_x emission factors.

The third reported emission factors after testing the same engine under different test cycles (Beardsley and Lindhjem, 1998). These test cycles were the 8-mode, Agricultural Tractor, Crawler/Dozer and Backhoe/Loader. In this case emission factors developed from the 8-mode test procedure were used in the database. This is because 8-

mode test is a steady state test unlike the others, which were all transient in nature. Also more information was available for the 8-mode procedure than the others and it mapped favorably with the chosen benchmark for diesel fueled CFI engines as shown in Section 4.4.2.

There was also a set of engines for which it was not clear which out of the two 21-mode and 13-mode test procedure was used to develop emission factors (Hare and Springer, 1973b). Since these two procedures have been found to be equivalent the emission factors developed from these engines were also included in the database.

4.5 Grouping the Test Data

The database compiled from the available literature was analyzed statistically to identify whether there are any significant differences in emissions that justify categorization of the data with respect to the type of fuel (gasoline or diesel) used, the technology (2-stroke or 4-stroke), and/or the engine type (naturally aspirated or turbocharged). To make the comparisons, 2-tailed *t* – tests for the difference in means at a five percent significance level were done. EPA has used different categories to group CFI emission factors in the past. For example, 2-stroke vs. 4-stroke, Diesel vs. Gasoline and groupings based on engine size (in hp) (EPA, 1991; Beardsley and Lindhjem, 1998). The following subsections discuss these proposed groupings and the results of the statistical analysis are presented in Table 4-9.

4.5.1 Categorizing Emission Factors By Fuel

The emission factors were broadly divided into two categories: those from diesel-fueled CFI engines and those from gasoline-fueled CFI engines. The database had only four gasoline-fueled CFI engines. Results of the statistical analysis showed that the emission factors should be grouped separately on the basis of diesel versus gasoline fueled engines. The diesel engines had higher NO_x emissions compared to the gasoline-fueled engines while the gasoline engines had higher THC emissions compared to the diesel-fueled engines. This results are similar to those published in literature (hare and Springer, 1973b; Beardsley and Lindjhem, 1998). There were 4 gasoline-fueled engines and 49 diesel-fueled engines in the database.

4.5.2 Categorizing Diesel Engine Emission Factors By Technology

The diesel emission factors were further sub-grouped by technology, namely as "2-Stroke" and "4-Stroke" CFI engines. Results of the statistical analysis showed that the NO_x emission factors should be grouped separately. Both these categories contained only diesel engines, as sufficient information to put the gasoline engines in either category was not available. The NO_x emissions from 4-stroke diesel-fueled engines were higher than those from 2-stroke diesel-fueled engines. However THC emissions from the 2-stroke and 4-stroke diesel-fueled engines were found to be comparable. This observation is similar to the emissions test results published by Hare and Springer (1973b). The sample size of the data sets used in the comparison was 4 for 2-storke engines and 37 for 4-stroke engines.

4.5.3 Categorizing 4-stroke Diesel Engine Emission Factors By Engine Type

The 4-stroke diesel emission factors were sub-grouped on the basis of the type of engine, namely "Naturally Aspirated" (4-stroke NA or 4SNA) or "Turbo Charged" (4-stroke TC or 4STC). Results of the statistical analysis showed that for both THC and NO_x emission factors need not be grouped separately. Both of these categories contained only diesel engines, as sufficient information to put the gasoline engines in either category was not available. The emissions of THC and NO_x for these two categories were found to be comparable. The sample sizes for the two categories differed for the different units of measurement. Table 4-7 gives the sample sizes for each of the measurement units for both the categories.

4.5.4 Categorizing Diesel Engine Emission Factors By Engine Age

In the NONROAD model the engines that were made before 1988 are grouped together under the "Pre-1988" category for different size ranges (Beardsley and Lindhjem 1998). The reports reporting diesel emission factors collected for the database ranged from some as old as being published in 1973 to those which were published in 1995. This wide range of time suggested a need to check whether the emission factors should be grouped on the basis of their age or the time when they were reported. Since data on the age of the engines was not available, it was assumed that a more recently published report would have tested a more recently made engines. Hence on this basis, all the emission factors from engines reported in reports published before 1988 were grouped as "Old" and the remaining ones as "New". Results of the statistical analysis showed that only the THC emission factors in units of g/hp-hr need to be grouped separately on this basis while for all the remaining possible cases their was no significant difference in means

between old and new diesel CFI engines emissions. The 95 percent confidence interval on the mean for the case of THC emission factors in units of g/hp-hr was 1.13 g/hp-hr to 1.83 g/hp-hr for old CFI engines and 0.57 g/hp-hr to 0.95 g/hp-hr for new CFI engines. Since these 95 percent confidence intervals are not very far apart from each other and in light of the other results obtained for this comparison it was decided not to group emission factors on the basis of the age of the engine.

4.5.5 Categorizing Diesel Emission Factors By Engine Size

In the NONRAOD model, the CFI emission factors are grouped by different size ranges (Beardsley and Lindhjem 1998):

- >0 hp to 11 hp
- >11hp to 16 hp
- >16 to 25 hp
- >25 hp to 50 hp
- >50 hp to 100 hp
- >100 hp to 175 hp
- >175 hp to 300 hp
- >300 hp to 600 hp
- >600 hp to 750 hp
- >750 hp

Hence the emission factors in the assembled database were tested to see if there were any groupings on the basis of engine size (in horsepower) that could be identified. For this scatter plots of the diesel-fueled 4-stroke engine emission factors in units for g/hp-hr were plotted versus the size of the corresponding engine (in hp) and a regression line was fit to the dataset. The scatter plots revealed that for the given database there were no size-differentiated groupings that could be identified since the slope of the regression line was not found to be statistically significantly different from zero and there were no visible groups of data that could be identified in the scatter. For example in Figure 4-18, given a

standard error of 0.0007, the 95 percent confidence interval on the slope is roughly minus 0.002 to plus 0.0005 which includes zero. Thus the slope is not significantly different from zero. Hence CFI emission factors were not grouped on the basis of size in this study. Typical scatter plots for this analysis are shown in Figures 4-18 and 4-19.

On the basis of the analysis presented the CFI emission factors were broadly grouped on the basis of fuel used i.e. gasoline versus diesel. The diesel-fueled CFI engine emission factors were then further sub grouped into 2-stroke diesel-fueled and 4-stroke diesel-fueled emission factors. For the 4-stroke diesel-fueled engines emission factor data was available for all the three different units namely g/hr, g/hp-hr and g/gallon. But for gasoline fueled engines and 2-stroke diesel-fueled engines, emission factor data were available only in g/hp-hr units.

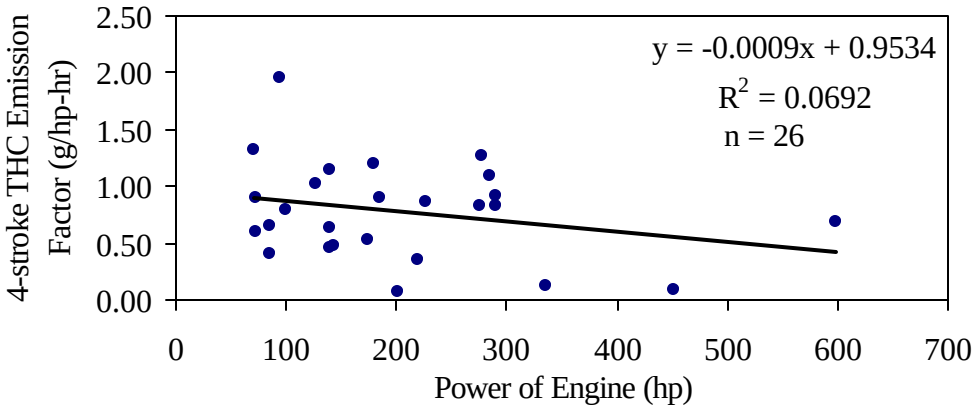


Figure 4-18.Scatter Plot of THC (g/hp-hr) Emission Factors for 4-Stroke Engines Versus the Size of the Engine (Rated Horsepower).

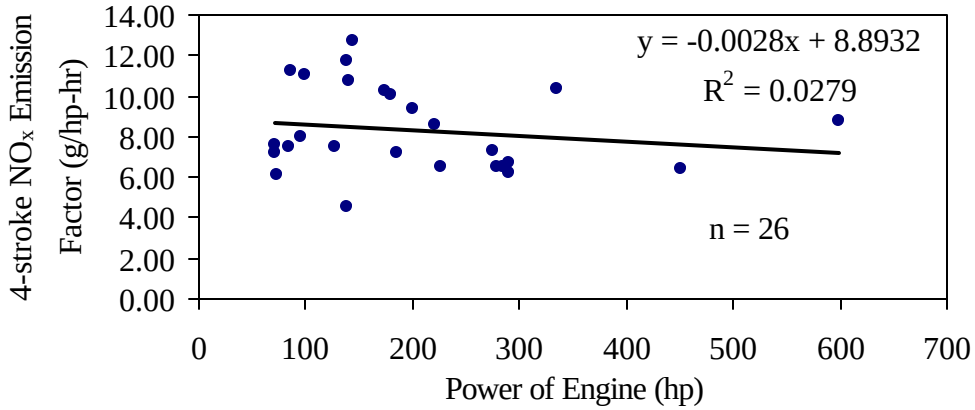


Figure 4-19. Scatter Plot of NO_x (g/hp-hr) Emission Factors for 4-Stroke Engines Versus the Size of the Engine (Rated Horsepower).

Table 4-9. Results of Comparison of Diesel versus Gasoline Engines, Old versus New Diesel Engines, 2-stroke versus 4-stroke Diesel Engines, 4-stroke Old versus 4-stroke New Diesel Engines and of 4SNA versus 4STC Diesel Engine Emission Data, Based Upon *t*-Tests for the Difference of Two Means at a 5% Level of Significance**.**

Comparison	Pollutant	Units	Significant Difference between Data Sets?
Diesel Engines versus Gasoline Engines	THC	g/hp-hr	Yes
	NO_x	g/hp-hr	Yes
Old (Pre 1988) (Diesel) versus New (Post 1988) (Diesel)	THC	g/gal	No
		g/hr	No
		g/hp-hr	Yes
	NO_x	g/gal	No
		g/hr	No
		g/hp-hr	No
2-Stroke Engines (Diesel) versus 4-Stroke Engines (Diesel)	THC	g/hp-hr	No
	NO_x	g/hp-hr	Yes
4-S Naturally Aspirated Diesel Engines versus 4-S Turbocharged Diesel Engines	THC	g/gal	No
		g/hr	No
		g/hp-hr	No
	NO_x	g/gal	No
		g/hr	No
		g/hp-hr	No

4.6 Analysis of Variability and Uncertainty

The previous sections focused upon development and exploration of a CFI engine emission factor database. In this section, variability in the emission factor data is quantified using parametric probability distribution models. Uncertainty in the mean emission factors, and regarding the fitted distributions, is quantified using bootstrap simulation. Estimates of uncertainty in mean emission factors are developed for the various groupings of emission factors as discussed in section 4.6, for both THC and NO_x and for three units for measurement of emissions (g/hr, g/hp-hr, and g/gallon).

4.6.1 Quantification of Inter-Engine Variability in Emissions

Measured emissions vary from one engine to another in the database. The variability in emissions can be described as an empirical cumulative distribution function (CDF) or by a parametric probability distribution function. Parametric distributions offer advantages of enabling interpolation within the range of the observed data and for extrapolation to the tails of the distribution beyond the range of observed data (Cullen and Frey, 1999). The latter is important because it is unlikely, with a finite sample of data, that the true minimum or maximum values are represented by the sample minimum and maximum values. In this work, alternative parametric probability distribution models were fit to the data and evaluated for goodness-of-fit based upon visualization of the fitted distribution compared with the data and based upon the results of bootstrap simulations of the fitted distribution. Statistical goodness-of-fit tests were not used because the data sample sizes are too small. The parametric distributions considered were Normal, Lognormal, Gamma and Weibull. Maximum likelihood estimation was used to estimate the parameters of the fitted distributions. Evaluation of the adequacy of fit is further addressed in the following sections.

4.6.2 Characterization of Uncertainty in CFI Engine Emission Factors

The probabilistic techniques were applied to each of the emission factor data groups identified as having statistically significant differences in mean emissions with respect to each other. To illustrate the application of the probabilistic methods, example results are presented for selected cases.

In Figure 4-19, results are shown for the gasoline-fueled CFI engine THC emission data set in units of g/hp-hr. The variability in emissions among these engines is from approximately 9 g/hp-hr to approximately 14 g/hp-hr. A fitted Weibull distribution is shown in comparison to the data. The Weibull distribution captures the overall trends of the empirical distribution of the data. There is some scatter of the data above and below the fitted distribution. In order to evaluate whether the deviations of the data with respect to the fitted distribution imply a poor fit, confidence intervals for the fitted CDF of the Weibull distribution are shown. These confidence intervals were obtained based upon bootstrap simulation. Half of the data (2 out of 4 data points) are enclosed by the 50 percent confidence interval, and all of the remaining data are enclosed by the 90 percent confidence interval. This comparison suggests that the Weibull distribution is an adequate fit to the data set and, therefore, is a reasonable representation of inter-engine variability in emissions. From the confidence intervals the fitted distribution appears to be negatively skewed, as it appears to have a heavier bottom than top. This is reflected in the negatively skewed 95 percent confidence interval of minus 22 percent to plus 17 percent on the mean as shown in Table 4-10.

Similar results are shown for 2-stroke diesel-fueled CFI engine category with respect to NO_x emissions in units of g/hp-hr in Figure 4-20. The fitted distribution is Weibull. The variability among the emissions from engines in this category is from approximately 10 g/hp-hr to approximately 20 g/hp-hr. More than half of the data (2 out of 4 data points) are enclosed by the 50 percent confidence interval, and all the remaining data points are enclosed by the 90 percent confidence interval of the bootstrap simulation.

Therefore, the fit appears to be adequate. Again the confidence intervals appear to be wider at the bottom and narrower at the top indicating a negatively skewed fitted distribution. This can be explained by the fact that the data set is itself negatively skewed with one value very close to 10 g/hp-hr and the remaining being very close to 20 g/hp-hr.

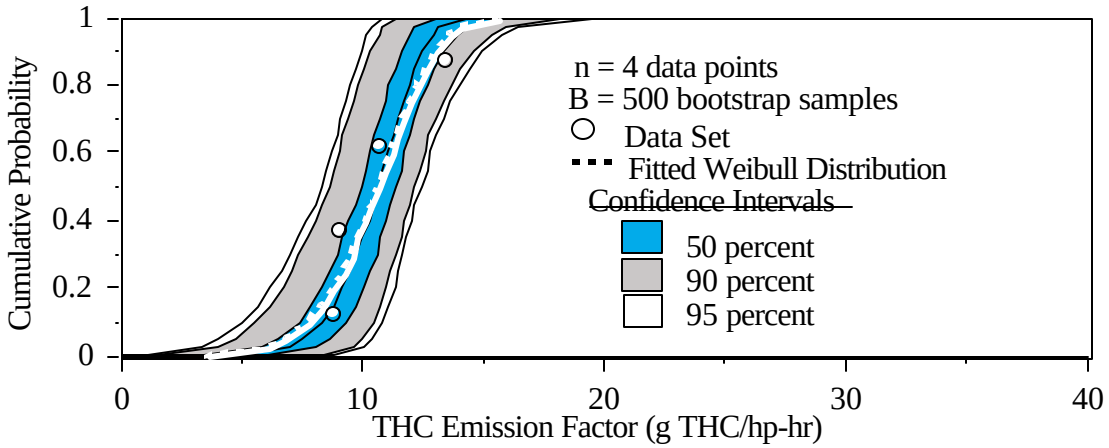


Figure 4-20. Fitted Weibull Distribution and Bootstrap Simulation Results for CFI Gasoline Engine THC Emission Data in Units of g/hp-hr

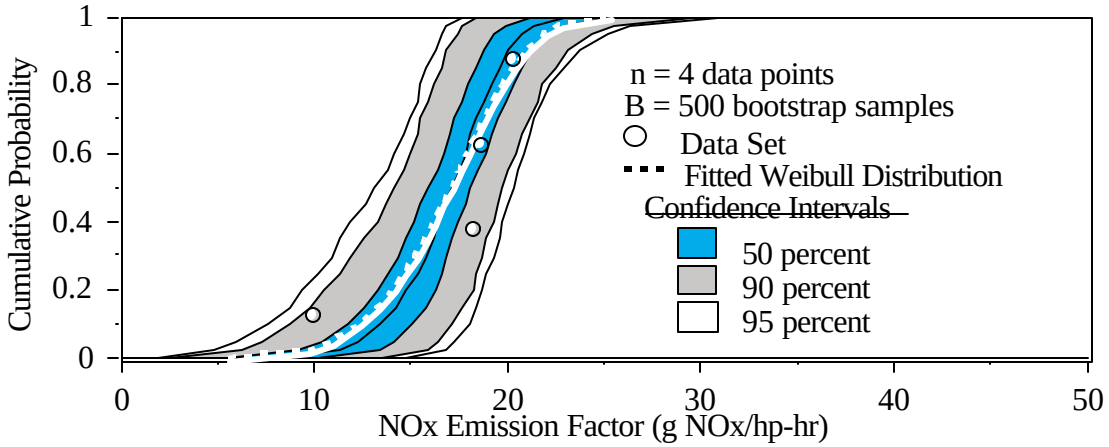


Figure 4-21. Fitted Weibull Distribution and Bootstrap Simulation Results for 2-Stroke CFI Diesel Engine NO_x Emission Data in Units of g/hp-hr

Table 4-10. Results of the Uncertainty Analysis of Mean NO_x and THC Emission Rates for Diesel and Gasoline fueled CFI Engines in units of g/hp-h.

Category	Pollutant	Units	# of Data	Fitted Dist. [a]	Mean [b]	95% CI on Mean[c]	Relative Uncertainty[d]
Gasoline	NO_x	g/hp-hr	4	WE	4.58	3.11 – 6.33	-32% to +38%
	THC	g/hp-hr	4	WE	10.5	8.22 – 12.3	-22% to +17%
Diesel 2S	NO_x	g/hp-hr	4	WE	16.8	13.2 – 20.2	-21% to +20%
	THC	g/hp-hr	4	WE	1.49	0.78 – 2.22	-48% to +49%
Diesel 4S	NO_x	g/gal	15	LN	149	126 – 177	-15% to +19%
		g/hr	20	GA	1670	1220 - 2140	-27% to +28%
		g/hp-hr	37	LN	8.46	7.62 – 9.37	-10% to +11%
	THC	g/gal	15	GA	16.7	11.5 – 22.3	-31% to +34%
		g/hr	20	GA	133	90.3 – 176	-32% to +32%
		g/hp-hr	37	WE	1.25	0.93 – 1.58	-26% to +26%

[a] WE ≡Weibull, LN≡ Lognormal, GA ≡ Gamma

[b] Mean of 500 Bootstrap Samples

[c] Numbers shown here are for the 95 percent confidence interval of the mean obtained from bootstrap simulation in terms of absolute emission rates

[d] Numbers shown here are for the 95 percent confidence interval of the mean obtained from bootstrap simulation in terms of relative deviation from the mean.

Figures 4-21 and 4-22 illustrate probabilistic analysis results for 4-stroke engines for THC and NO_x emission factors, respectively, in units of g/gallon. In Figure 4-21, the inter-engine variability in NO_x emissions among the 15 data points ranges from approximately 80 g/gallon to approximately 230 g/gallon. A little less than half of the data points are within the 50 percent confidence interval, all except one data point are within the 90 percent confidence interval, and all data are within the 95 percent confidence interval. Figure 4-21 thus illustrates that the fitted Lognormal distribution, though not perfect, is adequate as it captures the overall trends of the inter engine variability among the emission factors. Figure 4-21 also suggests that the given data set might be a mixture of two distributions as there could be two distributions fit to the data on either side of the 150 g/gallon mark on the x-axis. This also causes the given data set to be positively skewed and this positive skewness of the data set reflects in the positively

skewed confidence intervals on the mean ranging from –15 percent to plus 19 percent as given in Table 4-10.

In the case of the Figure 4-22, the inter-engine variability in THC emission ranges from approximately 2 g/gallon to approximately 45 g/gallon, which is more than an order of magnitude. About half (7 out of 15) data points lie within the 50 percent confidence interval and all of the data are within the 90 percent confidence interval. Thus, the Gamma distribution appears to fit the given dataset adequately. The dataset appears to be positively skewed for this case. This positive skewness in the dataset is reflected in the positively skewed fitted gamma distribution.

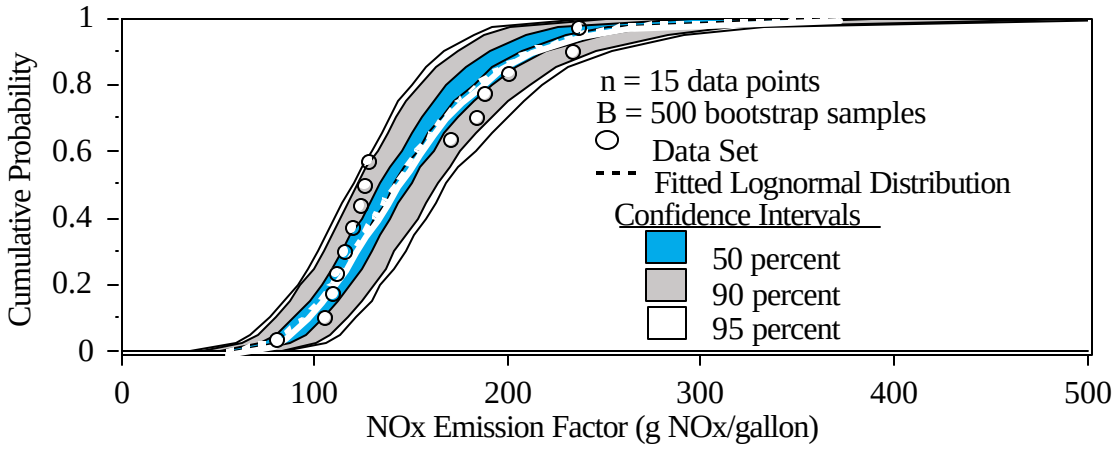


Figure 4-22. Fitted Lognormal Distribution and Bootstrap Simulation Results for 4-Stroke Diesel CFI Engine NO_x Emission Data in Units of g/gallon

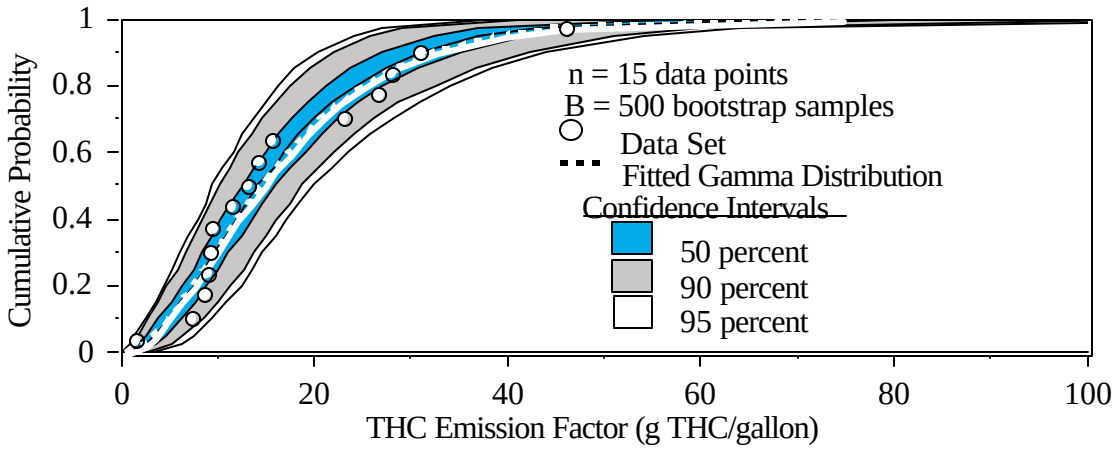


Figure 4-23. Fitted Gamma Distribution and Bootstrap Simulation Results for 4-Stroke Diesel CFI Engine THC Emission Data in Units of g/gallon

The remaining figures showing results of bootstrap simulation for other cases are presented in the appendix C. For all those cases the fitted distribution was found to adequately describe the inter engine variability among the emission factors.

4.6.3 Results of the Uncertainty Analysis

Results of the analysis of uncertainty in mean emission factors for all cases considered are given in Table 4-10. For example, for the diesel-fueled 4-stroke engine THC emissions in units of g/gallon depicted in Figure 4-22, the mean emission rate is 16.7 g/gallon. This corresponds to the approximately 55^{th} percentile of the fitted distribution. The mean occurs at a cumulative probability above the median (50^{th} percentile) because the data and the distribution are positively skewed. The 95 percent confidence interval for the mean is 11.5 g/gallon to 22.3 g/gallon, which is a positively skewed range of minus 31 percent to plus 34 percent of the mean value. The relatively wide range of uncertainty in the mean emission factor in this case is a result of both the relatively small sample size of this data set (n=15) and the wide range of variability in the data, which is more than an order of magnitude.

Of the ten cases shown in Table 4-9, all but three have uncertainty ranges of greater than approximately plus or minus 20 percent, and one has an uncertainty range of greater than approximately plus or minus 40 percent. Thus, there is substantial quantified uncertainty in the mean emission factors. For the same type of engine and pollutant, the range of uncertainty in emission factors varies because of the varying sample size and the variability in the emission factor data.

For the gasoline-fueled CFI engines the mean emission rate of NO_x is less than that of THC but for diesel-fueled CFI engines the mean emission rates for NO_x are more than those for THC for all the different units considered. This trend is similar to other published results in the literature (Hare and Springer, 1973b; Beardsley and Lindjhem, 1998b). Within the diesel CFI engines, NO_x emissions are higher for the 4-stroke engines compared to 2-stoke ones. However the THC emission from 2-stroke and 4-stroke diesel CFI engines are found to be comparable. This observation is again similar test results published by Hare and Springer (1973b). The similarities pointed out in the emission trends found in the compiled database and published literature add validity to this research.

Table 4-11 compares the mean of the data sets with the mean of the fitted distributions. In all the cases the means of the data set compare well with those of the fitted distributions. For any of the ten cases considered, the mean of dataset does not differ from the mean of the fitted distribution by more than 3 percent.

Table 4-11. Summary of the Comparison Between the Mean of the Data Sets and the Mean of the Fitted Distribution

Category	Pollutant	Unit	Number of Data	Mean of Dataset	Fitted Distribution[a]	Mean of Bootstrap Samples
Gasoline	NO_x	g/hp-hr	4	4.56	WE	4.58
	THC	g/hp-hr	4	10.5	WE	10.5
Diesel 2S	NO_x	g/hp-hr	4	16.7	WE	16.8
	THC	g/hp-hr	4	1.45	WE	1.49
Diesel 4S	NO_x	g/gal	15	149	LN	149
		g/hr	20	1670	GA	1670
		g/hp-hr	37	8.38	LN	8.46
	THC	g/gal	15	17	GA	16.7
		g/hr	20	132	GA	133
		g/hp-hr	37	1.24	WE	1.25

[a] WE ≡Weibull, LN≡ Lognormal, GA ≡ Gamma

5.0 CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

This work demonstrated a procedure for quantifying variability in emissions and uncertainty in mean emissions using parametric probability distributions and bootstrap simulation. The procedure has been demonstrated with respect to case studies of highway vehicles HAP emission factors, lawn and garden (L & G) equipment of less than 25 hp and construction, farm and industrial (CFI) equipment.

A key difficulty encountered in this work was to obtain a well-documented and complete database. For example, there were a lot of difficulties faced in getting the test reports from EPA, CARB, and other testing agencies. After months of searching it was finally decide to focus on obtaining a reasonable data set and analyzing it to develop relative measures of uncertainty which would provide an insight into the level of uncertainty anticipated in any emission factor calculated based upon a similar dataset in the NONROAD model. Regulatory agencies that make public policy should, as a matter of routine, make publicly available the data used in calculations used to develop emission factors. Such data should be made widely available through technical documents and databases on the World Wide Web. While in some cases data may be of proprietary origin, information that would identify a specific emission source with a particular company or facility need not be reported. Furthermore, in reporting values of emission factors, quantitative information regarding the variability in emissions and regarding the uncertainty in the average emissions should be provided.

In this research, uncertainty associated with statistical random sampling error was quantified. However, uncertainty associated with lack of representativeness and with measurement errors was not quantified. Each of these points is further addressed here.

Measurements of emissions from L&G and CFI engines have been made using a variety of test procedures. These procedures are not always comparable with each other. Care was taken in this work not to group together data that were obtained from dissimilar test methods. However because of lack of documented information and the unavailability of data issues related to engine age, hours of previous use, maintenance, etc. could not be addressed in this work. For emission factor purposes, it is important to have data that are representative of real world applications of these types of engines. Therefore, candidate test methods should be evaluated with respect to their representativeness. In this work, uncertainty associated with potential lack of representativeness has not been quantified. Such an analysis would require at least some benchmark measurements of real-world in-use emissions, which is a recommendation to regulatory agencies for future work.

Uncertainty in emissions measurements can, potentially, be a significant source of uncertainty, particularly for some pollutants and/or emission sources. According to author's judgment, the methods used to measure engine emissions are relatively well-known and of reasonably high quality. Therefore, it is expected that the measurement errors are not large with respect to the quantified uncertainty associated with random sampling error, except in cases when this quantified uncertainty is relatively small (e.g, plus or minus 10 percent). However, verification of this assumption is a need for future

work. An obstacle to verifying this assumption is the lack of information regarding the precision and accuracy of the test methods. Such information should be provided in any emission test report.

For the air toxic emission factors, the most useful measure of emissions was found to be the toxic percent of TOG as it had the least amount of variability associated with it compared to other mass per mile emission factors. It was also found that for Benzene and Formaldehyde, emissions need not be reported separately for high and normal emitters, whereas for 1,3-Butadiene, MTBE and Acetaldehyde emission factors for high and normal emitters should be reported separately. Another important conclusion from this research was that there was no significant difference found in emission factors reported in units of toxic percent of TOG on the basis of fuel type i.e. RFG, UnL or Indolene.

In this work, decisions regarding how to categorize the emission factor database were made based upon empirical evidence from the database regarding whether mean emissions differed in a statistically significant manner for different subgroups. Significant differences were found in the L&G database between 2-stroke and 4-stroke engines for both NO_x and THC, and also between handheld and non-handheld applications. Because handheld applications typically involve 2-stroke engines, and non-handheld applications typically involve 4-stroke engines, it is not useful to use both sets of categories. Therefore, only the first one was chosen. There was no significant difference in the mean emissions of 4-stroke OHV versus LHV engines. There was also

some evidence to suggest that emissions may differ by size for both 2-stroke and 4-stroke engines, and hence the 4-stroke emission factors were size differentiated but the evidence for 2-stroke emission factors was judged not to be sufficiently compelling at this time.

Similarly there were significant differences in the CFI database between engine emission factors for 2-stroke versus 4-stroke and diesel-fueled versus gasoline-fueled engines for both THC and NO_x emission factors. However there was no difference found between the emission factors for both NO_x and THC on the basis of engine type i.e. naturally aspirated versus turbo charged and the age of the engine assuming that the published emission tests did not test engines that were very old at that time.

The diesel engines in the CFI database had higher NO_x emissions compared to the gasoline-fueled engines. Gasoline-fueled engines had higher THC emissions compared to the diesel-fueled engines. Amongst the diesel engines, the 4-stroke engines had higher NO_x emissions compared to the 2-stroke engines, while the THC emissions from the 2-stroke and 4-stroke engines were found to be comparable. These trends are similar to those found in published results by Hare and Springer (1973b). These observations add validity to analysis of CFI database.

The database that was developed for the L&G and the CFI categories was compared with some of the published information about these emission factors to check for its validity. The trends in the emissions as reflected in the developed database match well with those of the published information in the literature. The NO_x and THC emission

factor trends as they varied between 2-stroke and 4-stroke engines compared well with those published by comparable studies done at CARB and the University of Michigan (CARB, 1990; Sun *et al.*, 1995). For example, among the gasoline-fueled L&G engines a general trend of THC emissions being more than NO_x was observed. Similarly the trend that the THC emissions of the 2-stoke engines being much higher than those of the 4-stroke engines was noticed. The reason for such high THC emissions has mainly been attributed to the scavenging losses of the 2-stroke engines by Sun *et al.* (1995). Again it was noted that the NO_x emissions of the 2-stroke engines are much lower than those of the 4-stroke engine. These low NO_x emissions can be attributed to grater fuel-rich combustion that takes place in the 2-stroke engines compared to the 4-stroke ones.

The inter-engine variability in emissions was found to be substantial, such as a factor of 10 or more variation from the smallest to largest values in a given data set. Although it is clear that there are often only a small number of large values in a given data set, unless there are known errors in the data, it is not appropriate to discard such values. Because of the relatively small data set sample sizes and the large range of variability, the uncertainty in the mean emissions were relatively large, with most cases evaluated having uncertainty ranges for the mean in excess of plus or minus 20 percent.

The comparisons that were done between the various test procedures for the L&G and the CFI categories provide many useful insights. The test procedures that were chosen as standards were SAE J1088 and CARB J1088 for L&G and 21-mode (diesel) and 23-mode (gasoline) for CFI categories. Thus researchers in future can take advantage

of this information when they are deciding on which emission test procedure to choose from the myriad number of available ones for a given emissions test program.

Also, for the CFI category there were some pairs of test procedures that were found to be equivalent on the basis of the modes included in them but had a different number of modes; e.g. 21-mode and 13-mode, 21-mode and 8-mode etc. This information can be used to reduce testing times and also save money when deciding on a particular test procedure to test a given engine. This is because the out of the two procedures found equivalent in this research the one with lesser number of modes can be chosen by the researchers for their engine testing requirements. However, there might be some emission testing programs where a specialized emission test procedure is need and not the standard ones that were identified in this research. For example there might some emissions testing research programs where it would be better to use for example the Lawn Mower Cycle for lawn mowers rather than the standard SAE J1088 or CARB J1088 test procedures as identified in this study. This is because in the specialized cycles like Lawn Mower cycle, the mode weightings or the modes themselves can be changed to suite the requirements of the testing program.

The large range of quantified uncertainty in emission factors suggests that it is important to quantify uncertainty. As the National Research Council noted in its recent report on modeling mobile source emissions, it is not possible to quantify all sources of uncertainty. Nonetheless, the quantifiable portion of uncertainty should be taken into account when reporting and using emission factors. Non-quantifiable contributions to

uncertainty should be acknowledged qualitatively. Decision-makers should be aware of both the strengths and limitations of emission factors and emission inventories, so that decisions regarding air quality management can be made that are robust to uncertainty. Furthermore, by understanding the key sources of uncertainty in an emission inventory, resources can be prioritized to reduce uncertainty, such as by collecting better and more data. Thus, the probabilistic methodology presented here is part of an overall approach to developing policy, program management, and research planning.

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7.0 APPENDIX A: ADDITIONAL FIGURES FOR CHAPTER 2

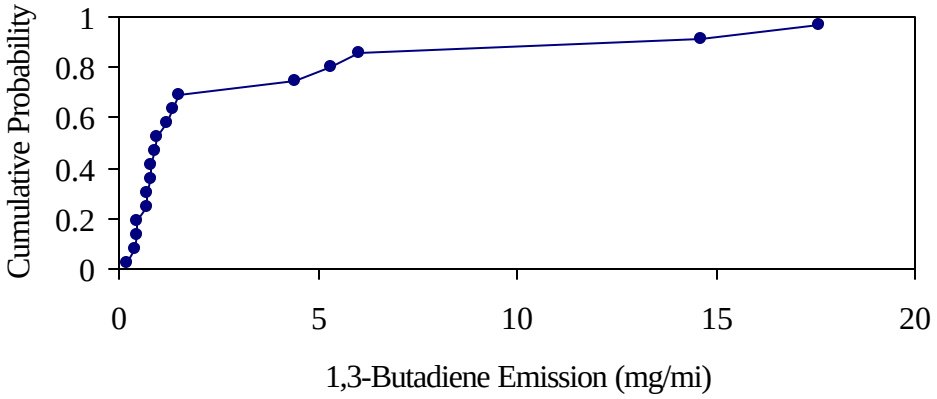


Figure 7-1. Variability in 1,3-Butadiene Emissions (mg/mi) Using FTP Cycle

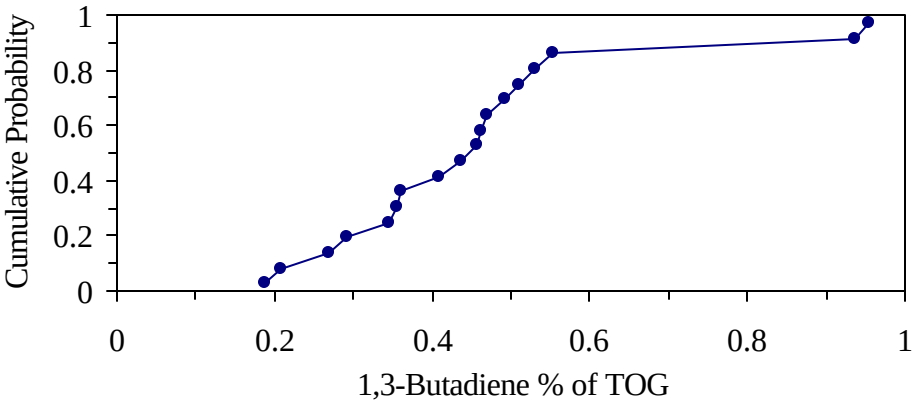


Figure 7-2. Variability in 1,3-Butadiene Emissions (% Fraction of TOG) Using FTP Cycle

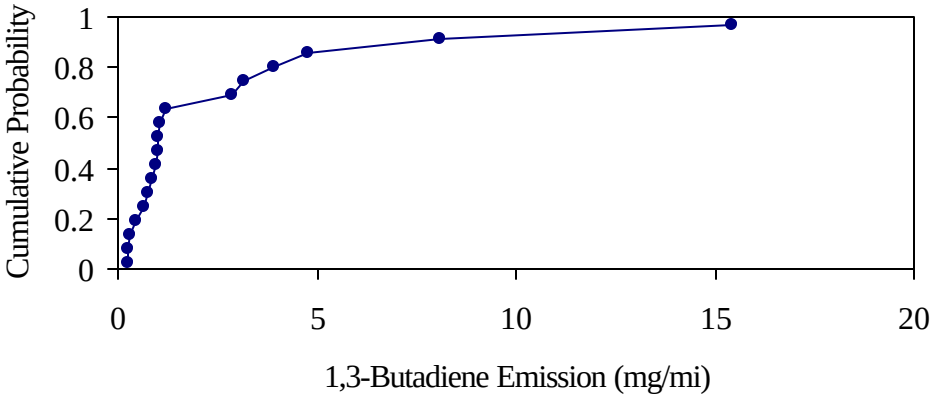


Figure 7-3 Variability in 1,3-Butadiene Emissions (mg/mi) Using UC Cycle

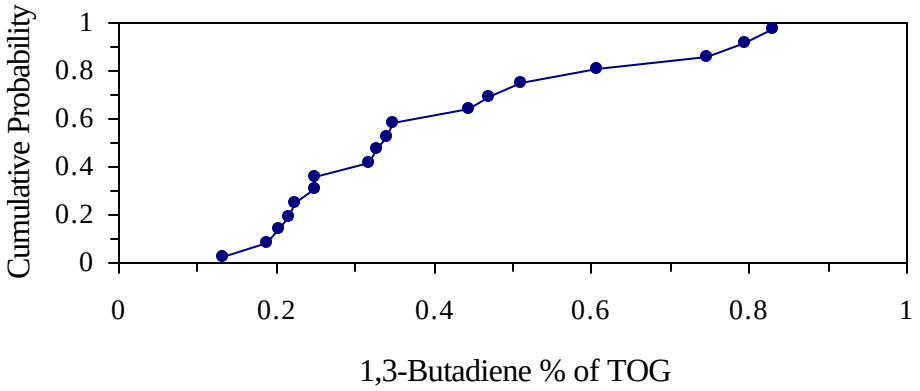


Figure 7-4 Variability in 1,3-Butadiene Emissions (% Fraction of TOG) Using UC Cycle

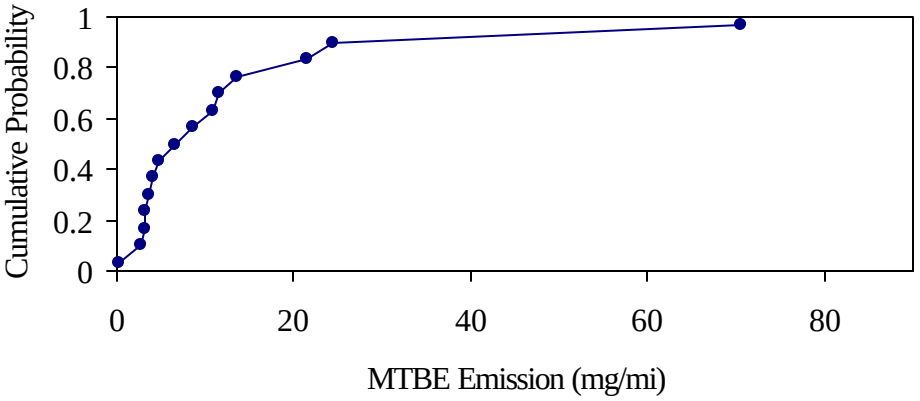


Figure 7-5 Variability in MTBE Emissions (mg/mi) Using FTP Cycle

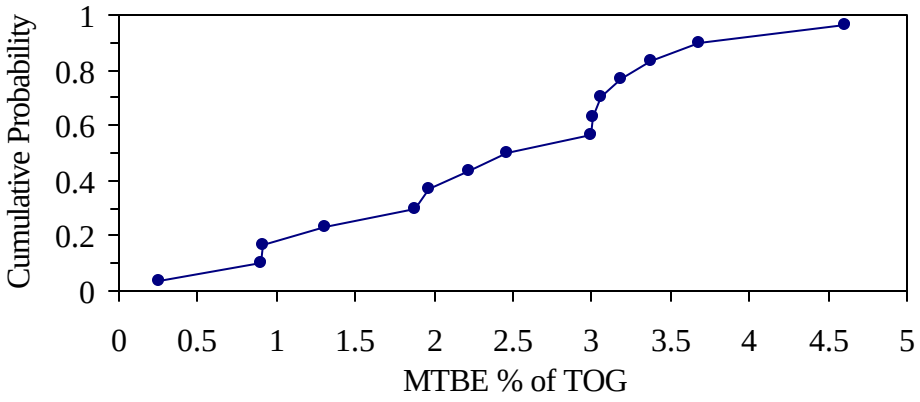


Figure 7-6 Variability in MTBE Emissions (% Fraction of TOG) Using FTP Cycle

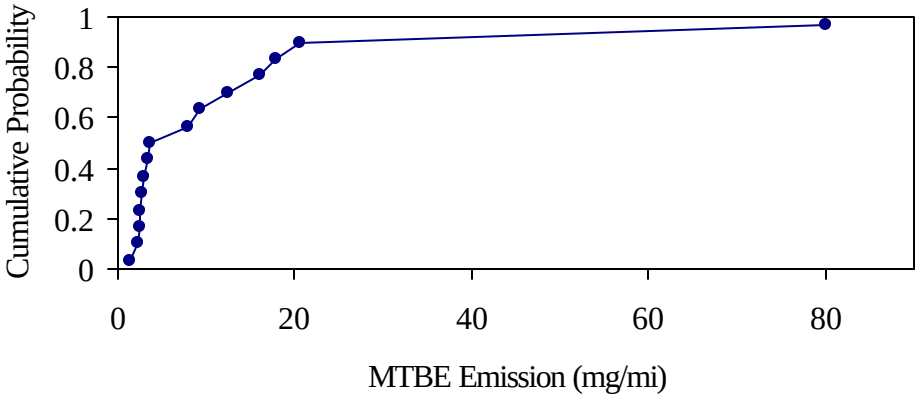
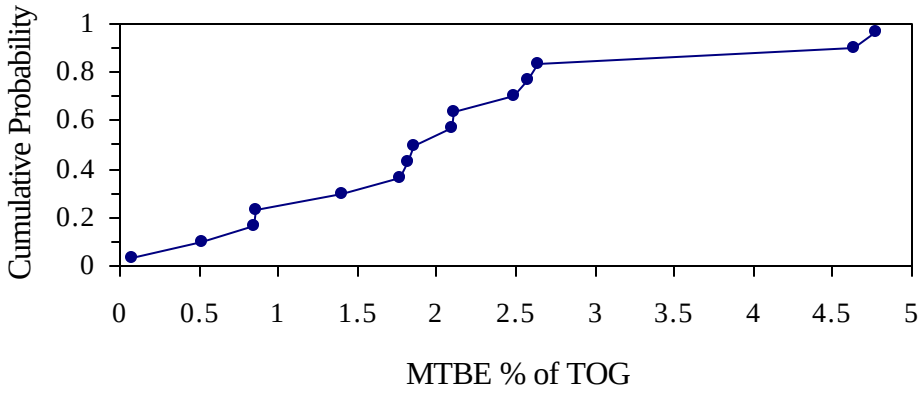


Figure 7-7 Variability in MTBE Emissions (mg/mi) Using UC Cycle



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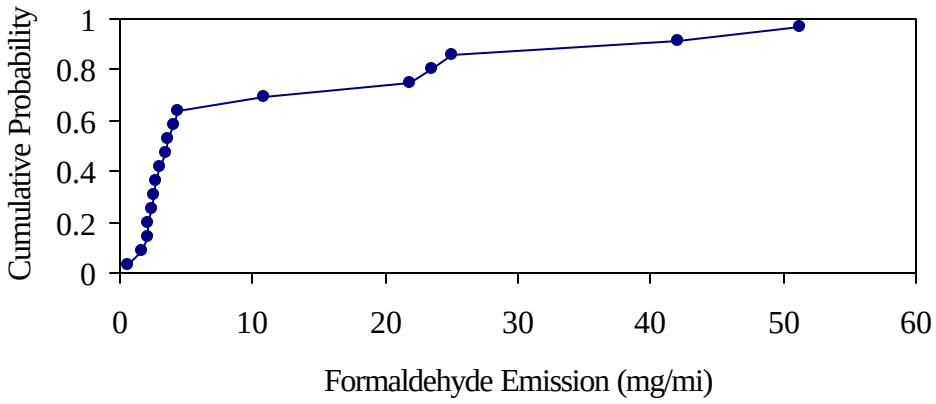


Figure 7-9 Variability in Formaldehyde Emissions (mg/mi) Using FTP Cycle

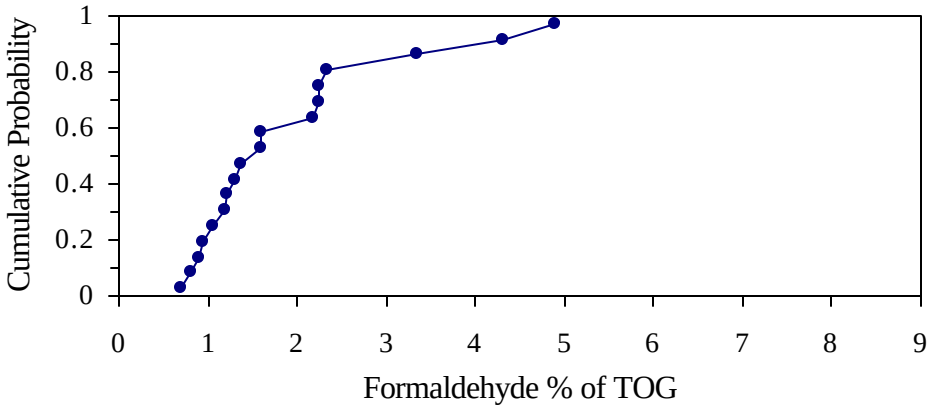
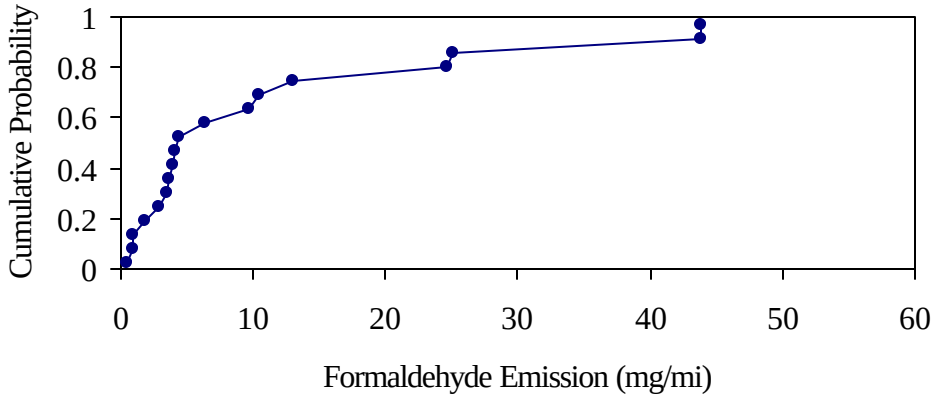


Figure 7-10 Variability in Formaldehyde Emissions (% of TOG) Using FTP Cycle



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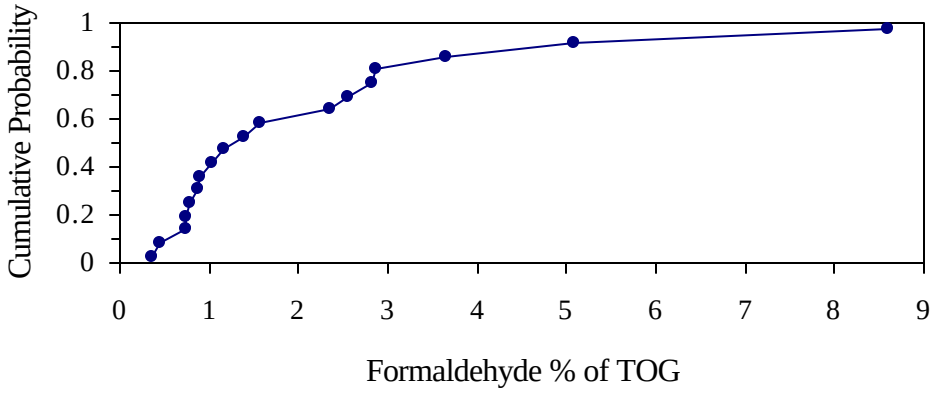

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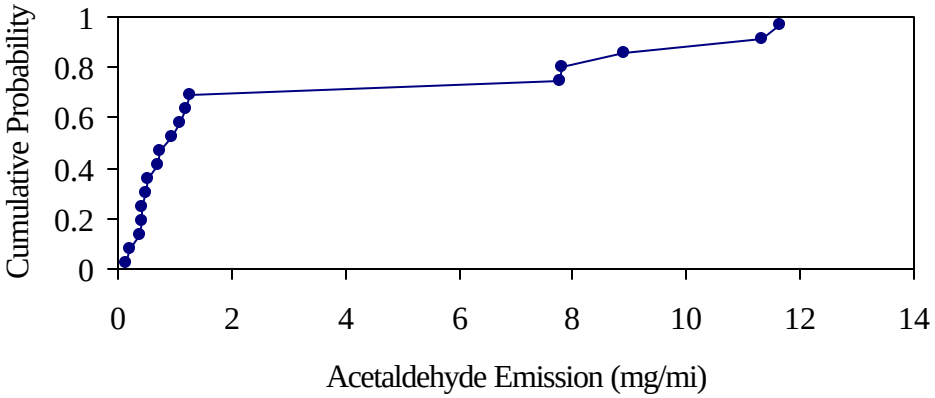


Figure 7-13 Variability in Acetaldehyde Emissions (mg/mi) Using FTP Cycle

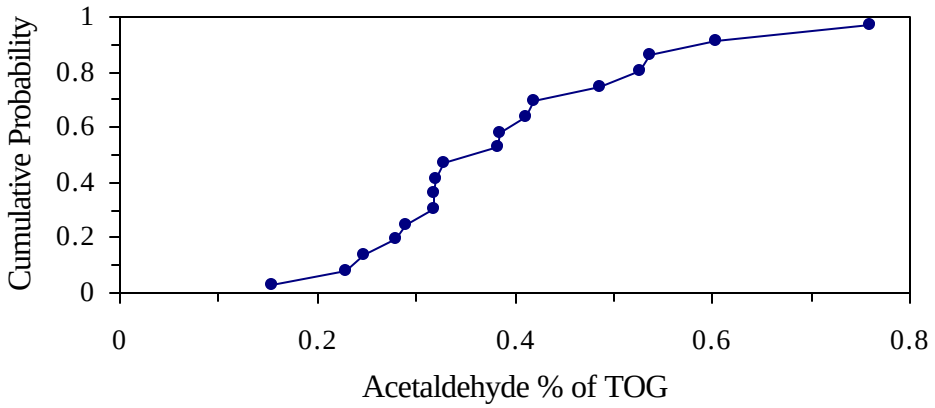
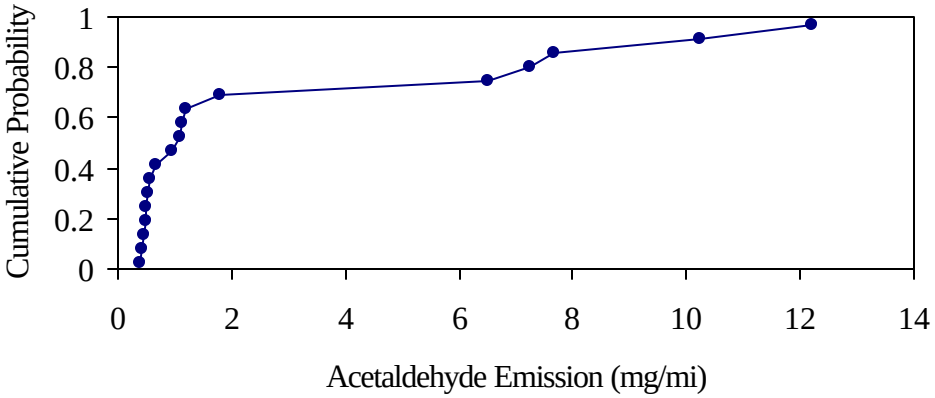


Figure 7-14 Variability in Acetaldehyde Emissions (% of TOG) Using FTP Cycle



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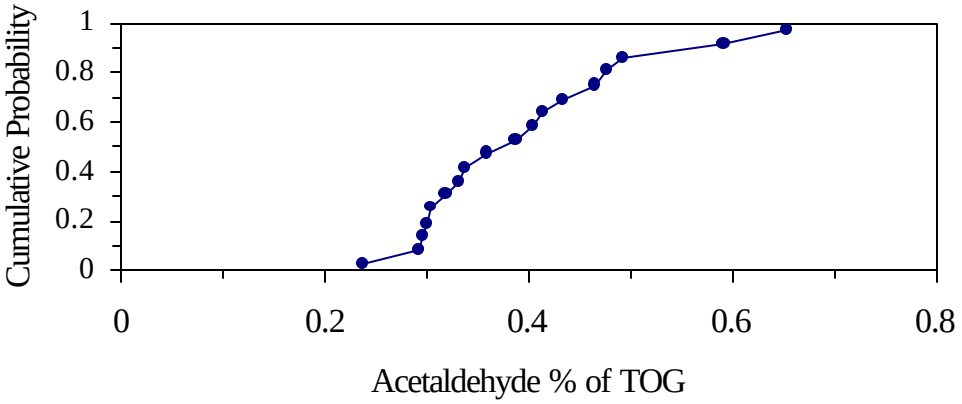


Figure 7-16 Variability in Acetaldehyde Emissions (% of TOG) Using UC Cycle

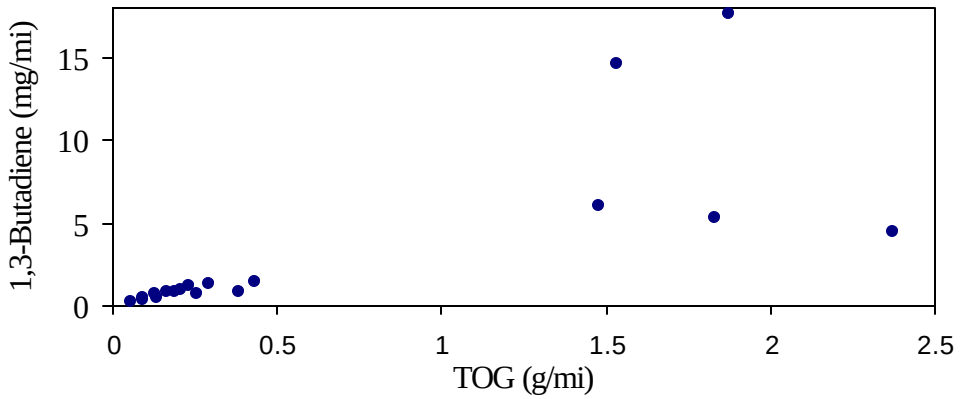


Figure 7-17 Scatter Plot of 1,3-Butadiene (mg/mi) vs. TOG (g/mi) Using FTP Cycle

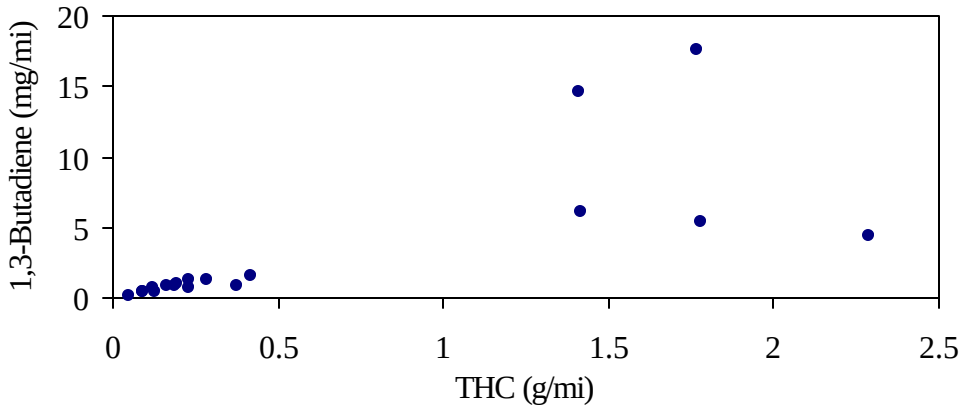


Figure 7-18 Scatter Plot of 1,3-Butadiene (mg/mi) vs. THC (g/mi) Using FTP Cycle

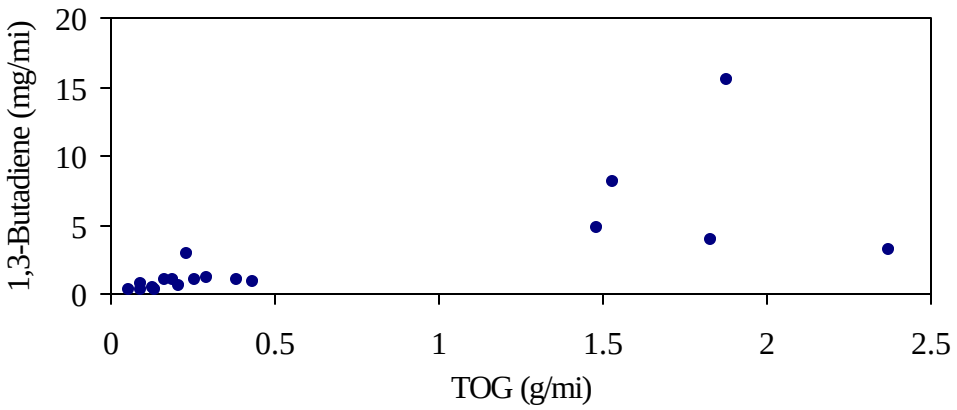


Figure 7-19 Scatter Plot of 1,3-Butadiene (mg/mi) vs. TOG (g/mi) Using UC Cycle

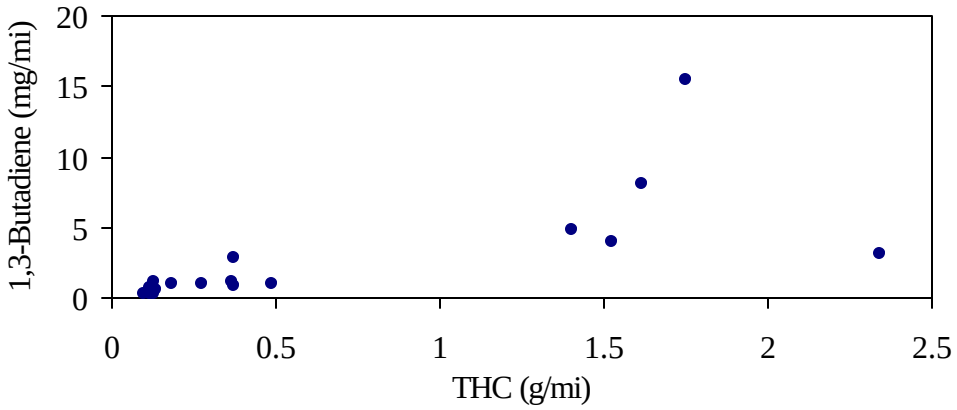
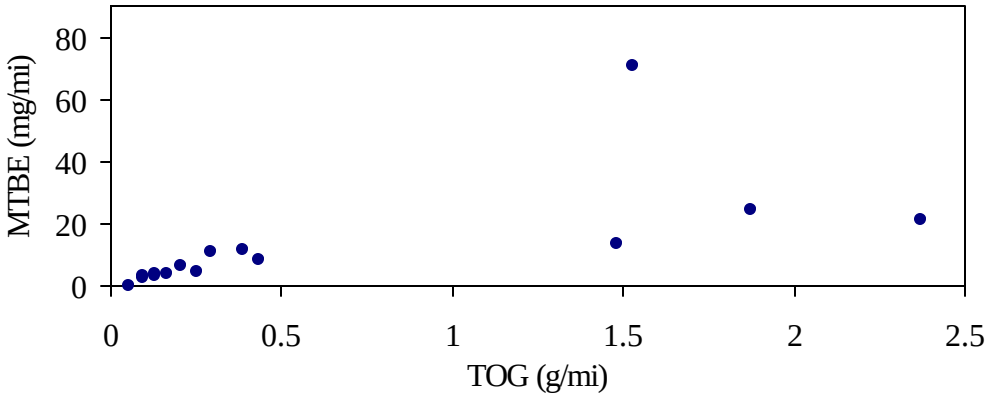


Figure 7-20 Scatter Plot of 1,3-Butadiene (mg/mi) vs. THC (g/mi) Using UC Cycle



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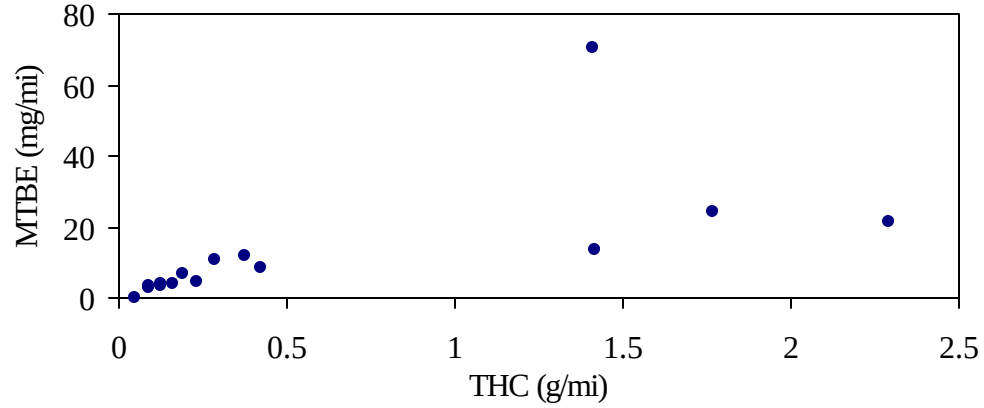

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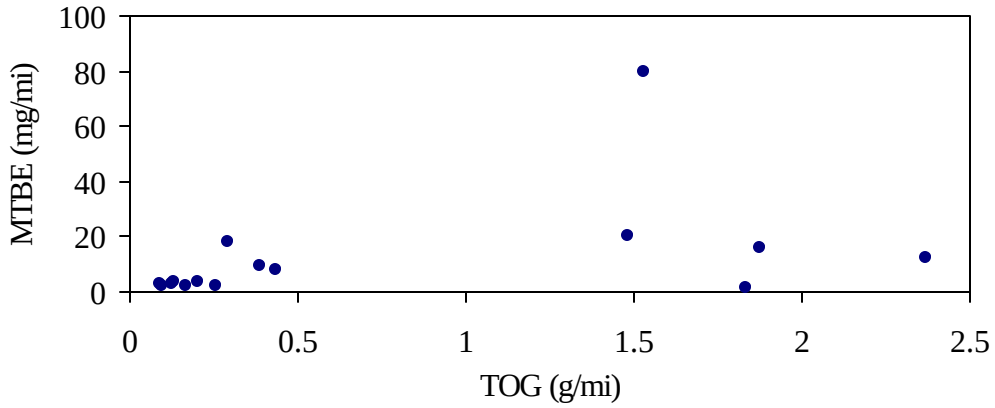

Figure 7-23 Scatter Plot of MTBE (mg/mi) vs. TOG (g/mi) Using UC Cycle

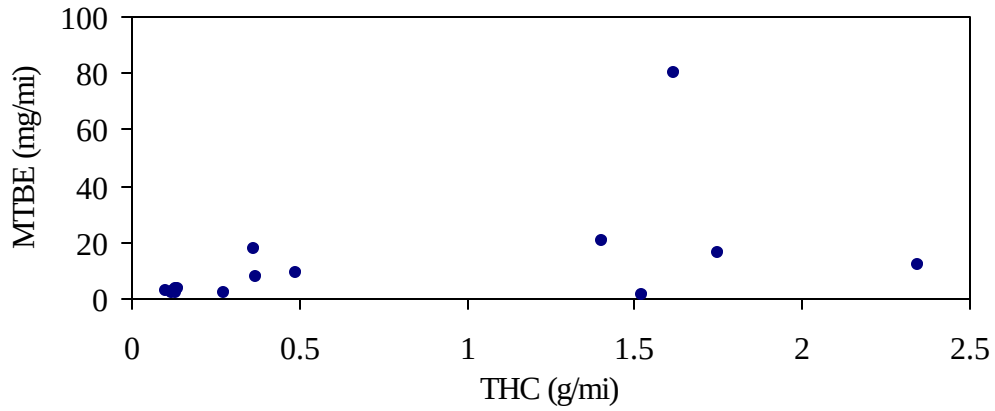

Figure 7-24 Scatter Plot of MTBE (mg/mi) vs. THC (g/mi) Using UC Cycle

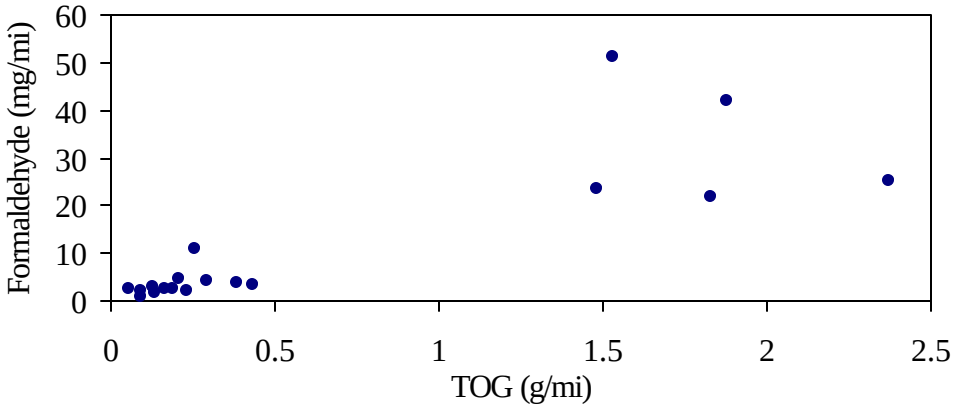

Figure 7-25 Scatter Plot of Formaldehyde (mg/mi) vs. TOG (g/mi) Using FTP Cycle

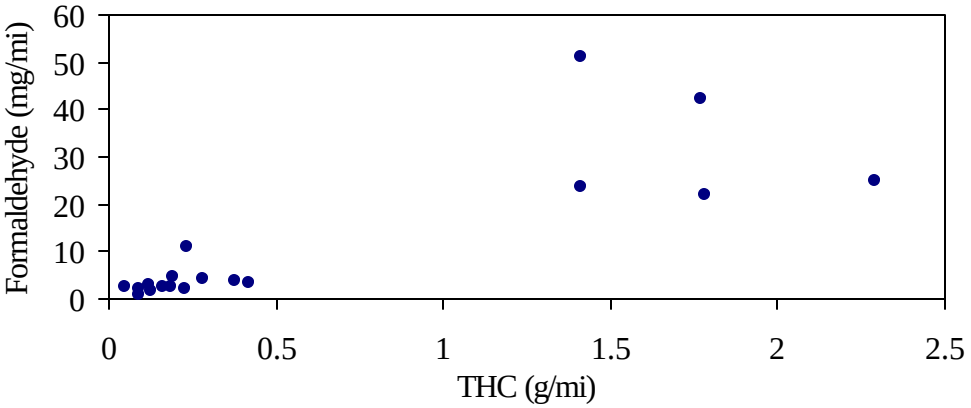

Figure 7-26 Scatter Plot of Formaldehyde (mg/mi) vs. THC (g/mi) Using FTP Cycle

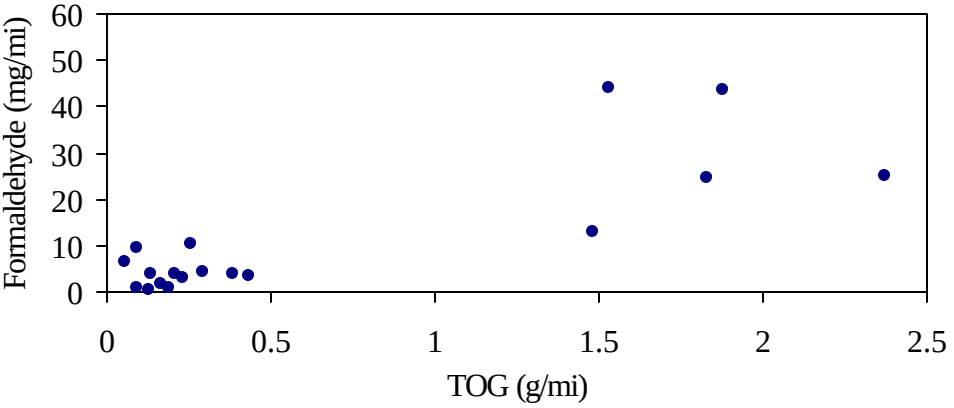

Figure 7-27 Scatter Plot of Formaldehyde (mg/mi) vs. TOG (g/mi) Using UC Cycle

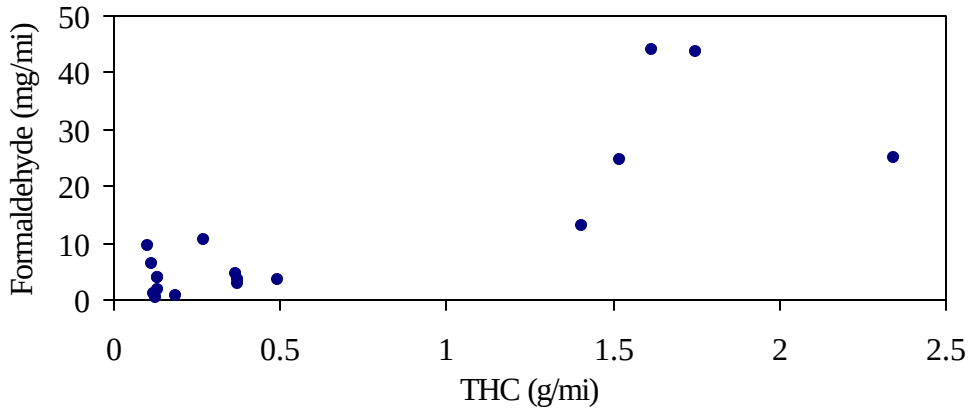

Figure 7-28 Scatter Plot of Formaldehyde (mg/mi) vs. THC (g/mi) Using UC Cycle

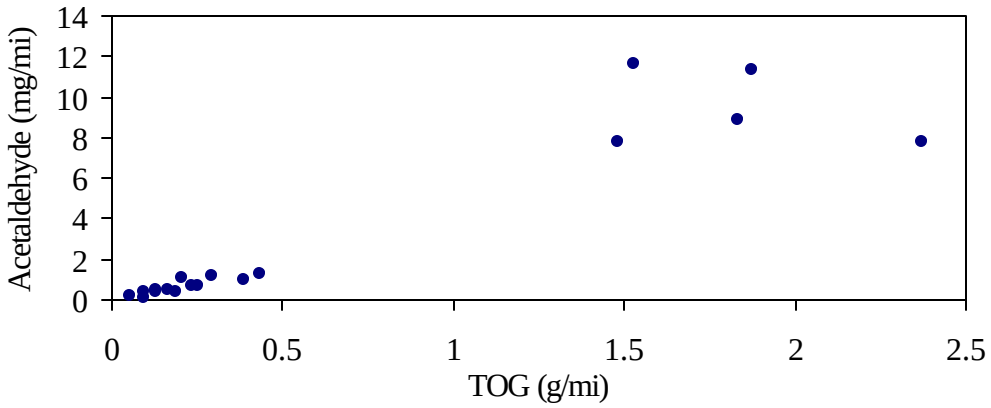

Figure 7-29 Scatter Plot of Acetaldehyde (mg/mi) vs. TOG (g/mi) Using FTP Cycle

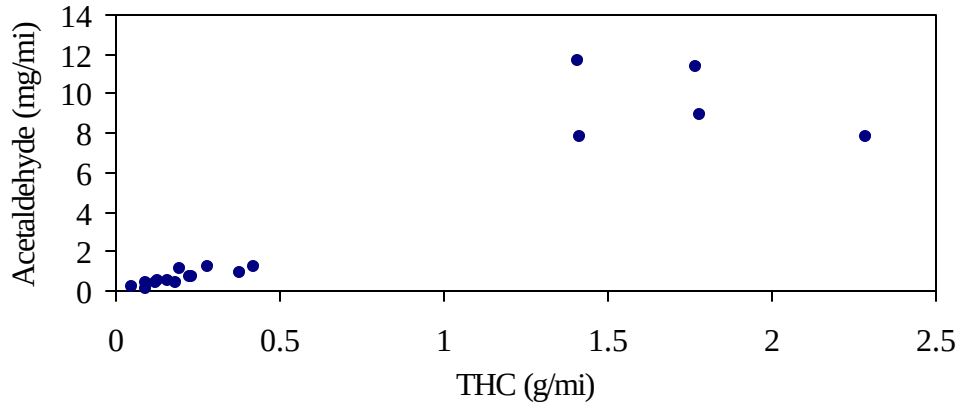

Figure 7-30 Scatter Plot of Acetaldehyde (mg/mi) vs. THC (g/mi) Using FTP Cycle

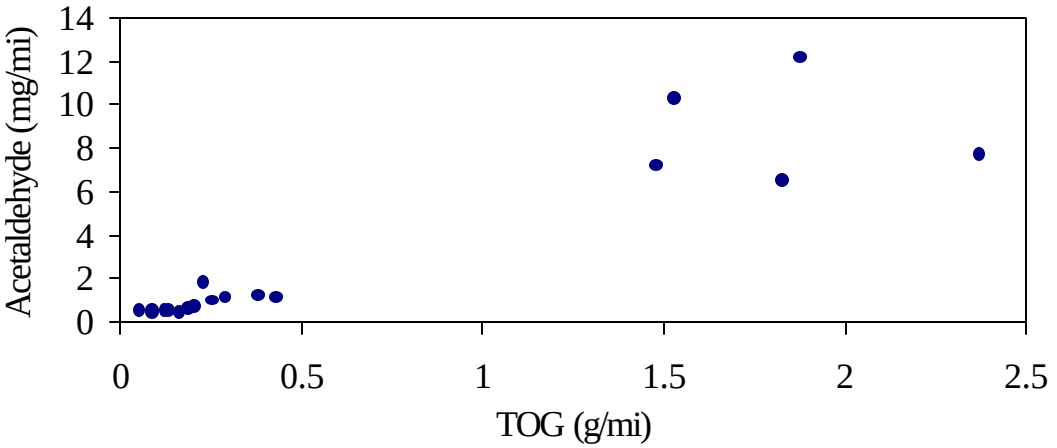

Figure 7-31 Scatter Plot of Acetaldehyde (mg/mi) vs. TOG (g/mi) Using UC Cycle

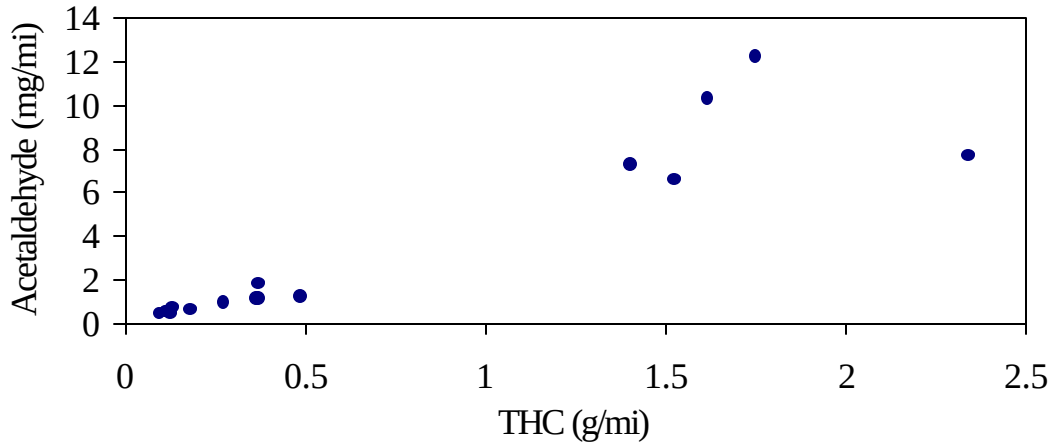

Figure 7-32 Scatter Plot of Acetaldehyde (mg/mi) vs. THC (g/mi) Using UC Cycle

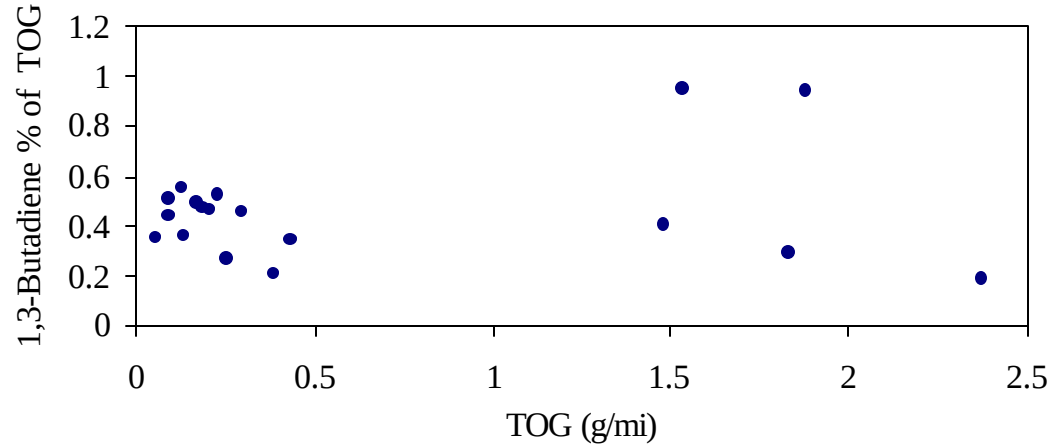

Figure 7-33. Scatter Plot of 1,3-Butadiene Concentration as Percent of TOG vs. TOG (g/mi) for FTP Cycle

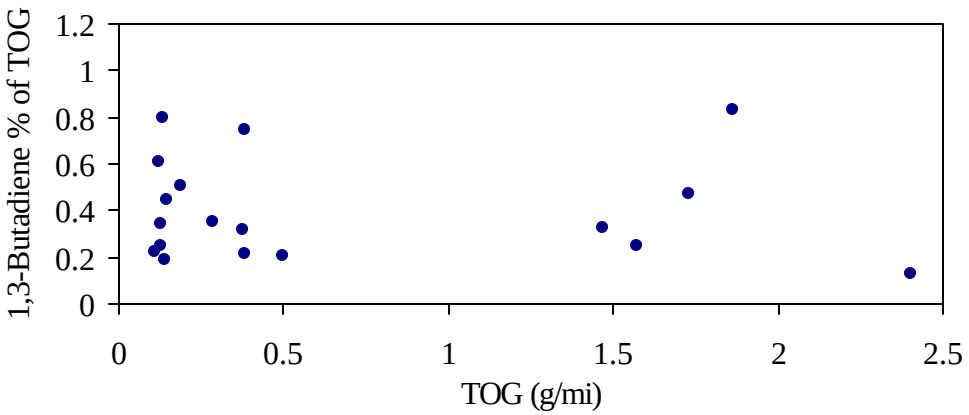

Figure 7-34. Scatter Plot of 1,3-Butadiene Concentration as Percent of TOG vs. TOG (g/mi) for the Unified Cycle.

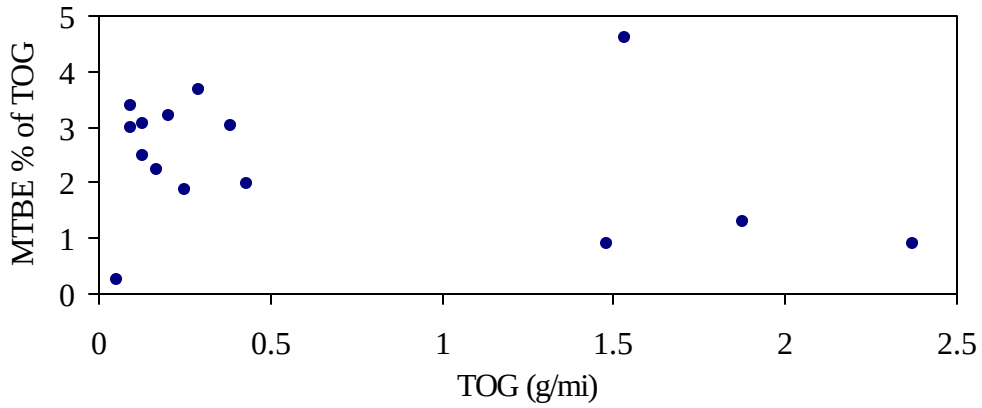

Figure 7-35. Scatter Plot of MTBE Concentration as Percent of TOG vs. TOG (g/mi) for FTP Cycle

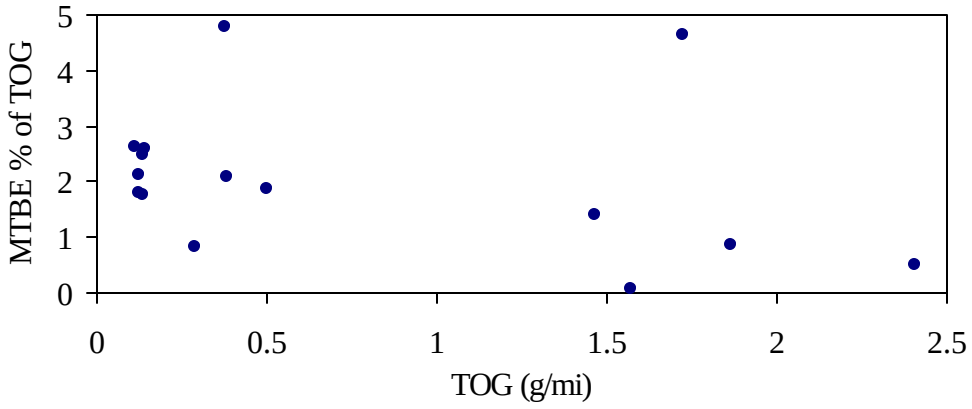

Figure 7-36. Scatter Plot of MTBE Concentration as Percent of TOG vs. TOG (g/mi) for the Unified Cycle.

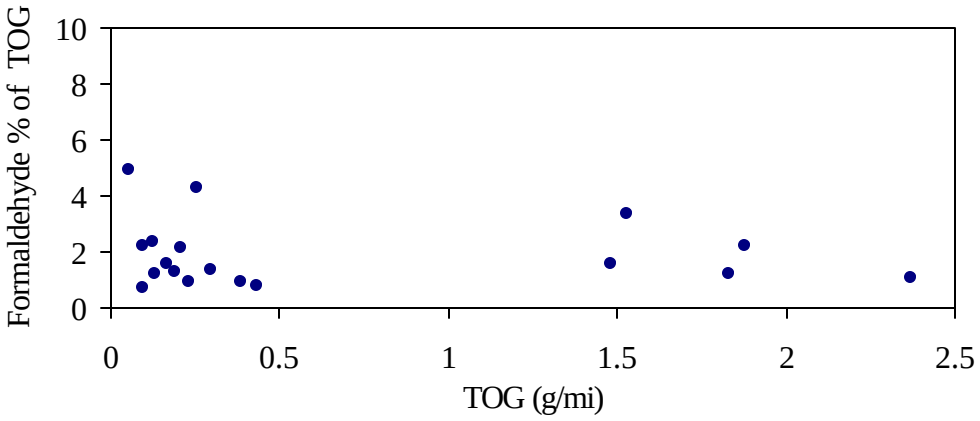

Figure 7-37. Scatter Plot of Formaldehyde Concentration as Percent of TOG vs. TOG (g/mi) for FTP Cycle

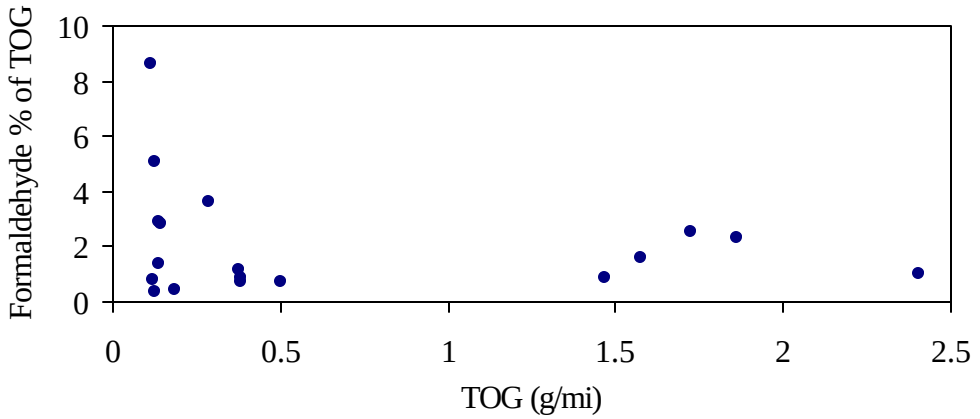

Figure 7-38. Scatter Plot of Formaldehyde Concentration as Percent of TOG vs. TOG (g/mi) for the Unified Cycle.

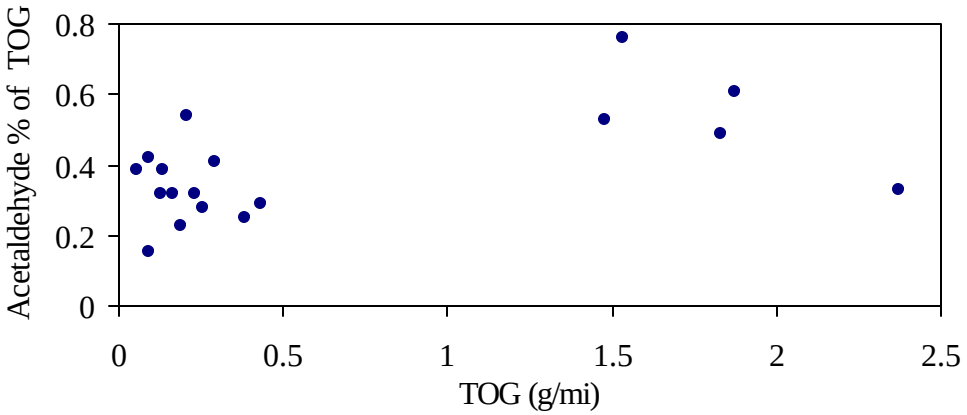

Figure 7-39. Scatter Plot of Acetaldehyde Concentration as Percent of TOG vs. TOG (g/mi) for FTP Cycle

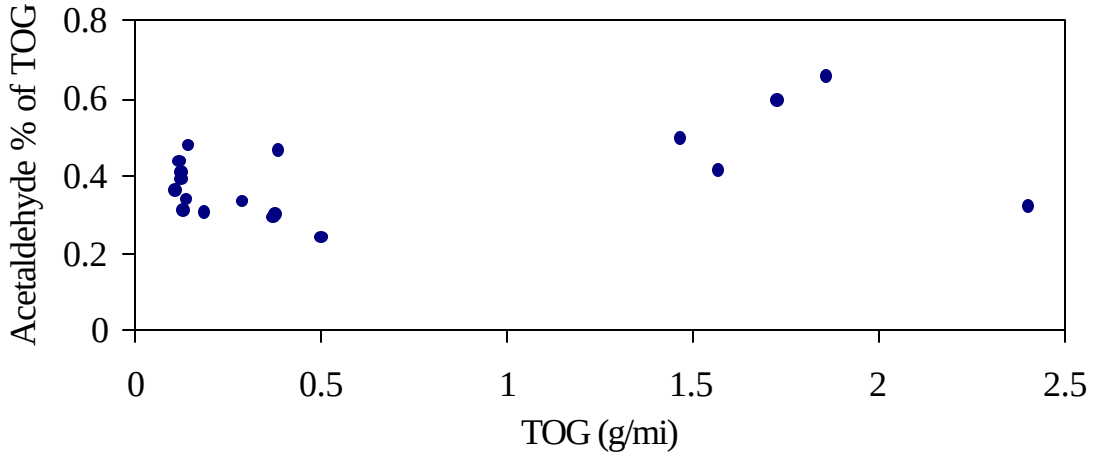

Figure 7-40. Scatter Plot of Acetaldehyde Concentration as Percent of TOG vs. TOG (g/mi) for the Unified Cycle.

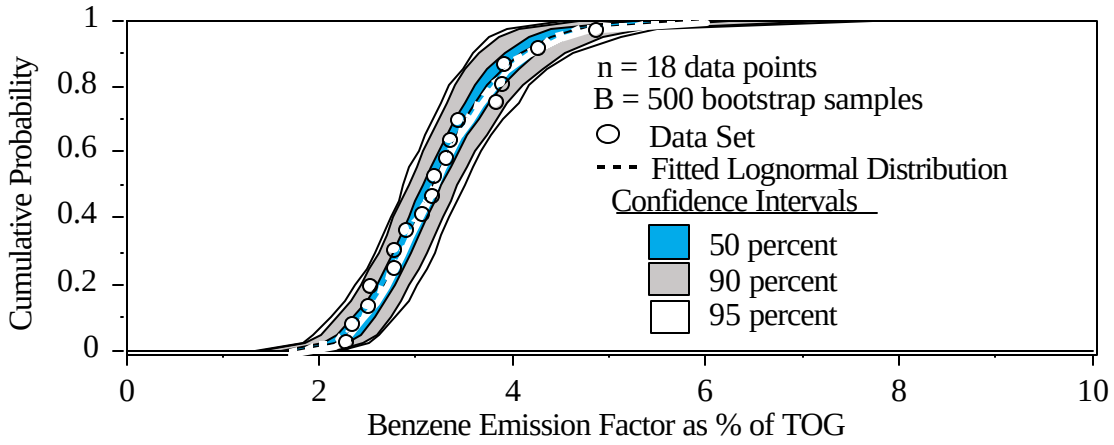

Figure 7-41 Bootstrap Simulation Results for Benzene Emissions as % of TOG for Both Normal and High Emitters.

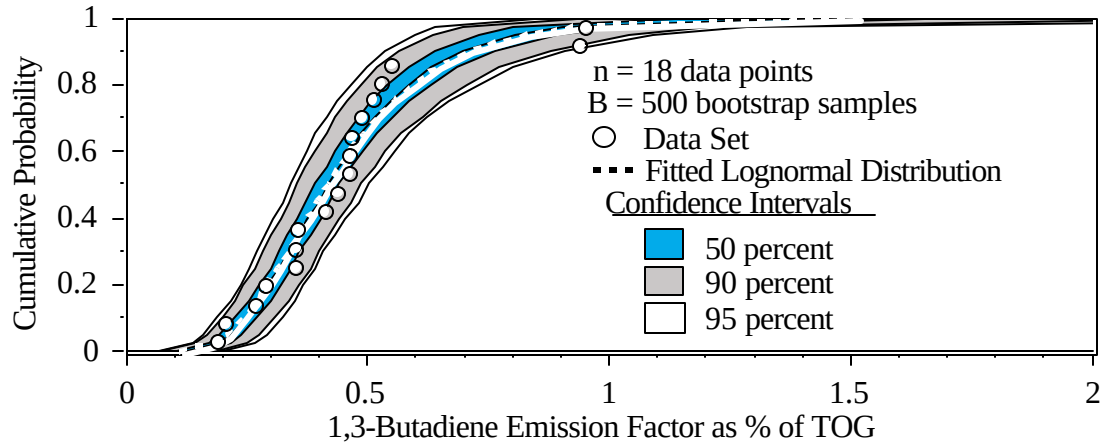

Figure 7-42 Bootstrap Simulation Results for 1,3-Butadiene Emissions as % of TOG for Both Normal and High Emitters.

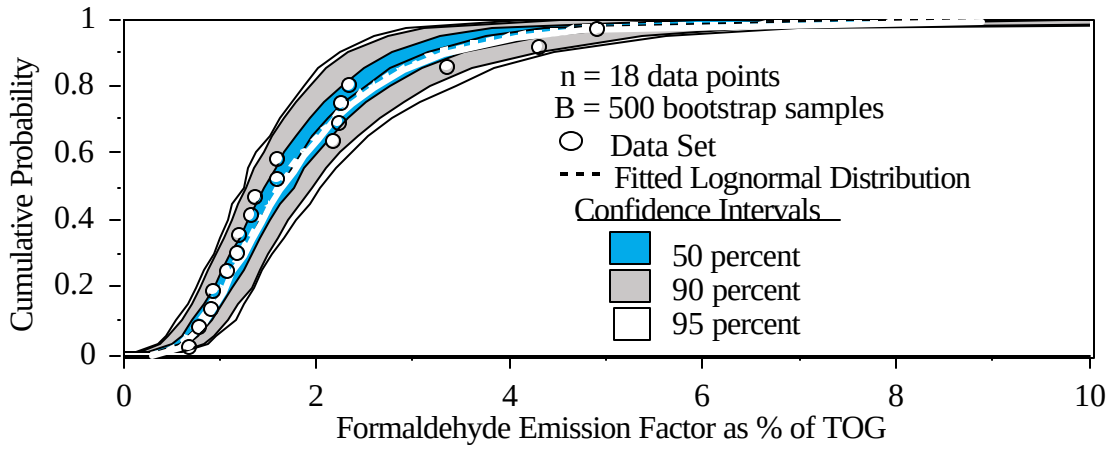

Figure 7-43 Bootstrap Simulation Results for Formaldehyde Emissions as % of TOG for Both Normal and High Emitters.

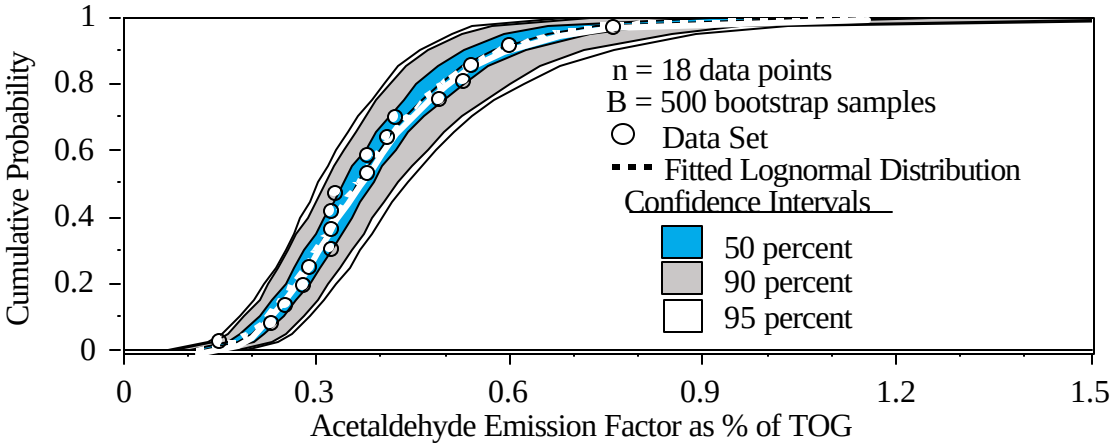

Figure 7-44 Bootstrap Simulation Results for Acetaldehyde Emissions as % of TOG for Both Normal and High Emitters.

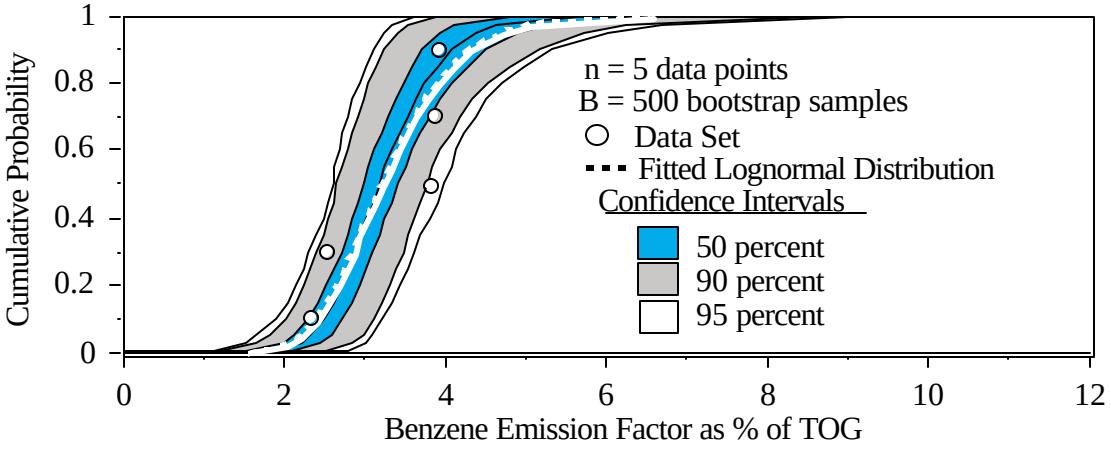

Figure 7-45 Bootstrap Simulation Results for Benzene Emissions as % of TOG for High Emitters Only.

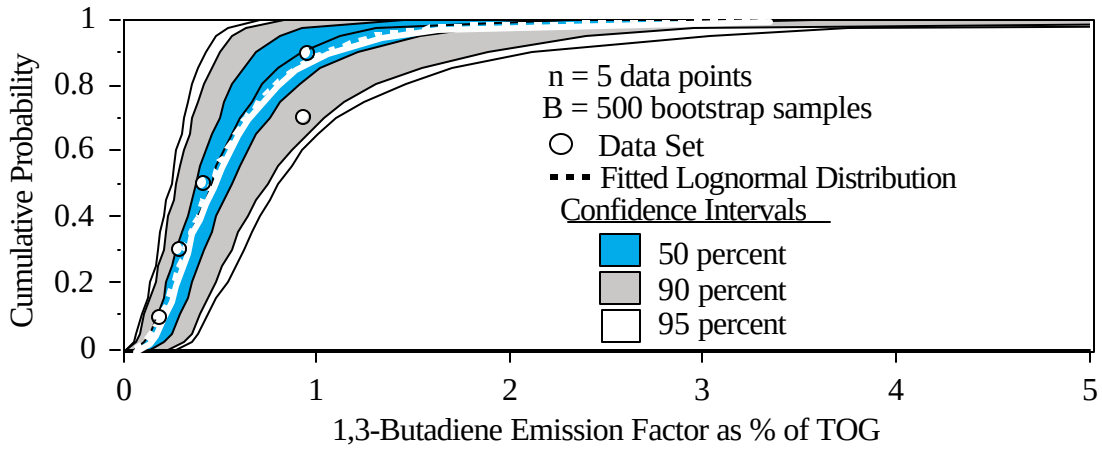

Figure 7-46 Bootstrap Simulation Results for 1,3-Butadiene Emissions as % of TOG for High Emitters Only.

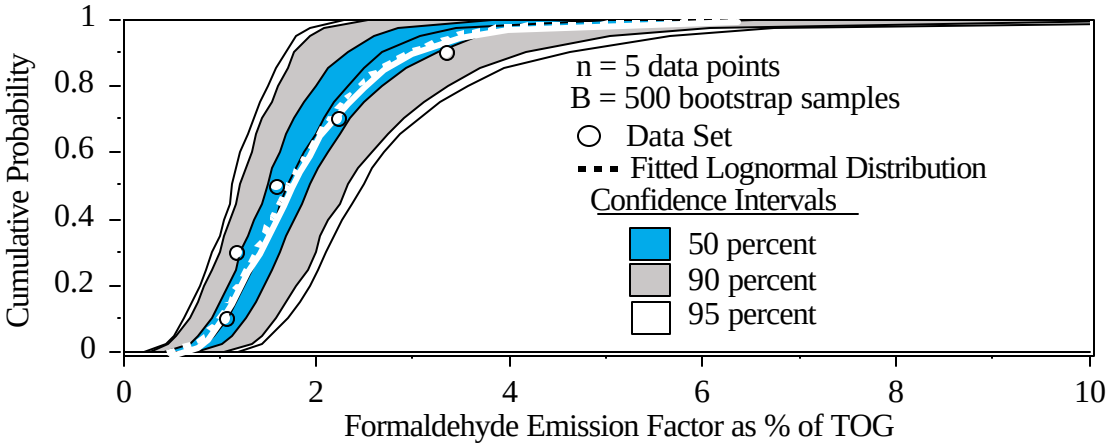

Figure 7-47 Bootstrap Simulation Results for Formaldehyde Emissions as % of TOG for High Emitters Only.

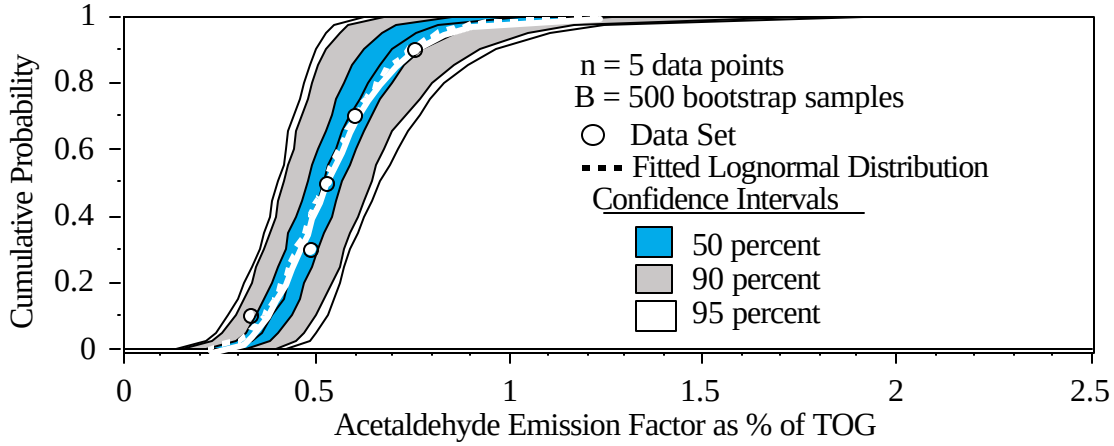

Figure 7-48 Bootstrap Simulation Results for Acetaldehyde Emissions as % of TOG for High Emitters Only.

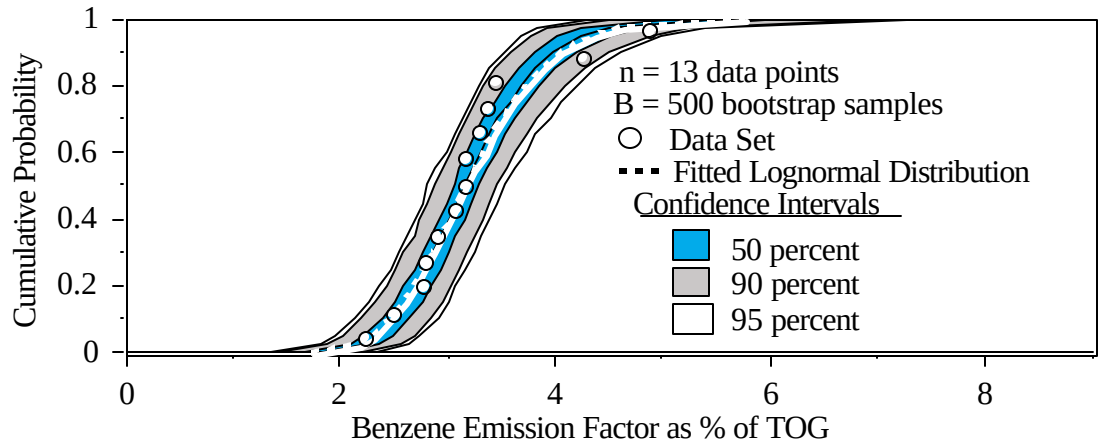

Figure 7-49 Bootstrap Simulation Results for Benzene Emissions as % of TOG for Low Emitters Only.

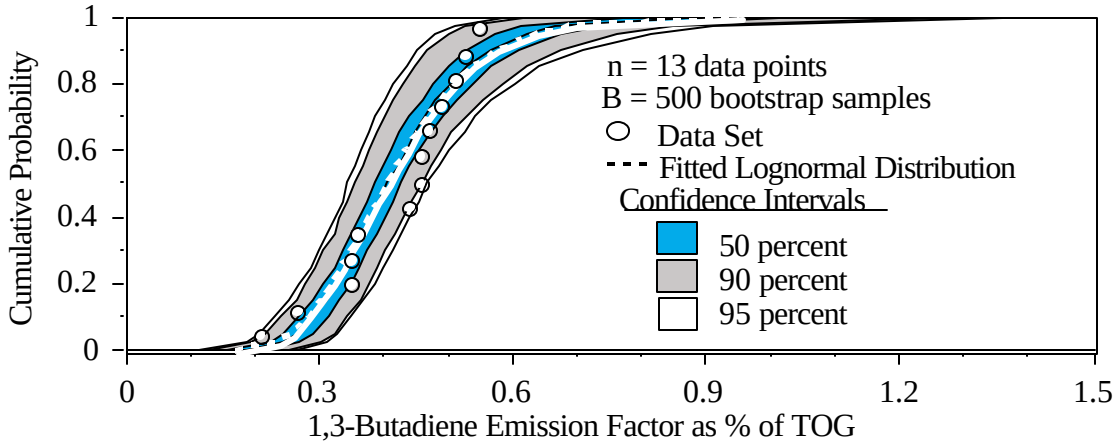

Figure 7-50 Bootstrap Simulation Results for 1,3-Butadiene Emissions as % of TOG for Low Emitters Only.

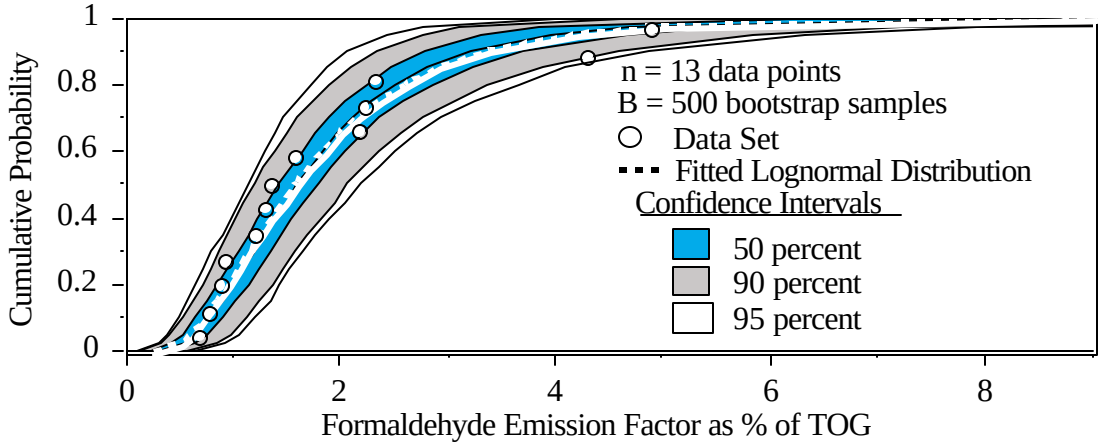

Figure 7-51. Bootstrap Simulation Results for Formaldehyde Emissions as % of TOG for Low Emitters Only.

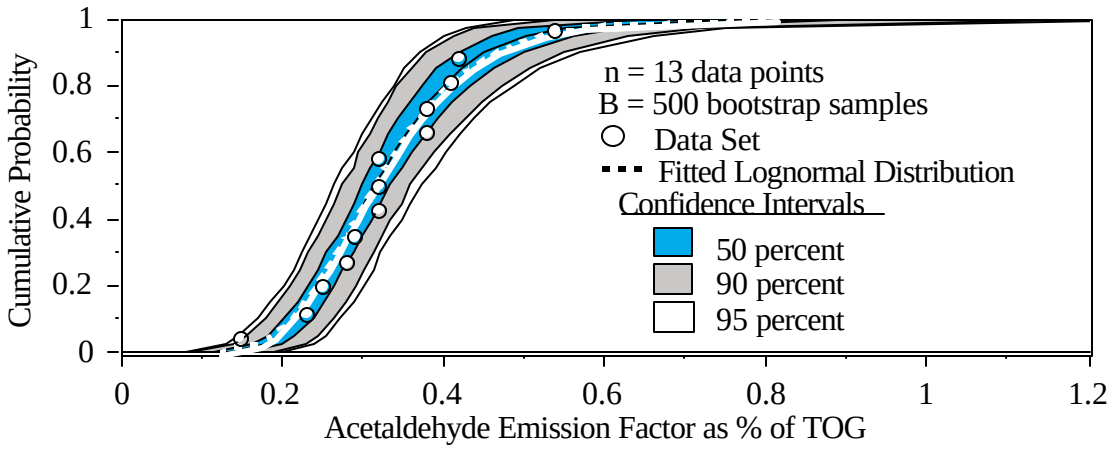

Figure 7-52 Bootstrap Simulation Results for Acetaldehyde Emissions as % of TOG for Low Emitters Only.

8.0 APPENDIX B: ADDITIONAL FIGURES FOR CHAPTER 3

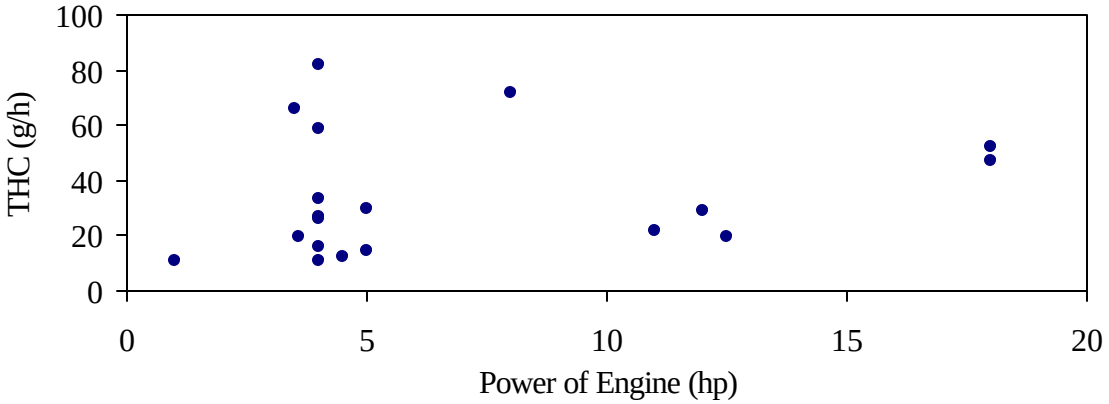

Figure 8-1. Scatter Plot of THC (g/h) Emission Factors for 4-Stroke L&G Engines Versus the Size of the Engine (Rated Horsepower)

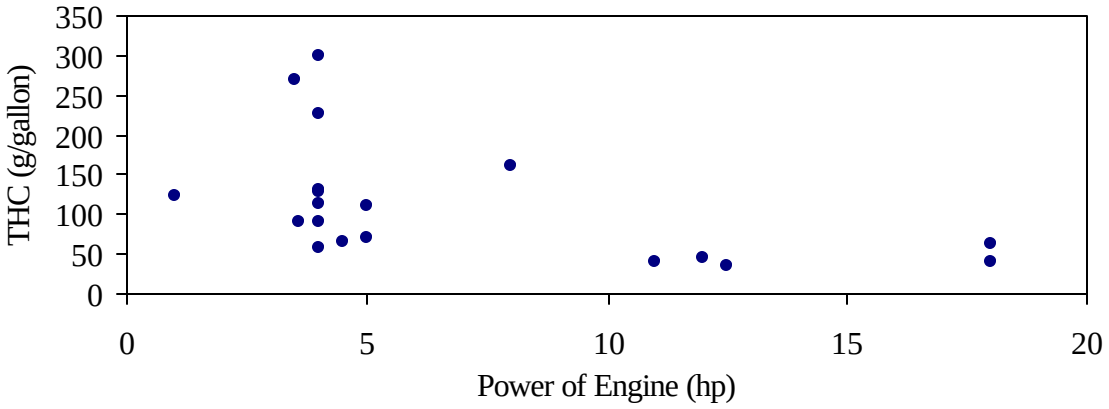

Figure 8-2. Scatter Plot of THC (g/gallon) Emission Factors for 4-Stroke L&G Engines Versus the Size of the Engine (Rated Horsepower)

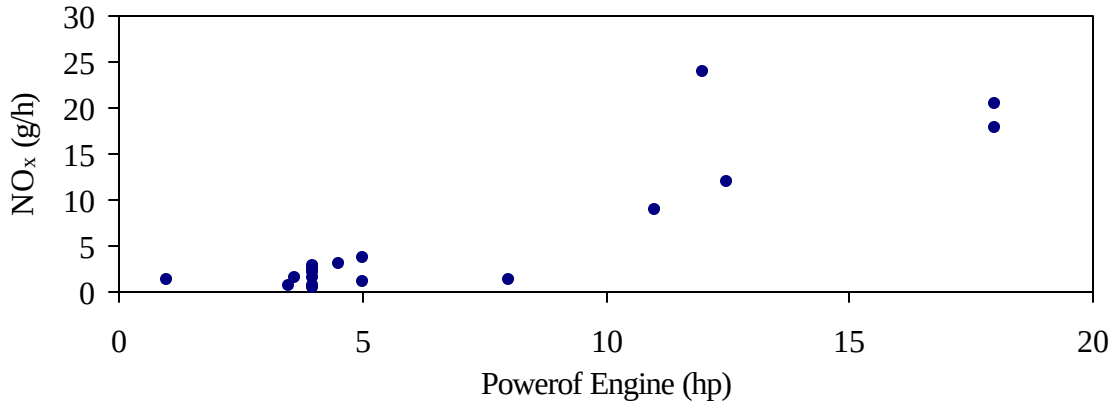

Figure 8-3. Scatter Plot of NO_x (g/h) Emission Factors for 4-Stroke L&G Engines Versus the Size of the Engine (Rated Horsepower)

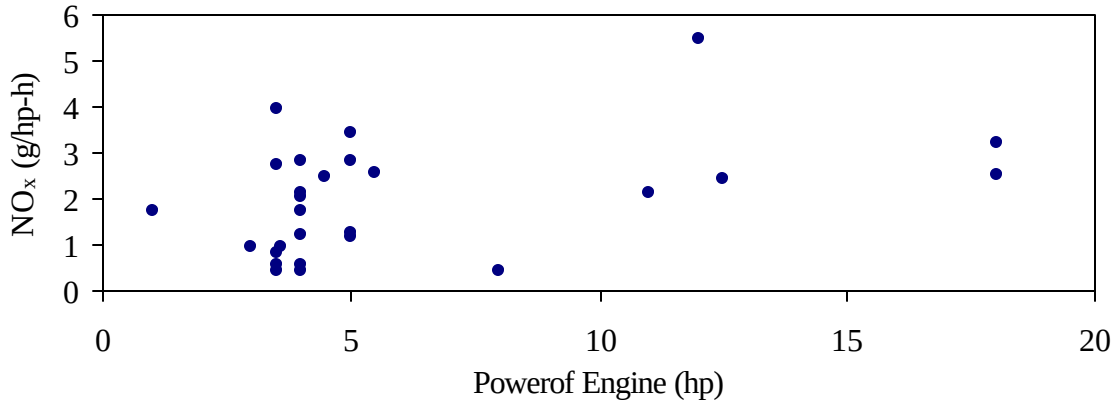

Figure 8-4. Scatter Plot of NO_x (g/hp-h) Emission Factors for 4-Stroke L&G Engines Versus the Size of the Engine (Rated Horsepower)

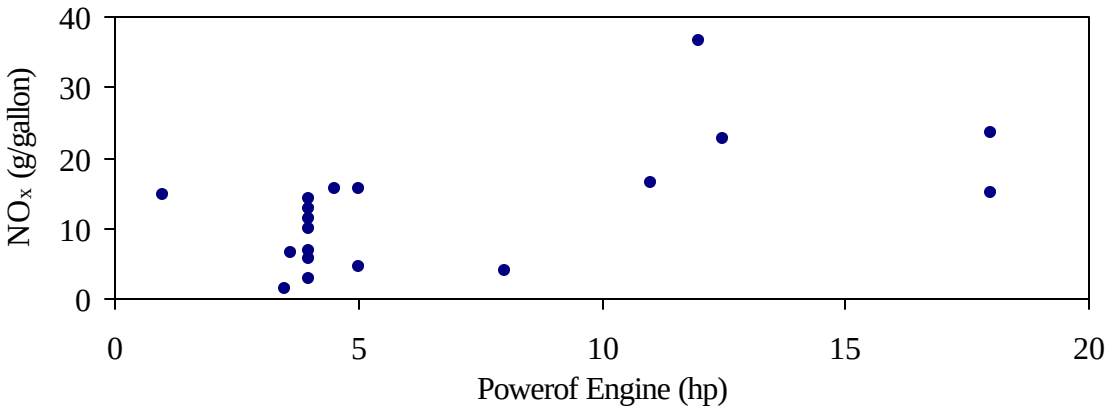

Figure 8-5. Scatter Plot of NO_x (g/gallon) Emission Factors for 4-Stroke L&G Engines Versus the Size of the Engine (Rated Horsepower)

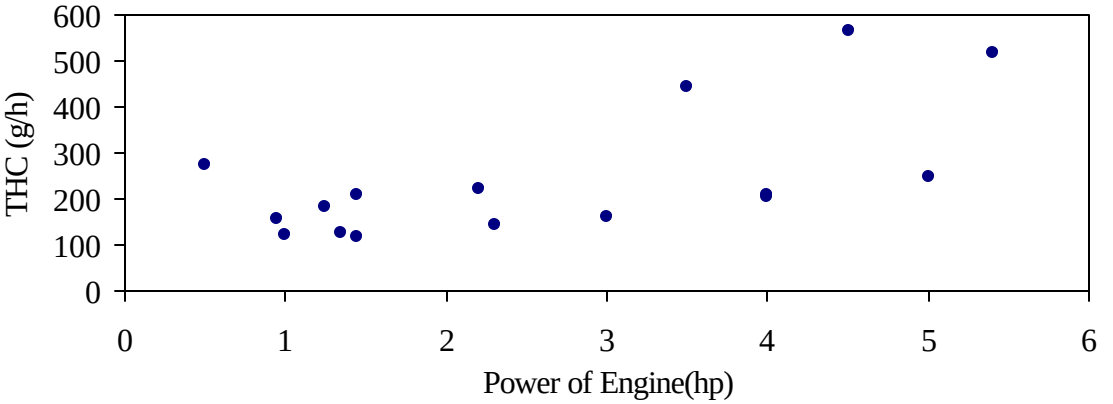

Figure 8-6. Scatter Plot of THC (g/h) Emission Factors for 2-Stroke L&G Engines Versus the Size of the Engine (Rated Horsepower).

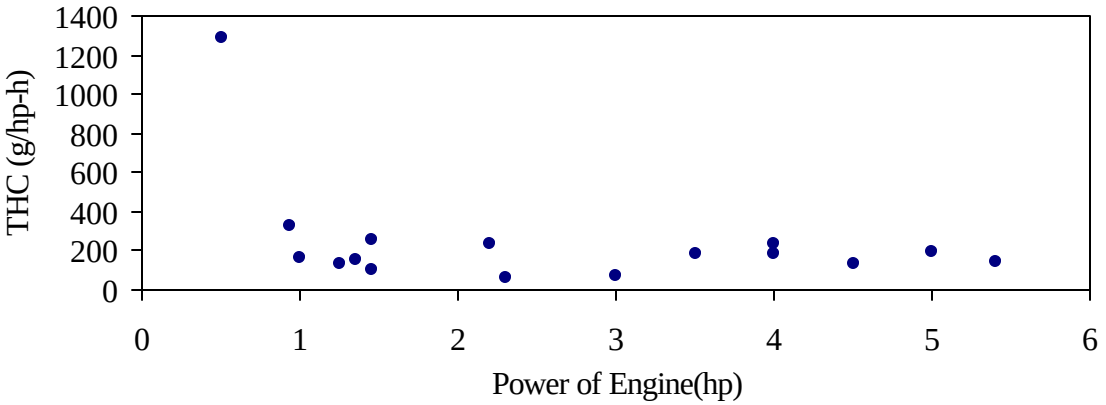

Figure 8-7. Scatter Plot of THC (g/hp-h) Emission Factors for 2-Stroke L&G Engines Versus the Size of the Engine (Rated Horsepower).

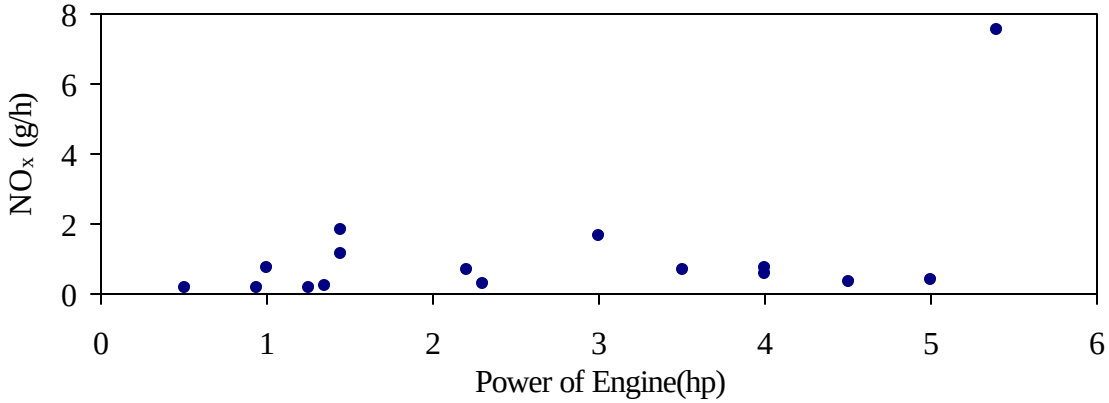

Figure 8-8. Scatter Plot of NO_x (g/h) Emission Factors for 2-Stroke L&G Engines Versus the Size of the Engine (Rated Horsepower).

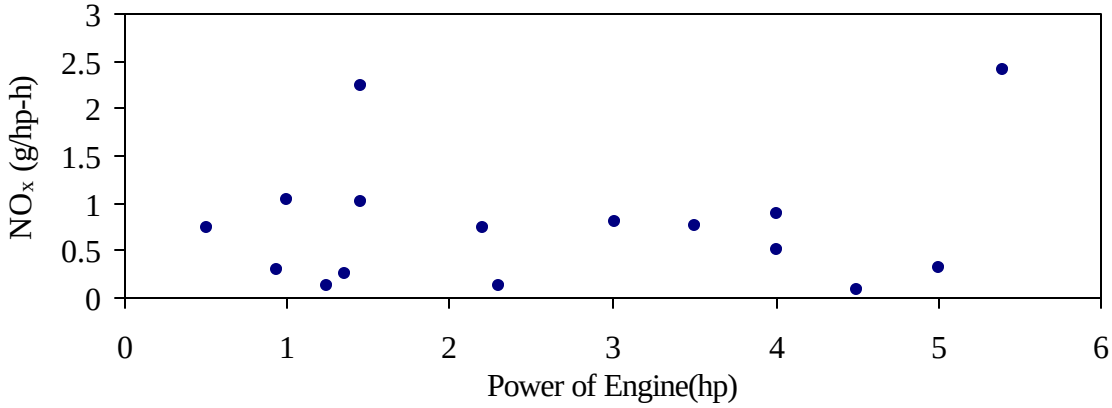

Figure 8-9. Scatter Plot of NO_x (g/hp-h) Emission Factors for 2-Stroke L&G Engines Versus the Size of the Engine (Rated Horsepower).

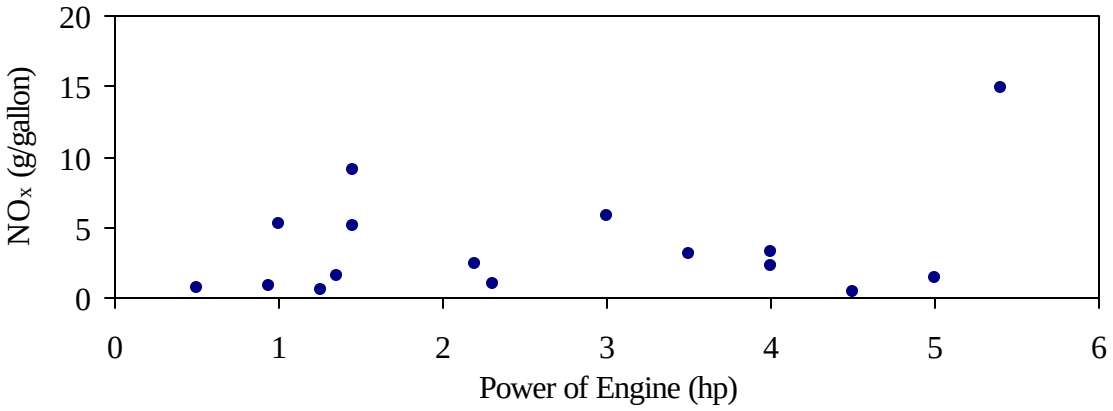

Figure 8-10. Scatter Plot of NO_x (g/gallon) Emission Factors for 2-Stroke L&G Engines Versus the Size of the Engine (Rated Horsepower).

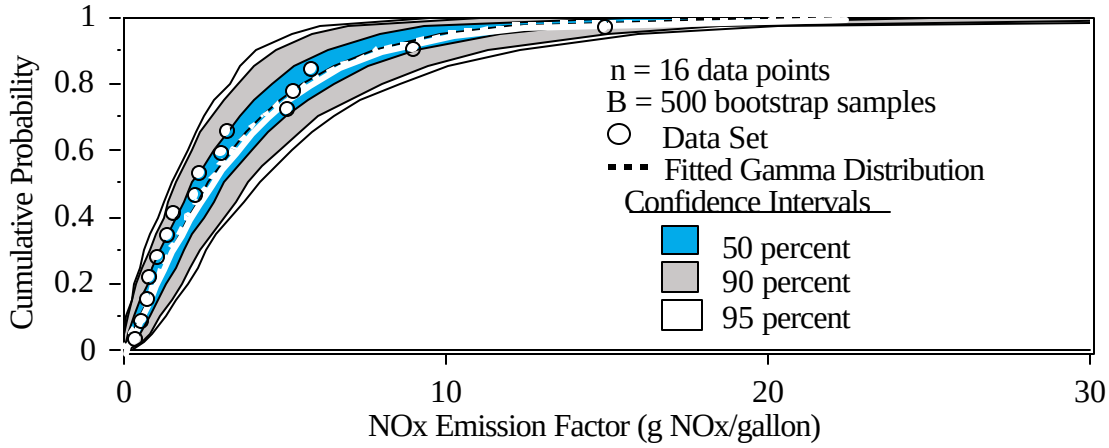

Figure 8-11. Bootstrap Simulation Results for 2-stroke L&G Gasoline Engine NO_x Emission Data in Units of g/gallon.

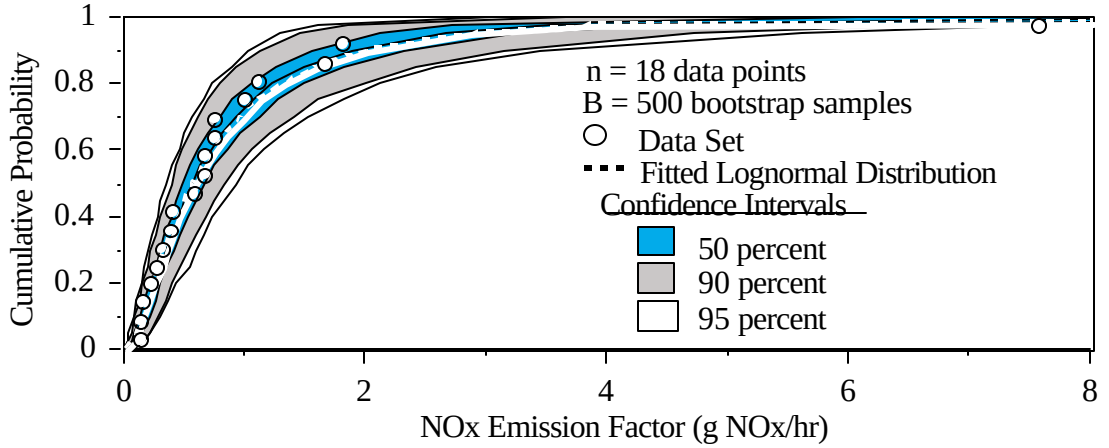

Figure 8-12. Bootstrap Simulation Results for 2-stroke L&G Gasoline Engine NO_x Emission Data in Units of g/hr.

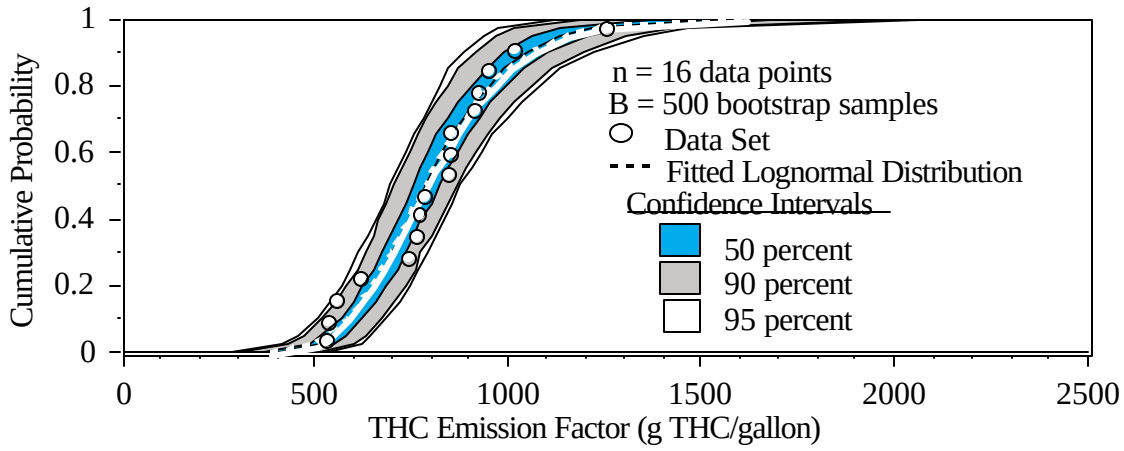

Figure 8-13. Bootstrap Simulation Results for 2-stroke L&G Gasoline Engine THC Emission Data in Units of g/gal.

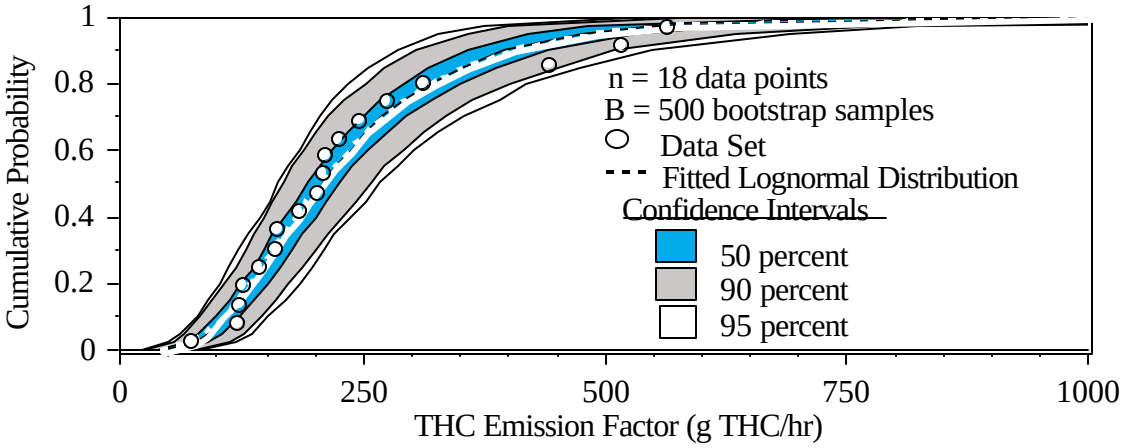

Figure 8-14. Bootstrap Simulation Results for 2-stroke L&G Gasoline Engine THC Emission Data in Units of g/hr.

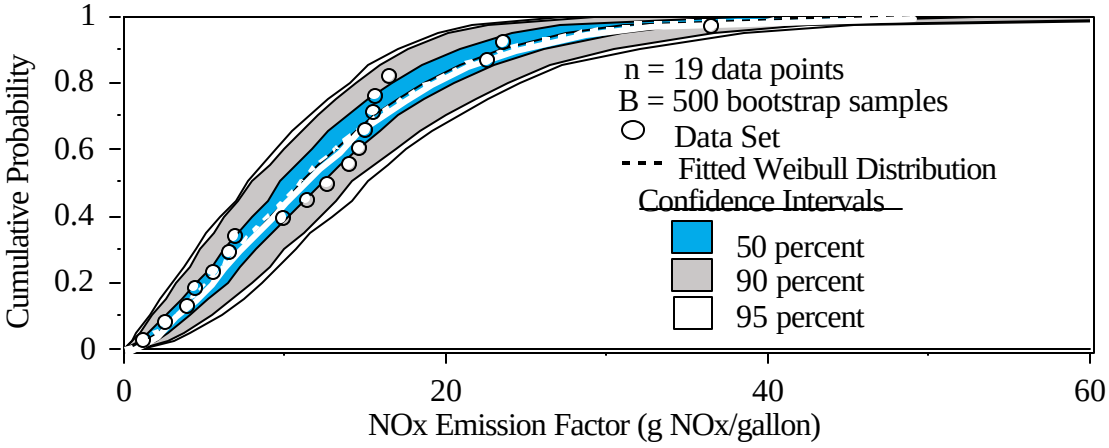

Figure 8-15. Bootstrap Simulation Results for 4-stroke L&G Gasoline Engine NO_x Emission Data in Units of g/gal.

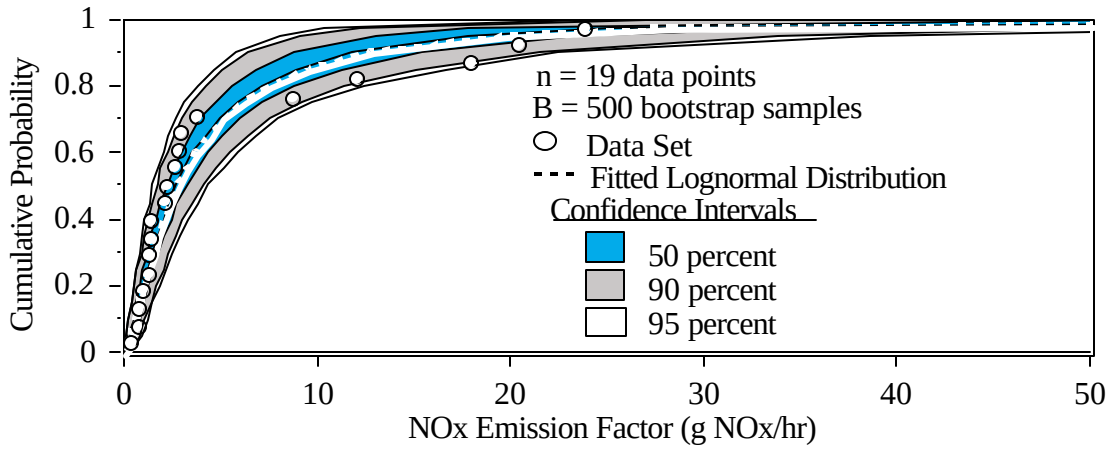

Figure 8-16. Bootstrap Simulation Results for 4-stroke L&G Gasoline Engine NO_x Emission Data in Units of g/hr.

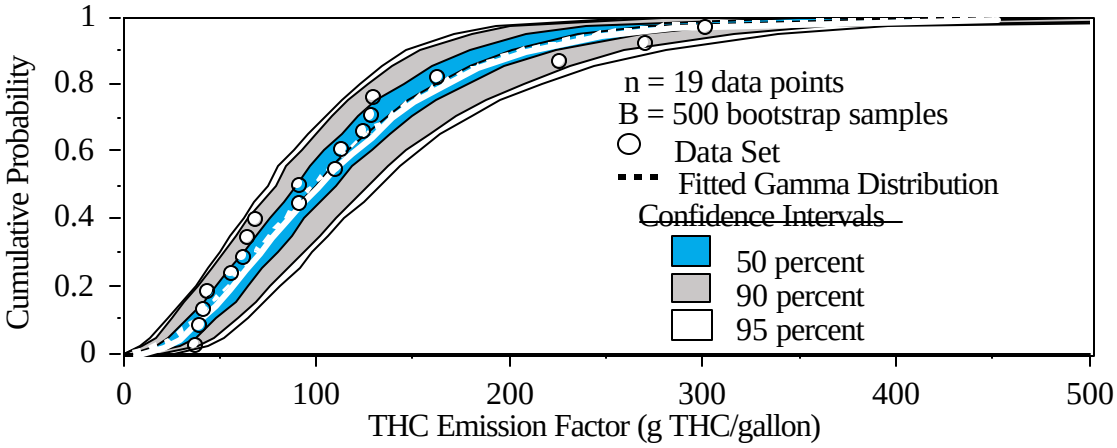

Figure 8-17. Bootstrap Simulation Results for 4-stroke L&G Gasoline Engine THC Emission Data in Units of g/gal.

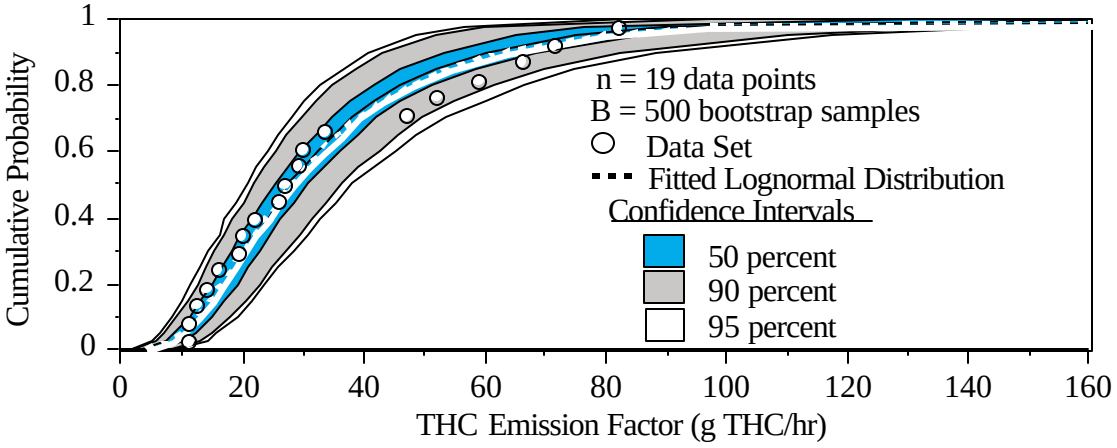

Figure 8-18. Bootstrap Simulation Results for 4-stroke L&G Gasoline Engine THC Emission Data in Units of g/hr.

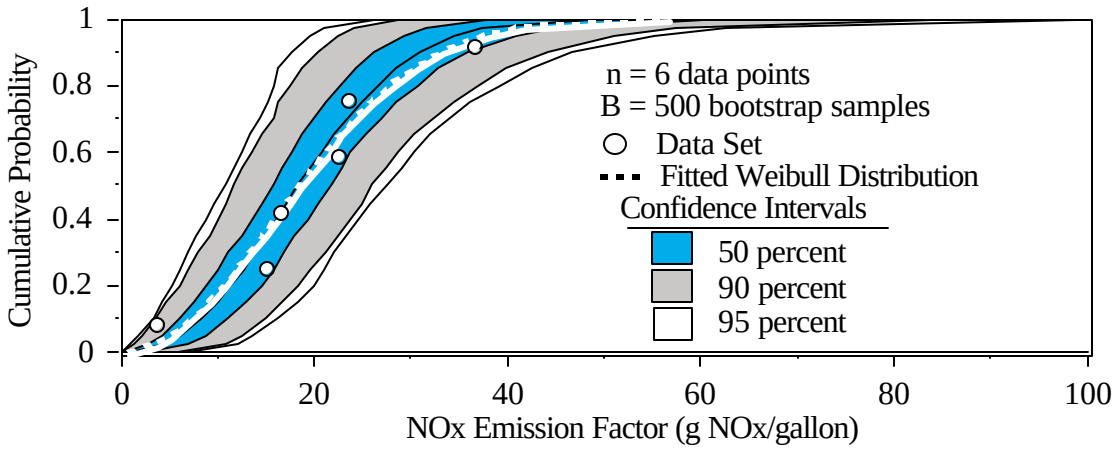

Figure 8-19. Bootstrap Simulation Results for 4-stroke L&G Gasoline Engine NO_x Emission Data in Units of g/gal (Size ≥ 8 hp).

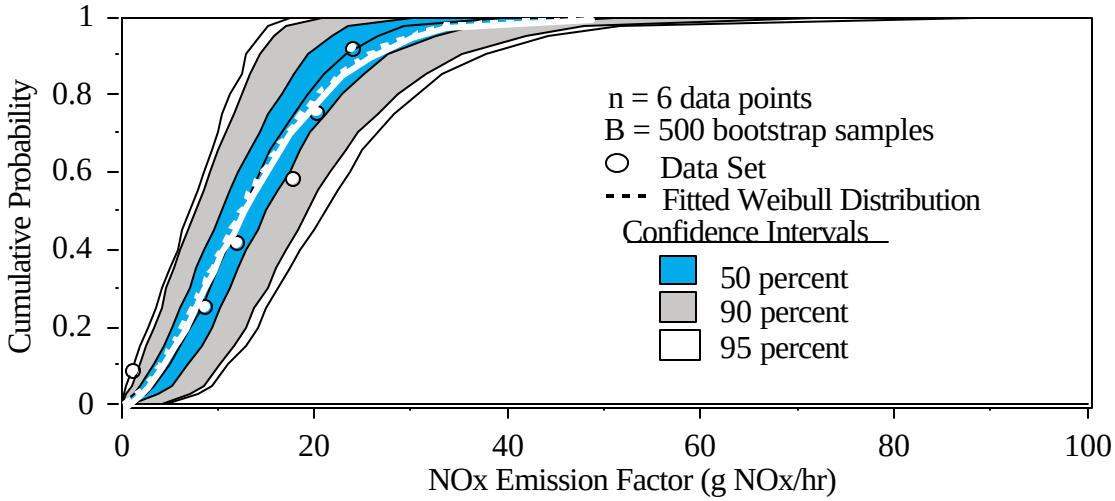

Figure 8-20. Bootstrap Simulation Results for 4-stroke L&G Gasoline Engine NO_x Emission Data in Units of g/hr (Size ≥ 8 hp).

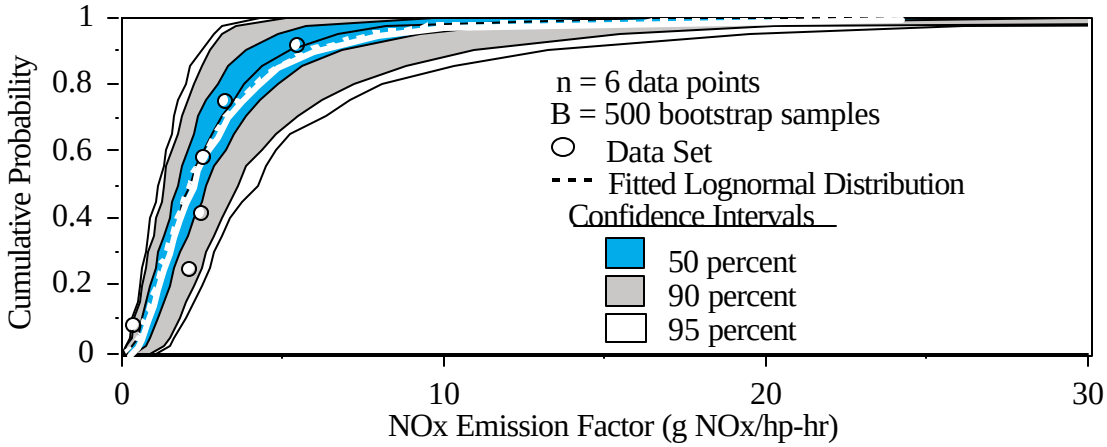

Figure 8-21. Bootstrap Simulation Results for 4-stroke L&G Gasoline Engine NO_x Emission Data in Units of g/hp-hr (Size ≥ 8 hp).

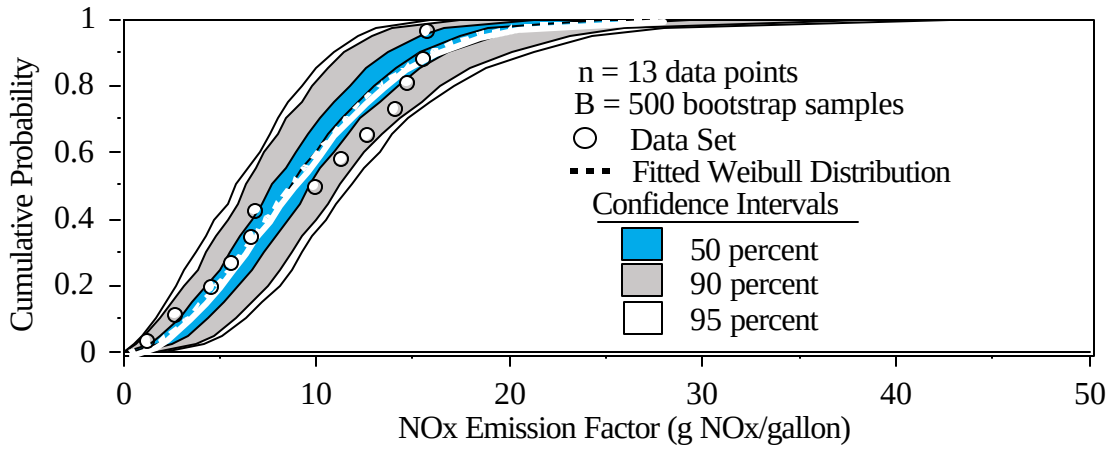

Figure 8-22. Bootstrap Simulation Results for 4-stroke L&G Gasoline Engine NO_x Emission Data in Units of g/gal (Size < 8 hp).

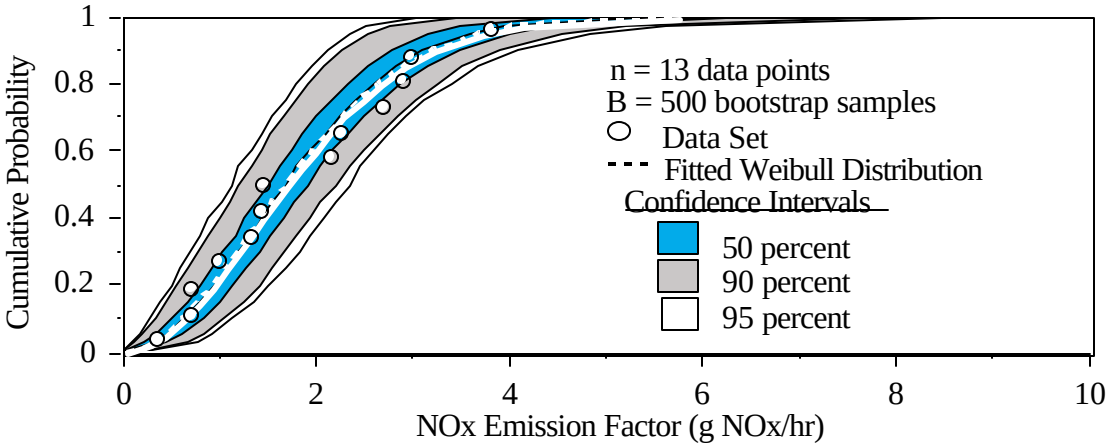

Figure 8-23. Bootstrap Simulation Results for 4-stroke L&G Gasoline Engine NO_x Emission Data in Units of g/hr (Size < 8 hp).

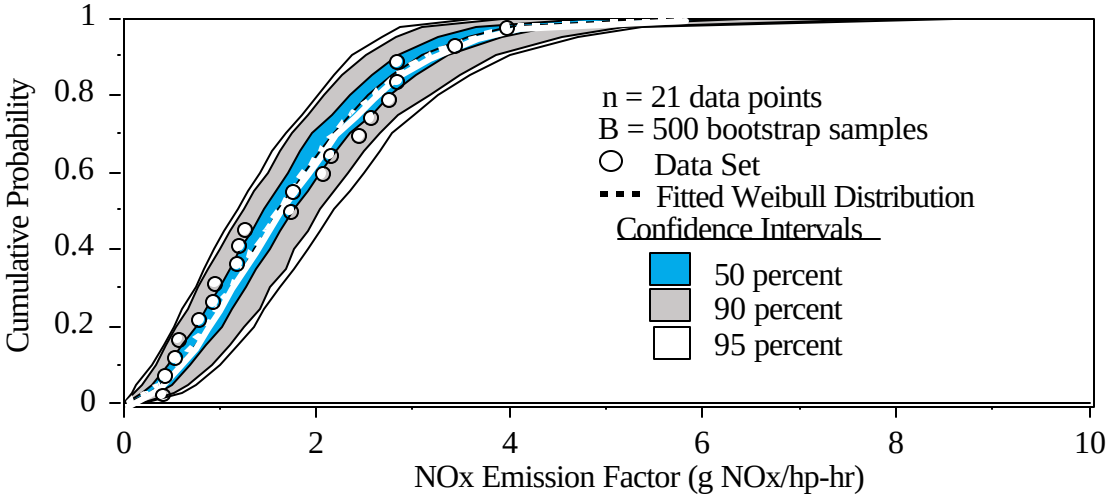

Figure 8-24. Bootstrap Simulation Results for 4-stroke L&G Gasoline Engine NO_x Emission Data in Units of g/hp-hr (Size < 8 hp).

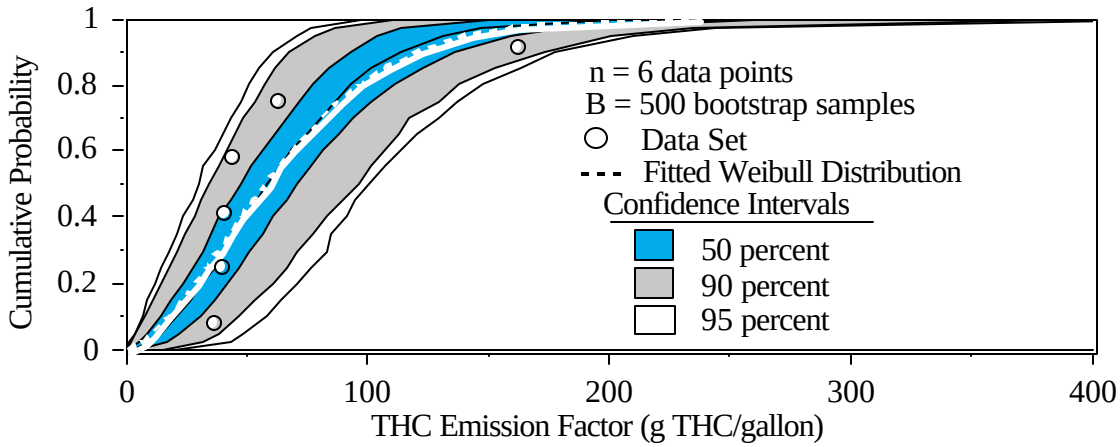

Figure 8-25. Bootstrap Simulation Results for 4-stroke L&G Gasoline Engine THC Emission Data in Units of g/gal (Size ≥ 8 hp).

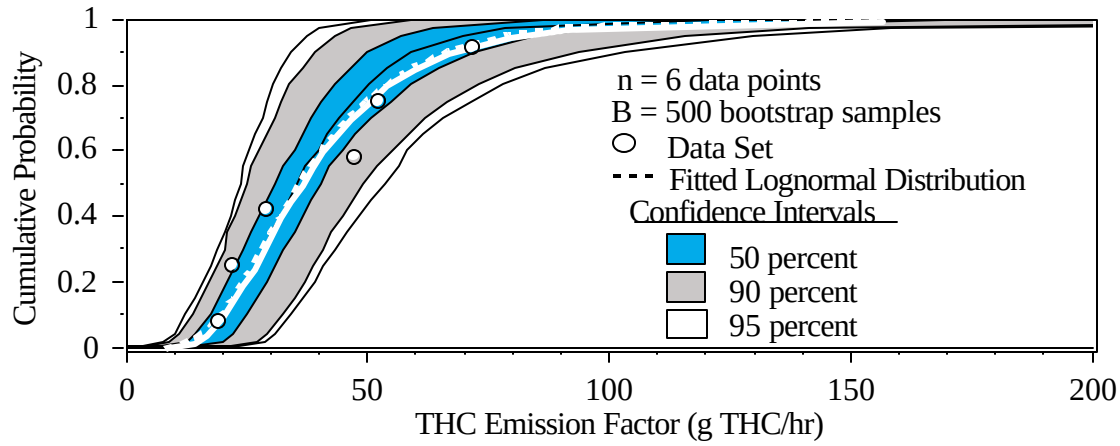

Figure 8-26. Bootstrap Simulation Results for 4-stroke L&G Gasoline Engine THC Emission Data in Units of g/hr (Size ≥ 8 hp).

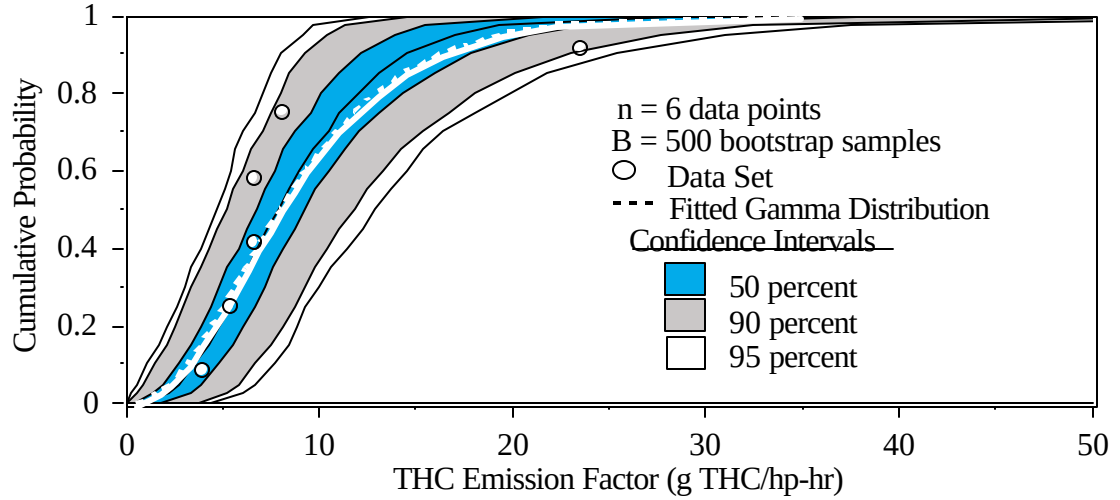

Figure 8-27. Bootstrap Simulation Results for 4-stroke L&G Gasoline Engine THC Emission Data in Units of g/hp-hr (Size ≥ 8 hp).

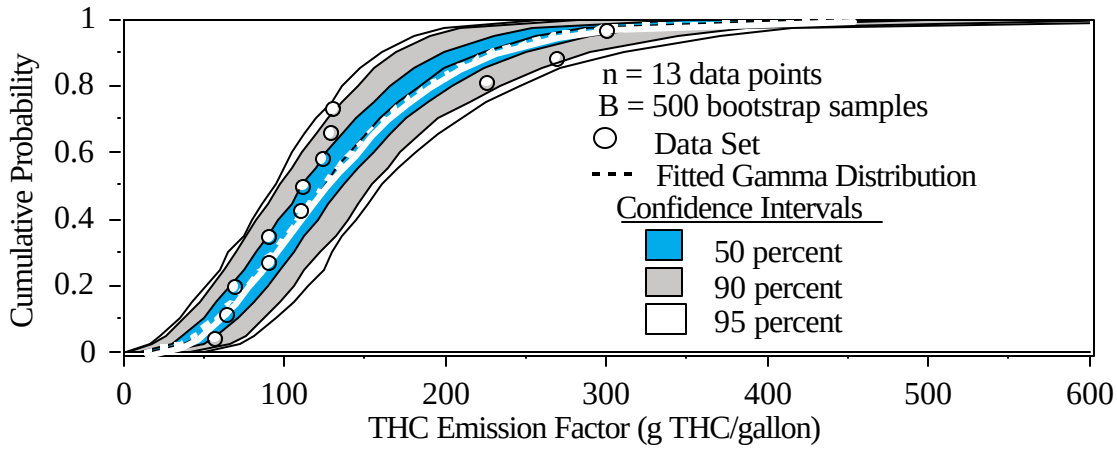

Figure 8-28. Bootstrap Simulation Results for 4-stroke L&G Gasoline Engine THC Emission Data in Units of g/gal (Size < 8 hp).

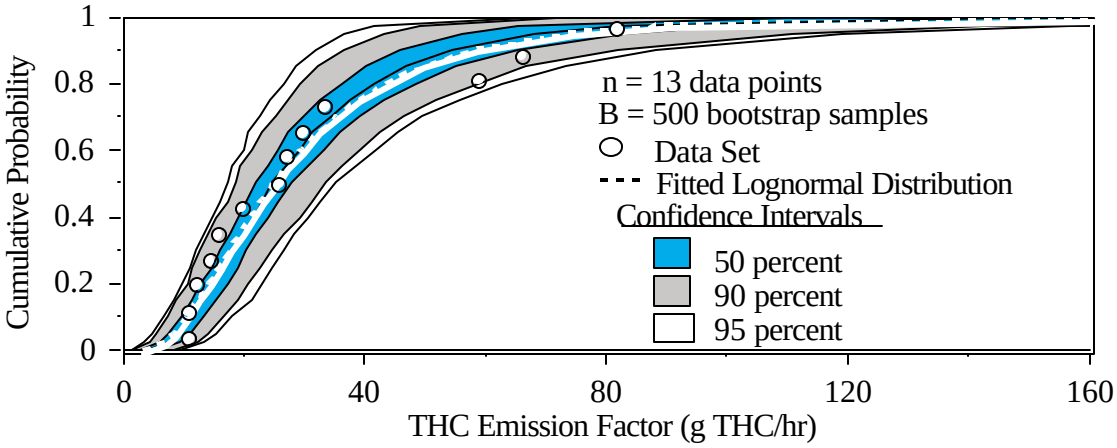

Figure 8-29. Bootstrap Simulation Results for 4-stroke L&G Gasoline Engine THC Emission Data in Units of g/hr (Size < 8 hp).

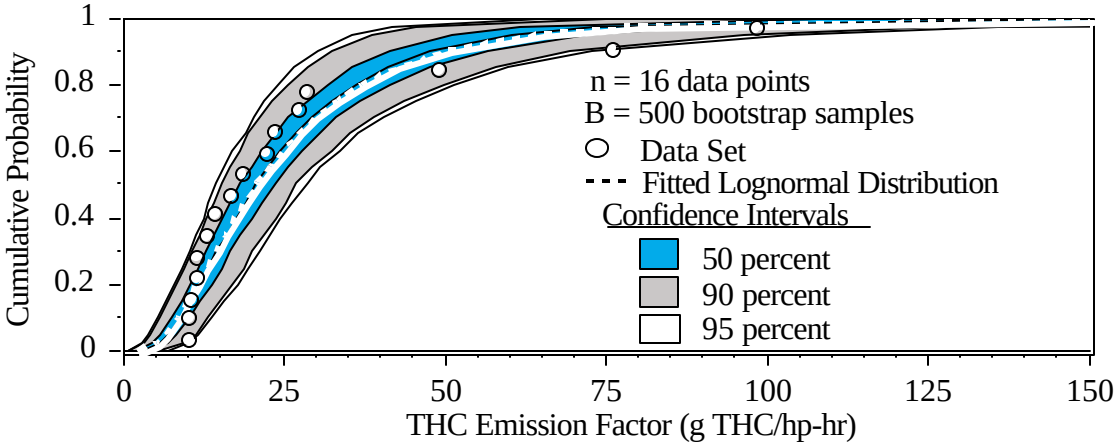

Figure 8-30. Bootstrap Simulation Results for 4-stroke L&G Gasoline Engine THC Emission Data in Units of g/hp-hr (Size < 8 hp).

9.0 APPENDIX C: ADDITIONAL FIGURES FOR CHAPTER 4

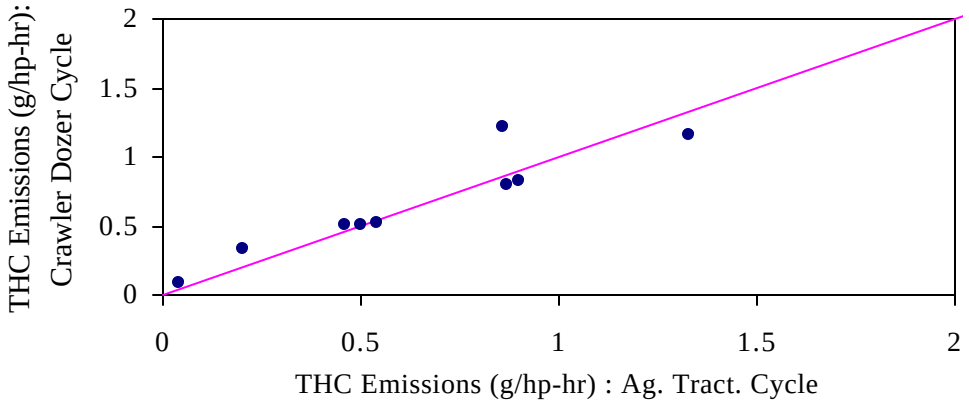

Figure 9-1. Scatter Plot to Compare the THC Emission Factors Developed Using the Crawler Dozer Cycle and the Agricultural Tractor Transient Cycles.

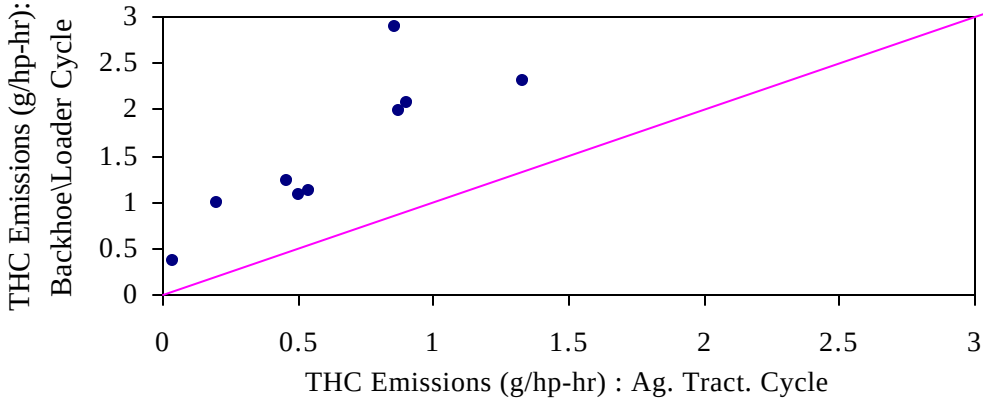

Figure 9-2. Scatter Plot to Compare the THC Emission Factors Developed Using the Backhoe Loader Cycle and the Agricultural Tractor Transient Cycles.

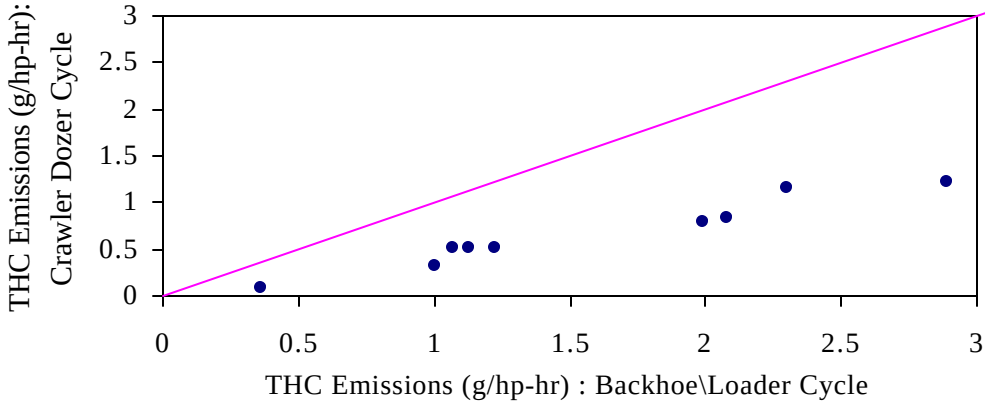

Figure 9-3. Scatter Plot to Compare the THC Emission Factors Developed Using the Crawler Dozer Cycle and the Backhoe Loader Transient Cycles.

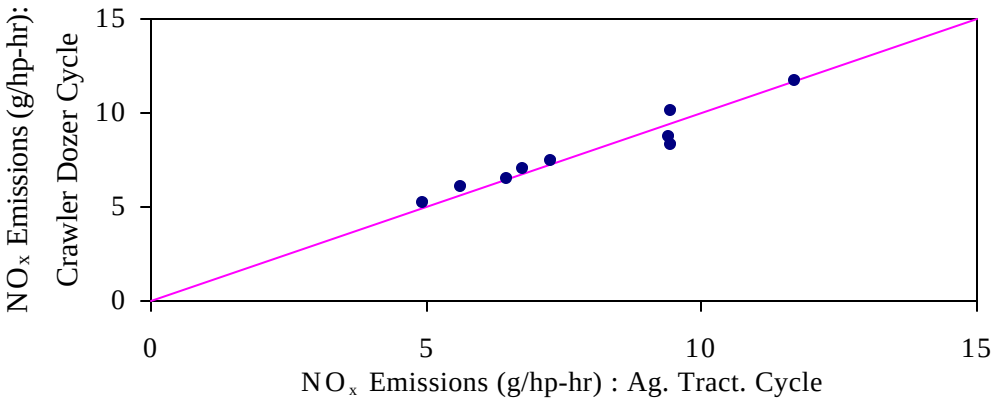

Figure 9-4. Scatter Plot to Compare the NO_x Emission Factors Developed Using the Crawler Dozer Cycle and the Agricultural Tractor Transient Cycles.

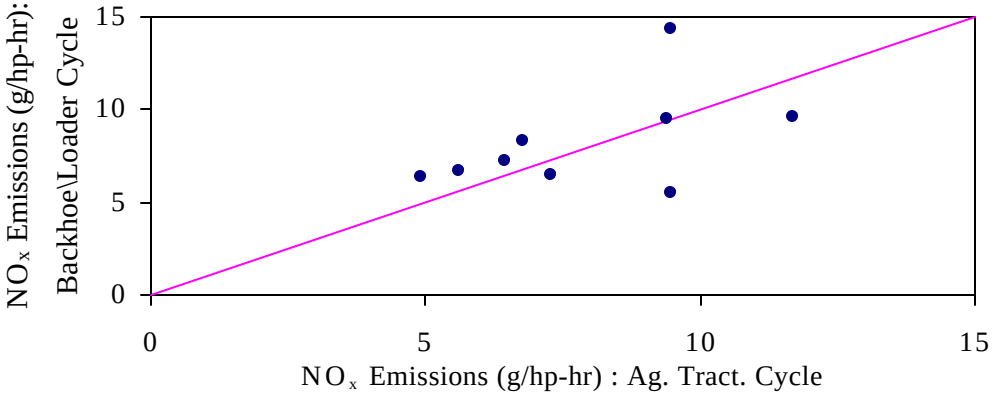

Figure 9-5. Scatter Plot to Compare the NO_x Emission Factors Developed Using the Backhoe Loader Cycle and the Agricultural Tractor Transient Cycles.

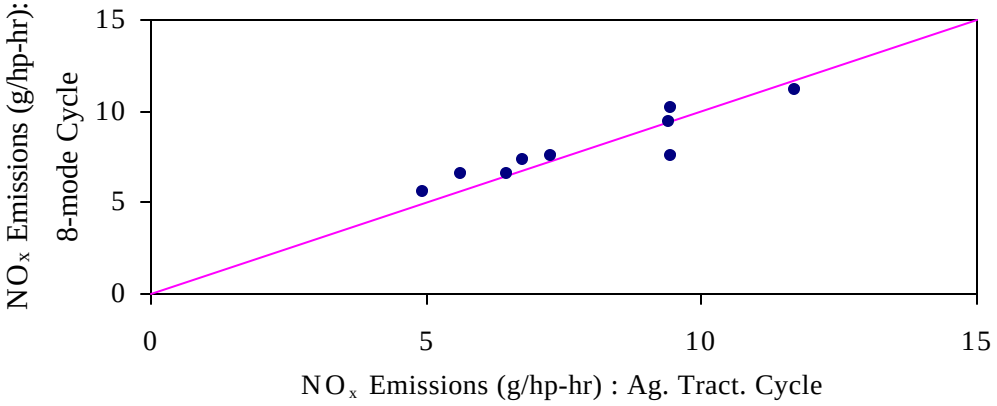

Figure 9-6. Scatter Plot to Compare the NO_x Emission Factors Developed Using the 8-Mode Steady State Cycle and the Agricultural Tractor Transient Cycles.

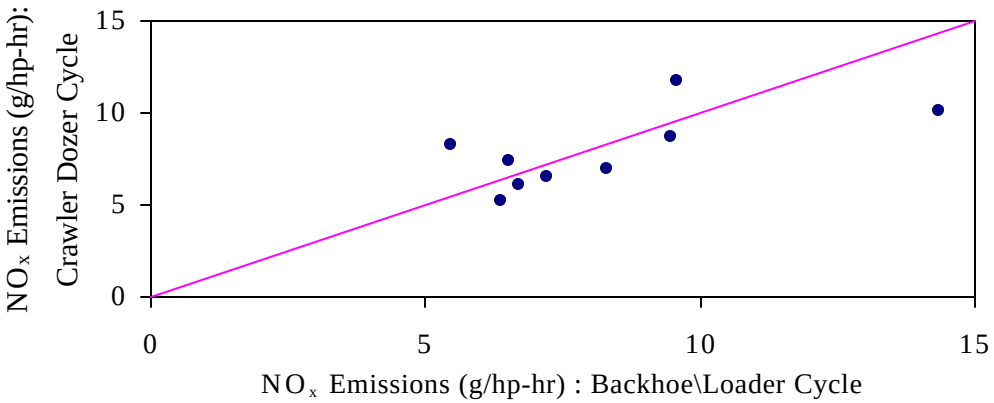

Figure 9-7. Scatter Plot to Compare the NO_x Emission Factors Developed Using the Crawler Dozer Cycle and the Backhoe Loader Transient Cycles.

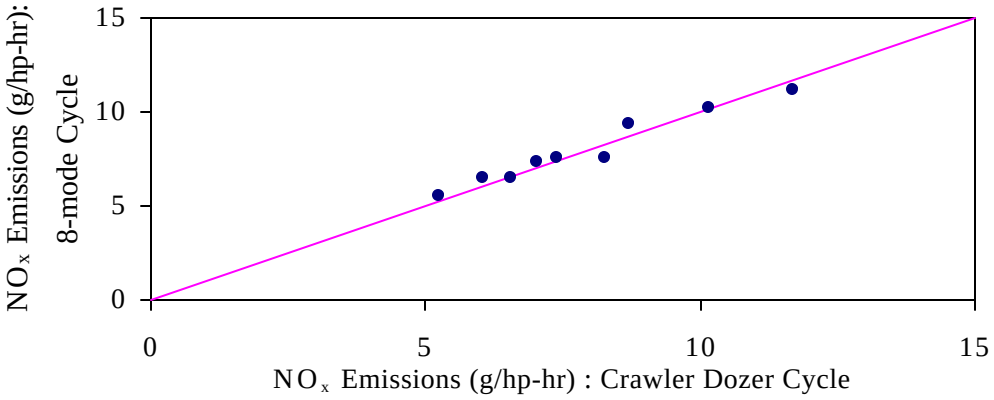

Figure 9-8. Scatter Plot to Compare the NO_x Emission Factors Developed Using the 8-Mode Steady State Cycle and the Crawler Dozer Transient Cycles.

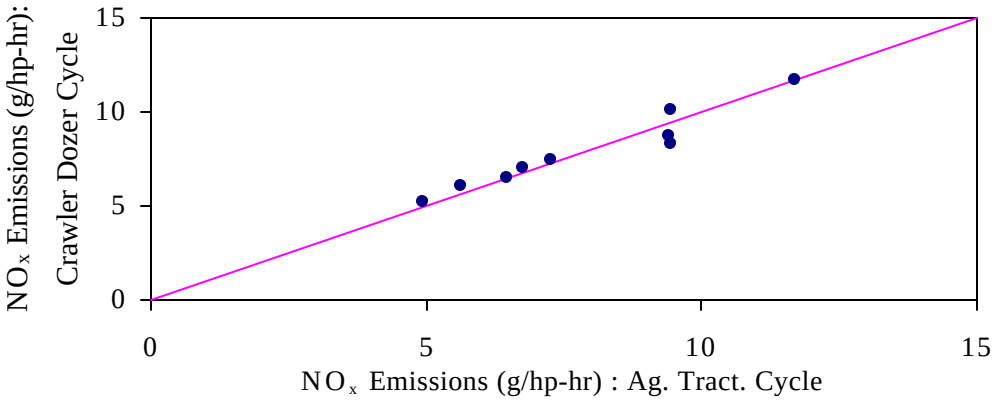

Figure 9-9. Scatter Plot to Compare the NO_x Emission Factors Developed Using the Crawler Dozer Cycle and the Agricultural Tractor Transient Cycles.

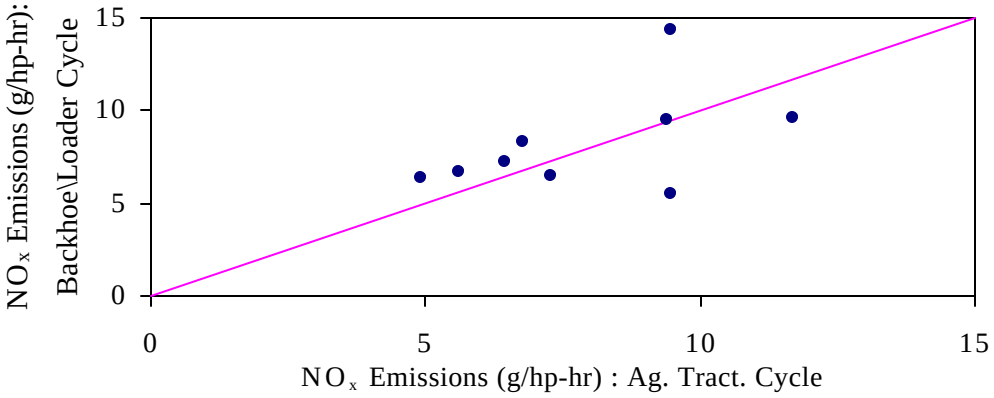

Figure 9-10. Scatter Plot to Compare the NO_x Emission Factors Developed Using the Backhoe Loader Cycle and the Agricultural Tractor Transient Cycles.

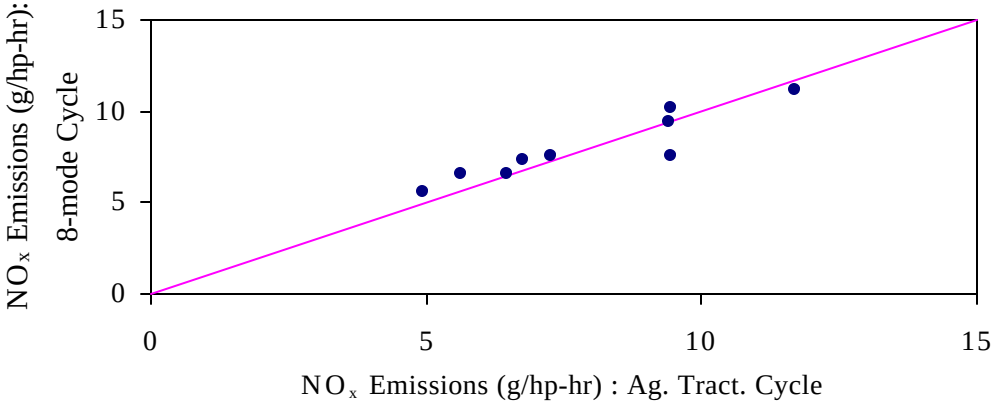

Figure 9-11. Scatter Plot to Compare the NO_x Emission Factors Developed Using the 8-Mode Steady State Cycle and the Agricultural Tractor Transient Cycles.

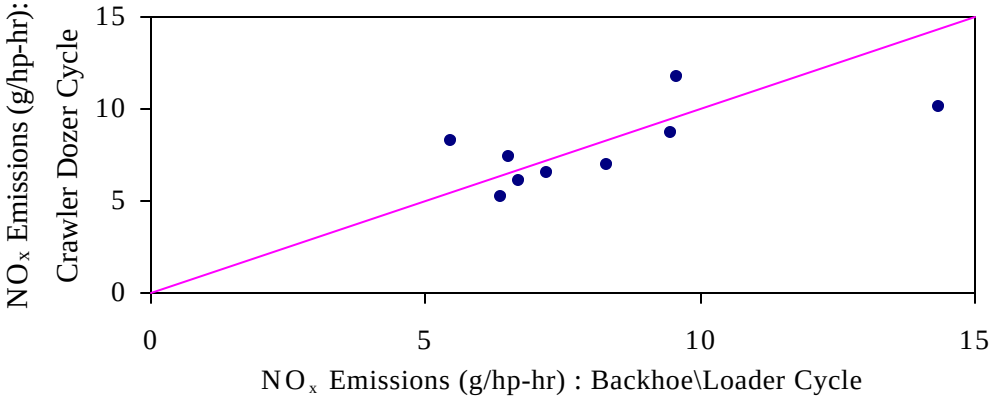

Figure 9-12. Scatter Plot to Compare the NO_x Emission Factors Developed Using the Crawler Dozer Cycle and the Backhoe Loader Transient Cycles.

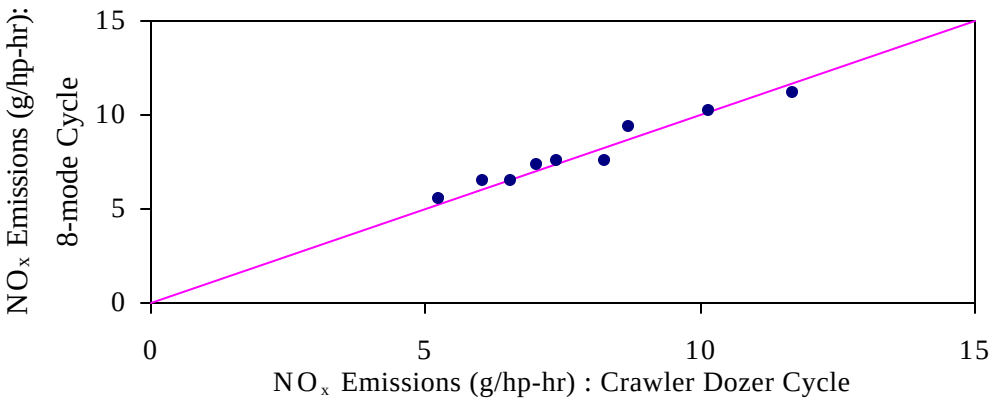

Figure 9-13. Scatter Plot to Compare the NO_x Emission Factors Developed Using the 8-Mode Steady State Cycle and the Crawler Dozer Transient Cycles

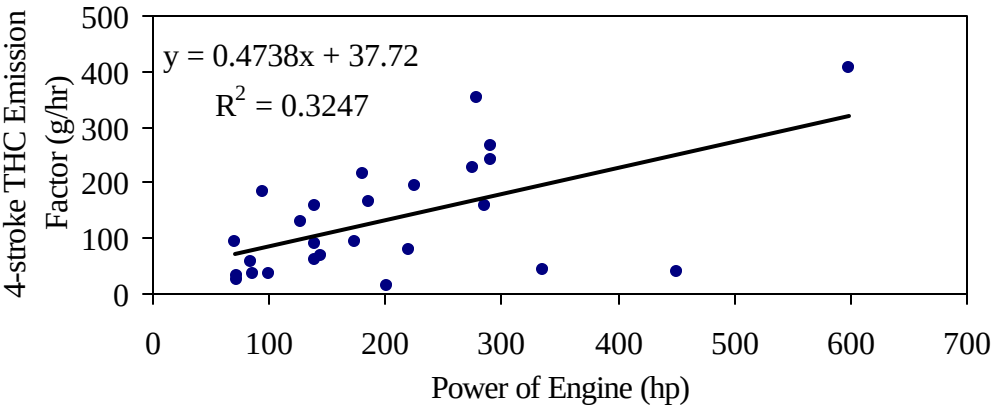

Figure 9-14.Scatter Plot of THC (g/hr) Emission factors for 4-Stroke Engines Versus the Size of the Engine (Rated Horsepower).

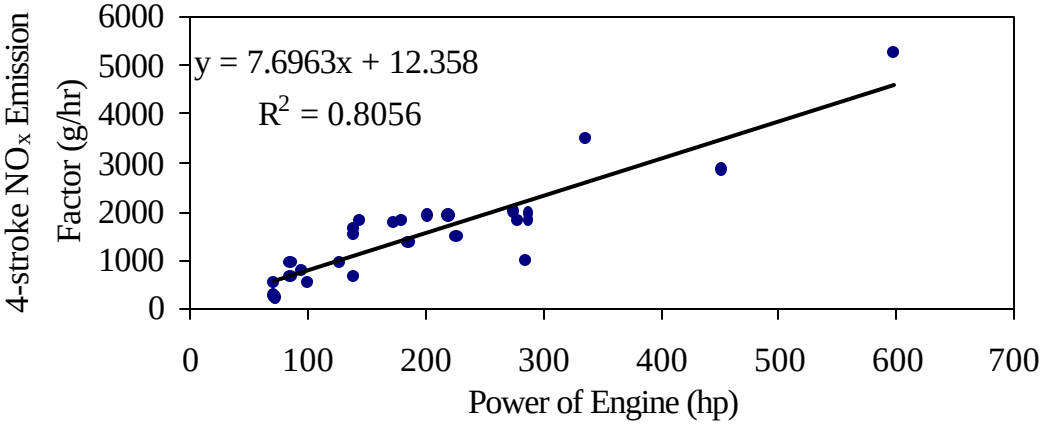

Figure 9-15. Scatter Plot of NO_x (g/hr) Emission Factors for 4-Stroke Engines Versus the Size of the Engine (Rated Horsepower).

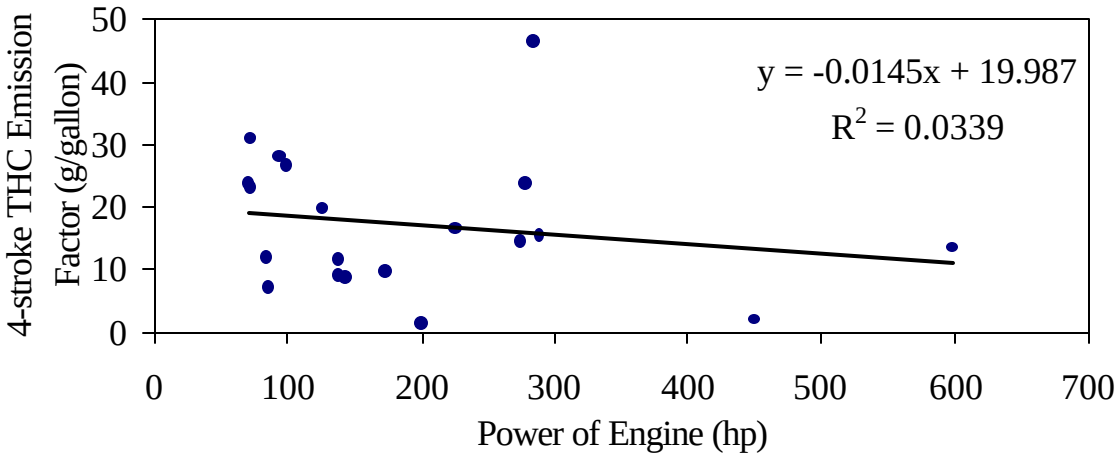

Figure 9-16.Scatter Plot of THC (g/gallon) Emission Factors for 4-Stroke Engines Versus the Size of the Engine (Rated Horsepower).

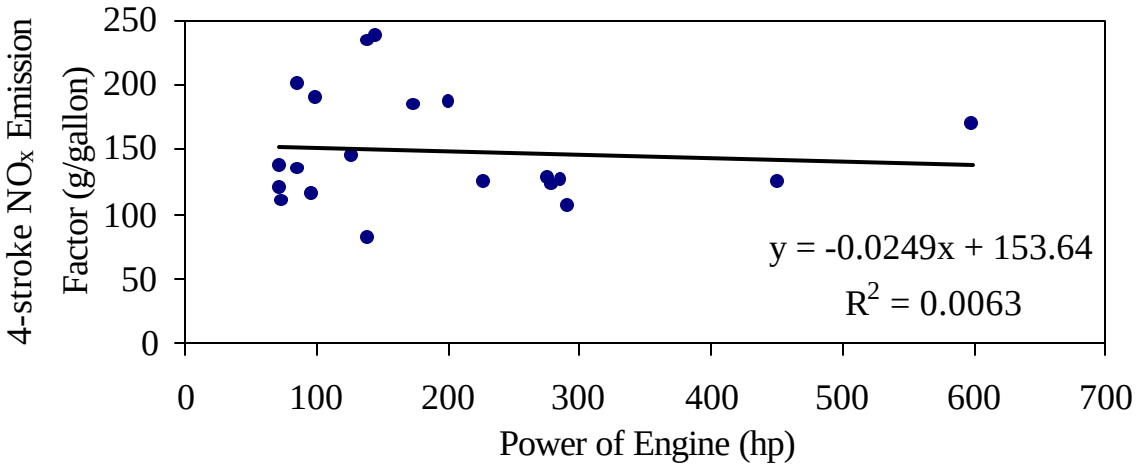

Figure 9-17. Scatter Plot of NO_x (g/gallon) Emission Factors for 4-Stroke Engines Versus the Size of the Engine (Rated Horsepower).

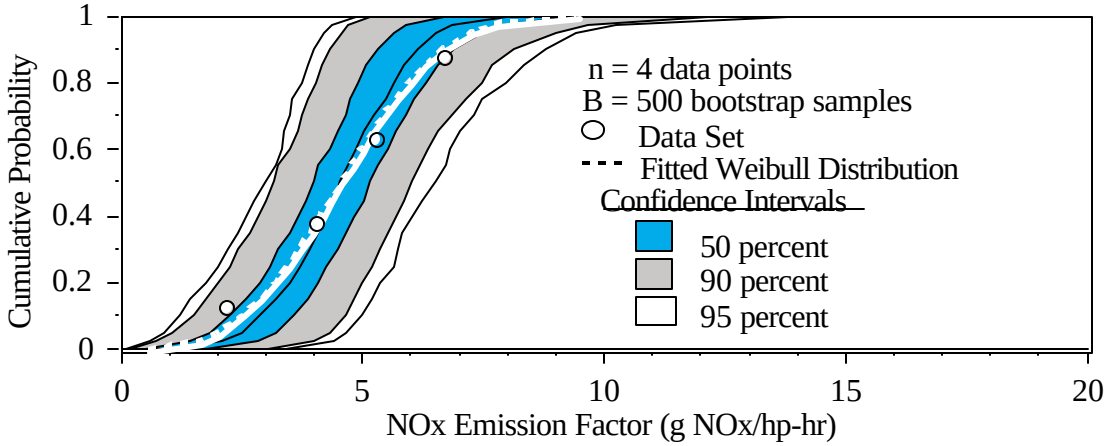

Figure 9-18. Bootstrap Simulation Results for CFI Gasoline Engine NO_x Emission Data in Units of g/hp-hr

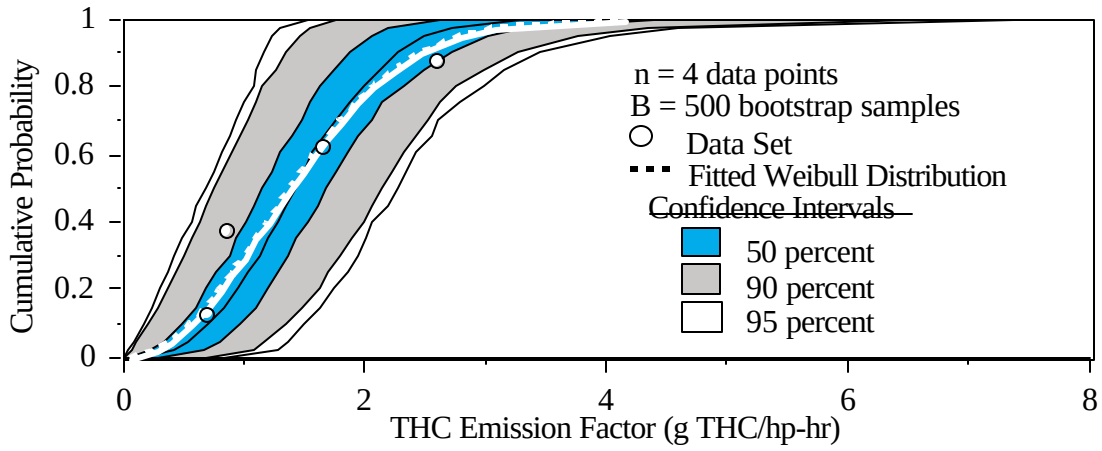

Figure 9-19. Bootstrap Simulation Results for 2-stroke CFI Diesel Engine THC Emission Data in Units of g/hp-hr

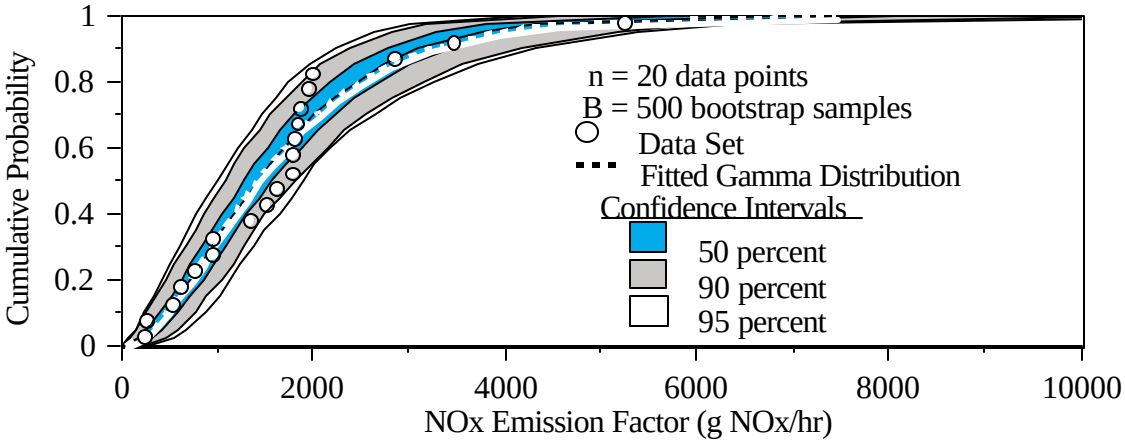

Figure 9-20. Bootstrap Simulation Results for 4-Stroke Diesel CFI Engine NO_x Emission Data in Units of g/hr

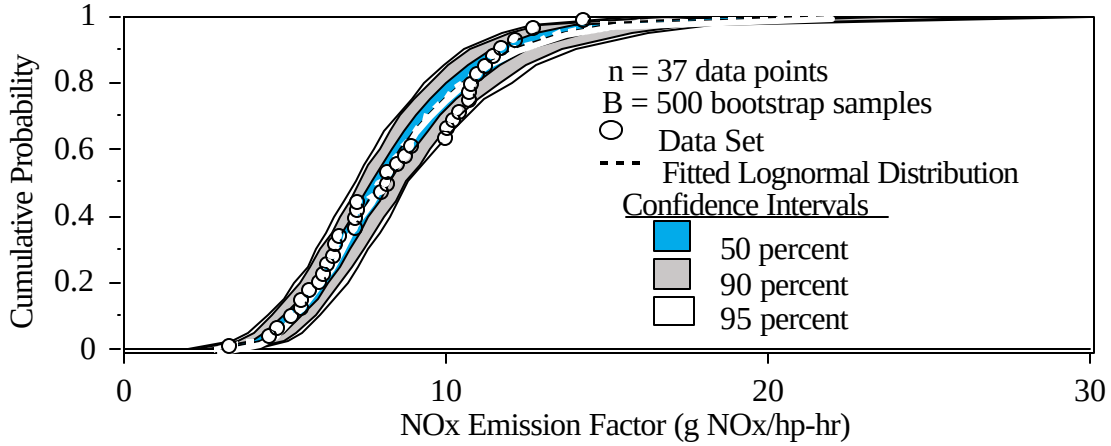

Figure 9-21. Bootstrap Simulation Results for 4-Stroke Diesel CFI Engine NO_x Emission Data in Units of g/hp-hr

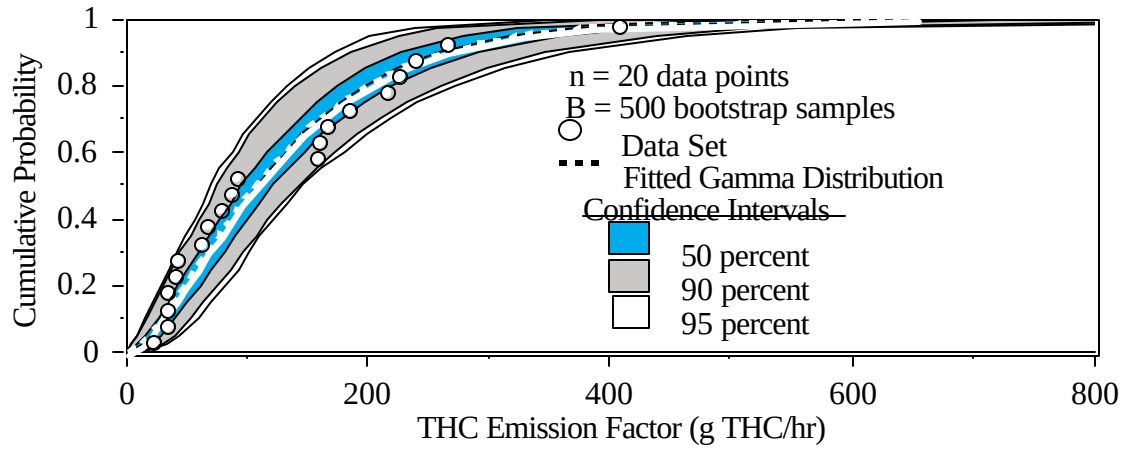

Figure 9-22. Bootstrap Simulation Results for 4-Stroke Diesel CFI Engine THC Emission Data in Units of g/hr

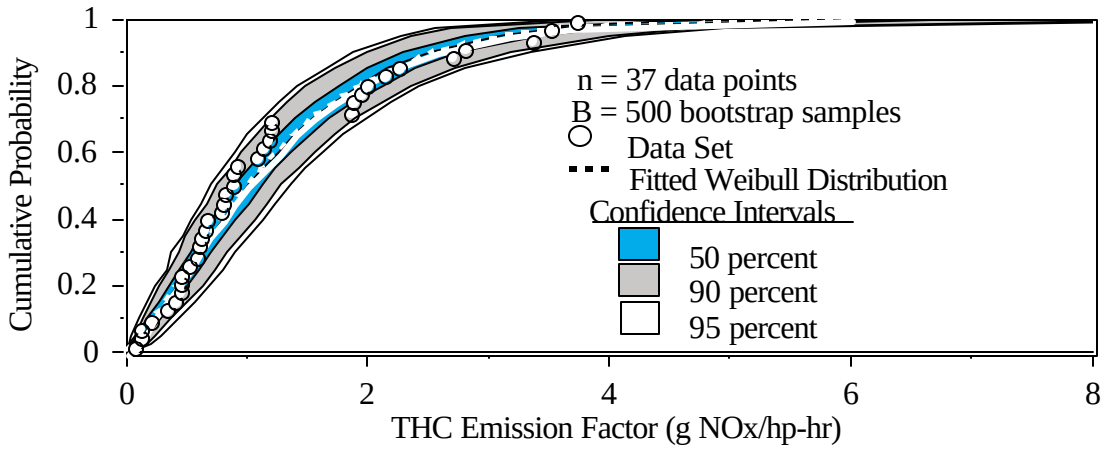

Figure 9-23. Bootstrap Simulation Results for 4-Stroke Diesel CFI Engine THC Emission Data in Units of g/hp-hr

10.0 APPENDIX D: CARB FTP/UC AIR TOXIC DATABASE

Test No.	Vehicle Make (Year)	Vehicle Model	Test Fuel	Test Type	High Emitter?	THC (g/mi)	TOG (g/mi)	Benzene (mg/mi)	1,3-Butad (mg/mi)	MTBE (mg/mi)	Formald (mg/mi)	Acetald (mg/mi)
1A	Ford 1996	Taurus GL	RFG	FTP	No	0.1257	0.1311	3.8733	0.4719	4.0072	1.5937	0.5032
1B				UC		0.1309	0.1377	3.4630	0.2598	3.4306	3.9426	0.4645
2A	Toyota 1995	Corrolla DX	UnL	FTP	No	0.1606	0.1662	4.6247	0.8189	3.6832	2.6499	0.5278
2B				UC		0.1301	0.1345	4.8528	1.0670	2.3777	1.8564	0.4098
3A	GM 1994	Sunbird LE4DR	RFG	FTP	No	0.1924	0.2045	4.6924	0.9455	6.5115	4.4394	1.0985
3B				UC		0.1344	0.1429	4.1695	0.6358	3.6821	4.0374	0.6821
4A	Ford 1993	Taurus GL	Ind	FTP	No	0.0501	0.0536	1.7666	0.1902	0.1345	2.6240	02053
4B				UC		0.1164	0.1244	5.8468	0.3080	NA	6.3267	0.5020
5A	Ford 1993	Taurus GL	UnL	FTP	No	0.1223	0.1272	6.2116	0.7034	3.1396	2.9638	0.4069
5B				UC		0.1239	0.1260	9.7737	0.4274	2.6549	0.4605	0.4898
6A	Ford 1993	Taurus GL	UnL	FTP	No	0.0913	0.0923	3.9428	0.4036	3.1161	0.6365	0.1414
6B				UC		0.1181	0.1209	9.3815	0.7331	2.1953	0.9556	0.5244
7A	Ford 1993	Taurus GL	RFG	FTP	No	0.0886	0.0920	3.1039	0.4695	2.7508	2.0666	0.3862
7B				UC		0.1005	0.1117	5.4411	0.2481	2.9428	9.6098	0.4014
8A	CHRY 1992	Wrangler 2DR	RFG	FTP	No	0.2833	0.2941	8.2053	1.3462	10.8351	4.0166	1.2080
8B				UC		0.3644	0.3763	9.0569	1.1907	17.9644	4.4172	1.0991
9A	Ford 1989	Tracer	Ind	FTP	No	0.1847	0.1888	6.0074	0.8885	NA	2.4745	0.4316
9B				UC		0.1844	0.1872	6.9607	0.9538	NA	0.8445	0.5624
10A	Ford 1989	Tracer	UnL	FTP	No	0.2324	0.2531	6.3636	0.6818	4.7496	10.9043	0.7099
10B				UC		0.2730	0.2870	9.1525	0.9992	2.4148	10.4562	0.9512
11A	Toyota 1989	Camry	UnL	FTP	No	0.2274	0.2318	7.9994	1.2267	NA	2.0930	0.7376
11B				UC		0.3742	0.3835	21.8217	2.8594	NA	2.8130	1.7792
12A	Mazda 1987	626Lxi 2DR	RFG	FTP	Yes	1.7677	1.8764	72.7795	17.5925	24.4603	42.0528	11.3426
12B				UC		1.7501	1.8629	76.8858	15.4418	16.0411	43.7857	12.1923
13A	Ford	P/U F-	RFG	FTP	Yes	0.3766	0.3841	12.1466	0.7973	11.5648	3.6149	0.9507

13B	1984	250		UC		0.4903	0.4985	24.0186	1.0149	9.2366	3.6696	1.1920
14A	MITS 1984	Colt	RFG	FTP	No	1.4099	1.5309	35.7490	14.6033	70.4496	51.3210	11.6262
14B				UC		1.6163	1.7264	42.4803	8.0979	80.0602	43.8942	10.2241
15A	CHRY 1983	Van Ram 150	RFG	FTP	Yes	2.2895	2.3704	59.8553	4.4287	21.4863	25.0328	7.7771
15B				UC		2.3424	2.4041	82.2424	3.1607	12.3718	25.0180	7.6806
16A	GM 1982	Corvette	Ind	FTP	Yes	1.7809	1.8317	69.9380	5.3410	NA	21.8404	8.8994
16B				UC		1.5220	1.5728	67.7398	3.9056	1.2878	24.6744	6.5080
17A	GM 1982	Corvette	UnL	FTP	Yes	1.414	1.4803	58.0894	6.0390	13.5599	23.5275	7.8022
17B				UC		1.4043	1.4656	59.3127	4.7875	20.4828	12.9383	7.2346
18A	Ford 1991	Taurus	UnL RFG	FTP	No	0.4205	0.4328	13.2492	1.4970	8.5297	3.4716	1.2526
18B				UC		0.3703	0.3828	10.7827	0.8301	8.0156	3.4596	1.1353

RFG: California Phase 2 Reformulated Gasoline
Ind: Indolene
UnL: Commercial Unleaded Gasoline
NA: Data not available
Source: (Sierra Research, 1999)

11.0 APPENDIX E: LAWN AND GARDEN ENGINE EMISSION FACTOR DATABASE

Database for 2-stroke Gasoline Fueled Engines

S. No.	Engine Manuf.	Type	H / NH	Size in hp (in cc)	Test Type	THC			NO_x			Source
						g/hr	g/hp-hr	g/gal	g/hr	g/hp-hr	g/gal	
1	Lawn Boy	WBM	NH	4 (126)	CARB J1088	**209**	**182**	789	**0.59**	**0.51**	2.22	Carroll, 1991
2	Ryan	String Trimmer	H	0.5 (31)	CARB J1088	**274**	**1290**	1250	**0.16**	**0.73**	0.71	Carroll, 1991
3		WBM. Tiller	NH	5	CARB J1088	247	**190**	848	0.4	**0.31**	1.39	CARB, 1994
4		Trimmer, Blower	H	1 (25)	CARB J1088	123	**167**	850	0.76	**1.04**	5.29	CARB, 1994
5	Suzuki 47PJ8			(121)	SAE J1088	442	**183**	744	0.67	**0.76**	3.09	White, 1990
6	Tecumseh TVS840			(138)	SAE J1088	203	**234**	852	0.76	**0.88**	3.2	White, 1990
7	Homelite	Residential Trimmer	H	0.94 (17.5)	CARB J1088	**157**	**324**	919	**0.16**	**0.3**	0.85	Carroll & White, 1994
8	Sears/ Poulan	Residential Chainsaw	H	1.4-1.5 (29.5)	CARB J1088	**207**	**253**	1020	**1.82**	**2.25**	9.03	Carroll & White, 1994
9	Weedeater	Residential Leafblower	H	1.3-1.4 (22)	CARB J1088	**126**	**149**	952	**0.23**	**0.25**	1.6	Carroll & White, 1994
10	ECHO	Comm. Trimmer	H	1.4-1.5 (30.5)	CARB J1088	**119**	**107**	536	**1.13**	**1.02**	5.11	Carroll & White, 1994
11	Partner	Comm. Chainsaw	H	5.4 (65)	CARB J1088	**517**	**148**	917	**7.57**	**2.41**	14.9	Carroll & White, 1994
12	Tecumseh	Snow		2	EMA	**158**	**214**		**1.16**	**1.58**		Hare and

	AH 520	Thrower			13							Springer, 1973a
13	Husqvarna 42		H	3 (42)	J1088 [a]	138	83.4	575	1.35	0.82	5.66	Sun *et al.*, 1995
					J1088 [b]	161	76.3	558	1.68	0.8	5.75	
14	Poulan 415		H	4.5 (65)	J1088 [a]	453	137	771	0.25	0.08	0.89	Sun *et al.*, 1995
					J1088 [b]	563	133	770	0.32	0.08	0.96	
15	Poulan 95 A-8		H	2.3 (40)	J1088 [a]	118	67.8	546	0.26	0.15	1.54	Sun *et al.*, 1995
					J1088 [b]	142	63.5	531	0.28	0.13	1.38	
16	Lawn-boy F-250		NH	2.2 (127)	CARB J1088	223	238	766	0.69	0.73	3.63	Sun *et al.*, 1995
17	Homelite 200		H	1.25 (32)	J1088 [a]	167	160	657	0.14	0.13	0.68	Sun *et al.*, 1995
					J1088 [b]	182	136	620	0.18	0.13	0.76	
18		Trimmer	H	(21)	SAE J1088	**73**			**0.41**			Liechty, 1995
19		Chainsaw	H	(38)	SAE J1088	**313**			**1.02**			Liechty, 1995

[a] J1088 C (70:30) Test Procedure
[b] CARB J1088 Test Procedure.
Emission factor values in **bold** imply the original reported emission factor. All the others are calculated values.

Database for 4-stroke Gasoline Fueled Engines

S. No.	Engine Manuf.	Type	OHV/ LHV	H / NH	Size in hp (in cc)	Test Type	THC			NO_x			Source
							g/hr	g/hp-hr	g/gal	g/hr	g/hp-hr	g/gal	
1	Tecumseh	WBM		NH	4 (164)	CARB J1088	**82.1**	98.2	301	**0.35**	**0.42**	6.94	Carroll, 1991
2	Briggs & Stratton	WBM		NH	3.5 (148)	CARB J1088	**66**	**76.1**	270	**0.7**	**0.81**	1.28	Carroll, 1991
3		WBM	OHV	NH	4 (148)	CARB J1088	25.9	**18.5**	113	2.88	**2.06**	12.6	CARB, 1994
4		WBM	LHV	NH	4 (148)	CARB J1088	59	**49.1**	226	1.46	**1.22**	5.62	CARB, 1994
5		Riding Mower	OHV	NH	11 (368)	CARB J1088	21.9	**5.31**	41	8.81	**2.14**	16.5	CARB, 1994
6		Generator, Tiller	LHV	NH	12 (400)	CARB J1088	29	**6.65**	44.3	23.9	**5.48**	36.5	CARB, 1994
7		Garden Tractor	LHV	NH	18 (675)	CARB J1088	47.2	**6.66**	39.7	17.9	**2.53**	15.1	CARB, 1994
8		WBM, pumps	OHV	NH	4.5 (140)	CARB J1088	12.4	**10.3**	65	2.96	**2.46**	15.6	CARB, 1994
9	Suzuki VMJ8		OHV		(141)	SAE J1088	16	**17**	90.2	2.25	**2.14**	11.4	White, 1990
10	Briggs & Stratton		LHV		(185)	SAE J1088	30	**28.6**	111	1	**1.17**	4.52	White, 1990
11	B & S Quantum	Garden Tractor	LHV	NH	18 (688)	CARB J1088	**52.1**	**8.17**	62.3	**20.4**	**3.2**	23.6	Carroll & White, 1993
12	Tecumseh TVS 105	WBM	LHV	NH	4 (172)	CARB J1088	**27.1**	**22.2**	128	**2.14**	**1.75**	9.85	Carroll & White, 1993
13	B & S 92908	WBM		NH	4	EMA 13	**29**	**24.5**		**3.49**	**2.98**		Hare and Springer, 1973a

14	B & S 100202	Lawn Mower			18	EMA 13	**14.7**	**12.9**		**11.3**	**9.81**		Hare and Springer, 1973a
15	Kohler K482	Portable Generators		NH	12.5	EMA 13	**152**	**30.4**		**18.1**	**3.53**		Hare and Springer, 1973a
16	Wisconsin S-12D	Garden Tractor		NH	5	EMA 13	**46.6**	**14.2**		**20.4**	**6.2**		Hare and Springer, 1973a
17	B & S Europa			NH	3.6 (147)	J1088[b]	19.8	13.3	90.5	1.44	0.97	6.49	Sun *et al.*, 1995
						LM	12	11	64	2.11	1.94	9.97	
18	Honda GXV 120		OHV	NH	4 (118)	CARB J1088	10.9	11.4	56.9	2.7	2.83	14.7	Sun *et al.*, 1995
19	Kohler CV 125ST		OHV	NH	12.5 (398)	CARB J1088	19.4	3.95	36.4	12	2.45	19.5	Sun *et al.*, 1995
20	B & S 130412			NH	5 (206)	GS	25.8	14.2	74	3.65	2.01	11.5	Sun *et al.*, 1995
21	Tecumseh			NH	4 (172)	CARB J1088	33.6	27.2	130	0.7	0.57	3.13	Sun *et al.*, 1995
22	Tecumseh OVRM55		OHV	NH	5 (172)	CARB J1088	14.3	10.7	69.3	3.8	2.83	15.7	Sun *et al.*, 1995
23	Tecumseh HM80			NH	8 (318)	CARB J1088	71.5	23.5	162	1.32	0.43	3.96	Sun *et al.*, 1995
24	Ryobi 990r		OHV	H	1 (26.2)	J1088[a]	10.2	17.7	137	1.79	3.11	18.5	Sun *et al.*, 1995
						J1088[b]	11.1	14.5	124	1.31	1.72	11.1	
25	B & S 12G702	Lawn Mower	LHV	NH	(190)	C6M		11.6			1.27		Gabele, 1997a
						6Mode		10.6			1.42		
26	B & S 92902	Lawn Mower	LHV	NH	(148)	C6M		23.3			2.76		Gabele, 1997a
						6Mode		21.8			2.76		
27	B & S 124702	Lawn Mower	LHV	NH	(190)	C6M 6Mode		10.4			3.43		Gabele, 1997a
								10.3			3.21		
28	B & S	Lawn	LHV	NH	(148)	C6M					0.94		Gabele, 1997b

	92502	Mower											
29	Tecumseh 20203D	Lawn Mower	LHV	NH	(148)	C6M					3.96		Gabele, 1997b
30	B & S 93502	Lawn Mower	LHV	NH	(148)	C6M					0.43		Gabele, 1997b
31	Kawasaki FC 150V	Lawn Mower	OHV	NH	(150)	C6M					2.57		Gabele, 1997b
32	B & S 92982	Lawn Mower	LHV	NH	(148)	C6M					0.55		Gabele, 1997b

[a] J1088 C (70:30) Test Procedure
[b] CARB J1088 Test Procedure.
LM: Lawn Mower Test Procedure
GS: Generator Set Test Procedure.
Emission factor values in **bold** imply the original reported emission factor. All the others are calculated values.

12.0 APPENDIX F: CONSTRUCTION, FARM AND INDUSTRIAL ENGINE EMISSION FACTOR DATABASE

S. No	Engine Manufacturer	Type	Size in hp (in liters)	Test Type	THC			NO_x			Source
					g/hr	g/hp-hr	g/gal	g/hr	g/hp-hr	g/gal	
1	Cummins VTB-903	4STC	290 (14.8)	13M	267	**0.92**	15.6	1800	**6.22**	106	Martin, 1981
2	DDA 8V-71TA			13M		**0.68**	11.3		**8.97**	149	Martin, 1981
3	IHC DTI-466B			13M		**0.77**	11.1		**3.86**	55.5	Martin, 1981
4	John Deere 4039D	4SNA	72 (3.9)	8M	23.93	**0.6**	23	271	**7.2**	120	Smith, 1992
5	John Deere 4045D	4SNA	73 (4.5)	8M	34.1	**0.9**	31	234	**6.1**	110	Smith, 1992
6	Cummins 4BT	4STC	100 (3.9)	8M	35.6	**0.8**	26.7	535	**11**	189	Smith, 1992
7	Caterpillar 3306	4STC	285 (10.5)	8M	159	**1.1**	46.3	975	**6.5**	126	Smith, 1992
8	Allis-Chalmers 3500	4STC	(7)	21M		**0.62**			**11.5**		Hare & Springer, 1973b
9	Caterpillar D6C	4STC	(10.5)	21M		**0.13**			**5.19**		Hare & Springer, 1973b
10	Detroit Diesel 6V-71	2SBS	(7)	21M		**0.7**			**20.2**		Hare & Springer, 1973b
11	International Harvester D407	4SNA	(6.7)	21M		**2.7**			**8.18**		Hare & Springer, 1973b
12	John Deere 6404	4STC	(6.6)	21M		**3.74**			**5.77**		Hare & Springer,

											1973b
13	Mercedes-Benz OM636	4SNA	(1.8)	21M		**1.21**			**3.33**		Hare & Springer, 1973b
14	Onan DJBA	4SNA	(1)	21M		**1.89**			**6.64**		Hare & Springer, 1973b
15	Perkins 4.236	4SNA	(3.9)	21M		**0.66**			**10.7**		Hare & Springer, 1973b
16	Ford G5000 (Gasoline)		(4.2)	23M		**8.86**			**6.7**		Hare & Springer, 1973b
17	Hercules G-2300 (Gasoline)		(3.7)	23M		**8.98**			**4.08**		Hare & Springer, 1973b
18	J.I. Case 159G (Gasoline)		(2.6)	23M		**13.4**			**2.2**		Hare & Springer, 1973b
19	Wisconsin VH4D (Gasoline)		(1.8)	23M		**10.7**			**5.27**		Hare & Springer, 1973b
20	Caterpillar 3208	4SNA	(10.4)	13M		**1.24**			**8.06**		Hare and Bradow, 1979
						1.11			**7.98**		
						1.62			**7.32**		
						1.88			**8.92**		
						1.1			**7.78**		
21	Detroit Deisel-Allison V-71	2SBS	(7)	13M		**0.5**			**8.84**		Hare and Bradow, 1979
						0.71			**10.2**		
						0.99			**9.1**		
						0.85			**9.87**		
						0.69			**9.3**		

22	Cummins NTCC 400	4STCDI	(14)	S-1		**0.38**			**5.43**		Ullman, 1988
				S-2		**1.08**			**2.66**		
				S-3		**0.24**			**3.6**		
				S-1		**0.36**			**5.77**		
				S-2		**1.08**			**2.91**		
				S-3		**0.28**			**3.94**		
23	Detroit Deisel DDAD 60	4STCDI	(11)	S-1		**0.12**			**4.09**		Ullman, 1988
				S-2		**0.28**			**3.42**		
				S-3		**0.04**			**3.02**		
				S-1		**0.28**			**6.55**		
				S-2		**0.56**			**5.42**		
				S-3		**0.06**			**3.18**		
24	Caterpillar/Ford 1145	4SNADI		13/21 M		**2.16**			**5.52**		Hare & Springer, 1973b
25	Caterpillar/Ford 1150	4SNADI		13/21 M		**3.37**			**9.97**		Hare & Springer, 1973b
26	Cummins NH -220	4SNADI	220 (12.2)	13/21 M	79.2	**0.36**		1880	**8.53**		Hare & Springer, 1973b
27	Cummins V-378	4SNADI	140 (6.2)	13/21 M	160	**1.14**		1510	**10.8**		Hare & Springer, 1973b
28	Cummins V-504	4SNADI	180	13/21 M	216	**1.2**		1810	**10.1**		Hare & Springer, 1973b
29	Cummins V-555	4SNADI	185 (9.1)	13/21 M	167	**0.9**		1340	**7.22**		Hare & Springer, 1973b
30	Cummins V-903	4SNADI	290 (14.8)	13/21 M	241	**0.83**		1940	**6.7**		Hare & Springer,

											1973b
31	GM DH-478	4SNADI		13/21 M		**2.81**			**7.24**		Hare & Springer, 1973b
32	Int. Harvester DV550B	4SNADI		13/21 M		**3.52**			**8.21**		Hare & Springer, 1973b
33	Cummins NTC - 335	4STCDI	335 (14)	13/21 M	43.6	**0.13**		3480	**10.4**		Hare & Springer, 1973b
34	Mack ENDT 673B	4STCDI		13/21 M		**2.27**			**14.3**		Hare & Springer, 1973b
35	Mack ENDT 675	4STCDI		13/21 M		**1.18**			**10.7**		Hare & Springer, 1973b
36	Mack ENDT 864	4STCDI		13/21 M		**2.00**			**12.1**		Hare & Springer, 1973b
37	Caterpillar 1674	4STCPC		13/21 M		**0.21**			**4.82**		Hare & Springer, 1973b
38	Detroit Diesel 6V-53	2SBSDI		13/21 M		**1.64**			**18.1**		Hare & Springer, 1973b
39	Detroit Diesel 8V-71	2SBSDI		13/21 M		**2.59**			**18.6**		Hare & Springer, 1973b
40	Ford New Holland (1991)		127	8M	130	**1.02**	19.9	950	**7.48**	146	Beardsley and Lindhjem, 1999
41	John Deere 7068T (1990)	4STC	139	8M	62.6	**0.45**	8.99	1630	**11.7**	234	Beardsley

			(6.8)								and Lindhjem, 1999
42	Volvo TD 71G (1984)	4STC	144 (7.1)	8M	67.7	**0.47**	8.78	1830	**12.7**	237	Beardsley and Lindhjem, 1999
43	Volvo TD73 KBE (1992)	4STC	139 (7.3)	8M	89	**0.64**	11.6	628	**4.52**	81.6	Beardsley and Lindhjem, 1999
44	Waterbeke 32BEDA (1995)		95	8M	185	**1.95**	28.1	754	**7.99**	115	Beardsley and Lindhjem, 1999
45	Caterpillar 3176B (1995)	4SNA	451 (10.3)	8M	40.6	**0.09**	1.75	2870	**6.37**	124	Beardsley and Lindhjem, 1999
46	Cummins KTA19-M3 (1995)	4STC	599	8M	407	**0.68**	13.2	5260	**8.78**	170	Beardsley and Lindhjem, 1999
47	Caterpillar 3116 (1991)		201	8M	14.1	**0.07**	1.39	1890	**9.38**	186	Beardsley and Lindhjem, 1999
				AT	8.04	**0.04**	0.78	1890	**9.4**	184	
				BL	72.4	**0.36**	6.11	1900	**9.46**	160	
				CD	18.1	**0.09**	1.73	1750	**8.7**	168	
48	Caterpillar 3054 (1991)		85	8M	56.1	**0.66**	11.7	640	**7.53**	134	Beardsley and Lindhjem, 1999
				AT	39.1	**0.46**	8.5	804	**9.46**	175	
				BL	104	**1.22**	19.1	463	**5.45**	85.2	
				CD	43.4	**0.51**	9.56	704	**8.28**	155	
49	John Deere 4039 (1994)	4S	86	8M	35.3	**0.41**	7.35	965	**11.2**	201	Beardsley

				AT	17.2	**0.2**	3.86	1010	**11.7**	226	and Lindhjem, 1999
				BL	86	**1**	14.8	1780	**9.57**	142	
				CD	28.4	**0.33**	6.18	1640	**11.7**	219	
50	John Deere 7076 (1993)	4S	174	8M	92.2	**0.53**	9.6	2500	**10.2**	185	Beardsley and Lindhjem, 1999
				AT	94	**0.54**	10.3	1760	**9.45**	180	
				BL	197	**1.13**	16	1480	**14.4**	203	
				CD	90.5	**0.52**	9.8	1270	**10.1**	191	
51	Consolidated Diesel 6TA-830		226	8M	194	**0.86**	16.4	1480	**6.53**	125	Beardsley and Lindhjem, 1999
				AT	203	**0.9**	16.6	1270	**5.62**	104	
				BL	470	**2.08**	33.1	1510	**6.69**	106	
				CD	188	**0.83**	15.6	1370	**6.06**	114	
52	John Deere 6619 (1993)	4S	275	8M	226	**0.82**	14.4	2000	**7.29**	128	Beardsley and Lindhjem, 1999
				AT	239	**0.87**	15.2	1860	**6.77**	118	
				BL	547	**1.99**	29.8	2280	**8.29**	124	
				CD	220	**0.8**	14	1930	**7.01**	123	
53	Consolidat ed Diesel 4039		71	8M	93.7	**1.32**	23.7	537	**7.57**	136	Beardsley and Lindhjem, 1999
				AT	61.1	**0.86**	16.3	517	**7.28**	138	
				BL	205	**2.89**	46.2	463	**6.52**	104	
				CD	86.6	**1.22**	23.4	525	**7.4**	142	
54	Caterpillar 3306 (1990)	NA	278	8M	353	**1.27**	23.7	1810	**6.52**	122	Beardsley and Lindhjem, 1999
				AT	370	**1.33**	24.9	1800	**6.46**	121	
				BL	639	**2.3**	38.6	2000	**7.22**	121	
				CD	322	**1.16**	21.9	1820	**6.54**	123	
55	John Deere 6101	4S		8M		**0.47**	9.36		**5.55**	111	Beardsley and Lindhjem, 1999
				AT		**0.5**	9.63		**4.93**	94.9	
				BL		**1.07**	17.2		**6.36**	102	
				CD		**0.51**	9.82		**5.25**	101	

4S and 2S mean 4-stroke and 2-stroke, NA means Naturally Aspirated; TC means Turbo Charged; BS means Blower Scavenged; DI means Direct Injection; PC means Pre-Combustion Chamber Injection.

8M, 13M, 21M, 23M = 8-Mode, 13-Mode, 21-Mode and 23-Mode Test Procedure. AT, BL, CD = Agricultural Tractor, Backhoe Loader and Crawler Dozer Test Procedures. 13/21M = For these engines it was not clear which of the 13-Mode or 21-mode test procedure was used.
Emission factor values in **bold** imply the original reported emission factor. All the others are calculated values.

13.0 APPENDIX G: UNAVAILABLE DATA SOURCES

Data Sources From Engine Manufactures Association (EMA)

Year	Title	Corporate Author	Personal Author/contact	ID/Report No.	Description
1994	OPEI/EMA 0-25 hp 4-Stroke Emissions Testing Database		Energy and Environmental Analysis, Inc.	Meszler DJ	EEA analyzed data provided by manufacturer members of OPEI and EMA. Data are in spreadsheet attached to memo. Results include average emissions for SV and OHV 4S engines by manufacturer, "actual emission testing results from over 500 individual emissions tests directly applicable to 74 specific four stroke engine famiilies/models"

Note: A lot of time and effort was spent in trying to get the data sources listed in this appendix. The concerned agencies know to be sources of this data including EMA, PPEMA and OPEI were contacted directly. These agencies on being contacted gave the Air Docket numbers in which they understood these data sources to be. On getting this information EPA was contacted to get these data sources from the corresponding dockets. However, on corresponding with EPA it was learned that the docket numbers suggested by these agencies did not have the data sources they were said to have. On contacting these agencies again nothing new was learned about the location of these data sources. These agencies still maintained that the particular data sources that were being looking for were in the air dockets they mentioned as before.

There seems to be apparently some misunderstanding between EPA and these agencies. On of the plausible reasons for this could be the fact that these test results were sent to EPA in forms of memos and letters to the EPA officials, which were never published as a report. The EPA put these memos and letters in dockets and supposedly communicated the docket numbers to the respective agencies. Apparently there seem to be have been some miscommunication between EPA and these agencies since they do not seem

to agree on the docket numbers in which these memos and letters were finally put by EPA. As a result all the efforts gone into getting these data sources have not borne any fruit.

Data Sources From Outdoor Power Equipment Institute (OPEI)

Year	Title	Corporate Author	Personal Author/contact	ID/Report No.	Description
1993	Fax: OPEI In-Use Emissions Testing	Onan	Bohlman B		fax to Cheryl Caffrey, USEPA, from Onan Corp., Technical Services, dated Dec. 17, 1993. Presents proportions of 0-hour emissions after 50, 100 and 150 hours. 50 engines tested, displacement <225 cc, hp not specified.
1994	Tecumseh Products Emissions Testing - Europa 5.0	Tecumseh			data and associated graphs of Catalyst/No-Air Transient Test Raw Data for EUROPAD5. Graphs results for EUROPAD7, EUROPAD9 and EUROPAD11
1995	Effect of a Transient Test on Emission Results: Investigations with and without Accelerator Pump Operating	Onan, Fuel Systems and Regulatory	Fanner J	TEST-4S-295-1	Unpublished memorandum dated February 15, 1995. Includes graphs showing transient test results designed to demonstrate effect of accelerator pump on emissions, expressed as gaseous concentrations. Engine tested: Onan Performer P220G, general purpose utility gasoline engine, 4S, 782 cc.
1994	OPEI/EMA 0-25 hp 4-Stroke Emissions Testing Database	Energy and Environmental Analysis, Inc.	Meszler DJ	memorandum	EEA analyzed data provided by manufacturer members of OPEI and EMA. Data are in spreadsheet attached to memo. Results include average emissions for SV and OHV 4S engines by manufacturer, "actual emission testing results from over 500 individual emissions tests directly applicable to 74 specific four stroke engine famiilies/models"

Data Sources From Portable Power Equipment Manufactures Association (PPEMA)

Year	Title	Corporate Author	Personal Author/contact	ID/Report No.	Description
1990	A California Baseline Emissions Inventory for Total Hydrocarbons and Carbon Monoxide Emissions from Portable Two-Stroke Power Equipment	Heiden Associates, Inc.			sponsored by PPEMA
1991	Homelite Corporation Exhaust Emission Test Results	Homelite	Dow P	unpublished data	NB: labelled CBI. Test data for single hedge trimmer, 16 cc, following SAE J1088 procedure @ full load and no load. Includes test description, graphs and tables.
1993	Small Engine Test Data	McCulloch Corporation	Harm R	unpublished data	memo and data to Cheryl Caffrey, US EPA, May 11,1993. Data includes graphs of emission factors versus CO concentration for three equipment types.
1993	Small Engine Test Data	McCulloch Corporation	Harm R	unpublished data	memo and data to Cheryl Caffrey, US EPA, May 13,1993. Appears to contain raw data for graphs in 5/11/93 memo. All data collected at max power.

1993	unpublished data and reports provided by manufacture/members (?)	Portable Power Equipment Manufacturers Association	Wiessner DE		50 engines tested, including "legible data" on 8 chainsaws, 1-3 hp; 11 chainsaws, 3-6 hp; 2 trimmers, 0-1 hp. "Heiden Report" (attach 1) cited in ARB Technical Support Document
1993	PPEMA/AQC In-Use Emissions Test Report: 25 cc String Trimmers	Portable Power Equipment Manufacturers Association			unpublished report dated Feb. 5, 1993. 3 identical string trimmers tested according to PPEMA/AQC "In-use" Emissions Test Plan over 50 hours of operation.
1993	EPA/PPEMA "In-use" Emissions Test Report: 30cc Chainsaws	Portable Power Equipment Manufacturers Association			unpublished report dated Feb. 8, 1993. Presents emissions test data for 3 30-cc "occasional -use chainsaws.
1993	"38cc Chain Saw Summary"	Portable Power Equipment Manufacturers Association			Undated unpublished report. Presents emissions test data for 3 38-cc "occasional user" chainsaws. Copies of selected pages from 151-page report.

1993	EPA/PPEMA "In-use" Emissions Test Report: 24cc Handheld Blower	Portable Power Equipment Manufacturers Association			unpublished report dated Feb. 4, 1993. Presents emissions test data for 3 24-cc blowers.
1993	PPEMA/AQC In-Use Emissions Test Report: 53-cc Chainsaw	Portable Power Equipment Manufacturers Association			unpublished report dated Feb. 25, 1993. Presents emissions test results for 4 53-cc chainsaws, according to PPEMA/AQC In-use Emissions Test Plan
1994	Final Report: Handheld Subgroup of the Test Procedures Task Group	Handheld Subgroup of the Test Procedures Task Group	Ericsson D, Green K, Liechty K, Lombard R, Swanson M, Trimble T, Wiessner D	TEST-2S-295-1	Presents test data for single chainsaw engine, from series of tests designed to determine if SAE J1088 procedure could be considered representative for future engines. HHSG developed transient cycle also used. Engine tested: Poulan/Weedeater P600 chainsaw.
1995	PPEMA Proposal for Controlling Particulate Matter from Handheld Equipment: Proposal to Reg-Neg Committee	Personal Power Equipment Manufacturers Association		TEST-PM-295-1	Two sheets, data and associated graph showing association between HC and PM emissions
1995	Handheld Composite Duty Cycle Report	PPEMA Test Procedure Task Group		TEST-2S-295-2	Presents results of in-use testing designed to serve as basis for development of test cycle for handheld equipment. Variables measured included engine speed over time. No emissions measured. Equipment included 11 trimmers, 5 chainsaws, 6 blowers and 1 brushcutter, Manufacturers represented included Husqvarna, Poulan/Weedeater and Stihl