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Development of a heavy duty diesel vehicle emissions inventory prediction methodology

Prakash Gajendran
West Virginia University

Development of a Heavy Duty Diesel Vehicle Emissions Inventory Prediction Methodology

Prakash Gajendran

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Nigel Clark, Ph.D., Chair
Mridul Gautam, Ph.D.
Scott Wayne, Ph.D.
Gregory Thompson, Ph.D.
Shahab Mohaghegh, Ph.D.

Department of Mechanical and Aerospace Engineering

Morgantown, West Virginia
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ABSTRACT

Development of a Heavy Duty Diesel Vehicle Emissions Inventory Prediction Methodology

By Prakash Gajendran

Emissions from heavy-duty diesel vehicles are known to contribute a substantial fraction of the oxides of nitrogen (NO_X), and particulate matter (PM) to the atmospheric inventory. Prediction of heavy-duty diesel vehicle emissions inventory is substantially less mature than the prediction of gasoline vehicle emissions.

Heavy-duty truck emissions are affected by various parameters like vehicle weight/load, driving schedule used, and injection timing control strategies employed to operate the engine at more fuel-efficient (but higher NO_X) mode.

Research has revealed a variety of options for inventory prediction, including the use of emissions factors based upon instantaneous engine power and instantaneous vehicle behavior. Effects of various parameters on the heavy-duty diesel emissions were studied in great detail and a speed-acceleration based emissions prediction approach was developed for heavy-duty diesel vehicle emissions prediction. A suite of emissions factor tables was generated for emissions inventory prediction. Driving schedules, vehicle weight, and off-cycle injection strategy were found to affect emissions to varying extents. Detailed analyses of a large body of data enabled to quantitatively as well as qualitatively characterize effect of various parameters on heavy duty diesel vehicle emissions. A doubling of vehicle weight was found to result in roughly a 50% increase in NO_X emissions. The accuracy was found to improve with the inclusion of a large number of data covering wide range of model year groups and driving schedules.

Off-cycle operation was found to increase the NO_X emissions by more than double. The speed-acceleration model predicted the emissions with reasonable accuracy.

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NOMENCLATURE

14-C	14-peak cycle
5-Peak Cycle	WVU 5-Peak Cycle
5-Mile Route	WVU 5-Mile Route
AAMA	American Automotive Manufacturers Association
ALT – 1	An Alternative for CSC
ALT – 2	An Alternative for CSC
ANN	Artificial Neural Network
Arterial	SAE recommended practice J1376 cycle
ASME	American Society of Mechanical Engineers
BSFC	Brake Specific Fuel Consumption
CARB	California Air Resources Board
CBD	Central Business District
CFR	Code of Federal Regulations
City	A cycle represnting slow downtown operation
CO	Carbon monoxide
CO_2	Carbon dioxide
CSC	City/Suburban Heavy Vehicle Cycle
CSHVR/CSR	City Suburban Heavy Vehicle Route
D2	Number 2 diesel
DDC	Detroit Diesel Corporation
EGR	Exhaust Gas Recirculation
EMFAC	CARB's emissions factor program
EPA	Environmental Protection Agency
FIGE	European FIGE driving
FTP	Federal Test Procedure
GVW	Gross Vehicle Weight
GVWR	Gross Vehicle Weight Rating
HC	Hydrocarbons
Highway	A high-speed cycle representing highway speeds
IHC	Inventory Highway Cycle
MOBILE5	EPA's emissions factor program
NCHRP	National Cooperative Highway Research Program
ND	No data
NFRAQS	Northern Front Range Air Quality Study
NMHC	Non-methane hydrocarbons
NO_X	Oxides of nitrogen
NREL	National Renewable Energy Laboratory
NYBUS	New York Bus Cycle
P	Vehicle Axle Power (hp)
PM	particulate matter
ppm	parts per million
SAE	Society of Automotive Engineers
SAP	speed - acceleration profile
TB	Transit Bus

TEOM	Tapered Element Oscillating Microbalance
UDDS	Urban Dynamometer Driving Schedule defined by 40 CFR 86
Translab	Transportable Heavy-Duty Vehicle Emissions Testing Laboratory
TT	Tractor Truck
VMT	vehicle miles traveled
WVU	West Virginia University
Yard	A cycle representing very slow operation of tractor-trailer

1 Introduction

Diesel (or compression ignition) engines are the most fuel-efficient internal combustion engines available today and are widely used in heavy-duty on-road and off-road vehicles. Although diesel engines emit less carbon dioxide (CO_2), carbon monoxide (CO), and hydrocarbon (HC) emissions compared to a gasoline engine, they tend to have high oxides of nitrogen (NO_X) and particulate matter (PM) emissions. The United States Environmental Protection Agency (EPA) has set regulations limiting the production of certain chemical species that are emitted from diesel engines. The two of primary interest are NO_X and PM.

Emissions from Heavy-Duty Diesel Vehicles (HDDV) are known to contribute a substantial fraction of the NO_X, PM less than 10 microns (PM_{10}) and PM less than 2.5 microns ($PM_{2.5}$) to the atmospheric inventory [Johnson, 2000; Dementhon, 1997]. Oxides of nitrogen contribute to ozone formation and create secondary PM in the air, and both ozone and PM are regulated to maintain ambient air quality standards. Polluted states are obliged to pay close attention to the heavy-duty mobile source inventory in preparing State Implementation Plans (SIP) for air quality improvement. In the United States, the highway diesel engines contribute to about 17% of the total mobile source NO_X and 22% of the total mobile source PM_{10} emissions [EPA, 2001].

Current federal regulations do not require that complete heavy-duty diesel vehicles be chassis certified, instead requiring certification of their engines. The diesel engines powering these vehicles are certified separately from the vehicle, so that there is little information on actual emissions arising from trucks in real use. Truck emissions inventories have traditionally employed average fuel economy and engine efficiency factors to translate certification data into distance-specific (g/mile) data, so that inventories do not take into account the real effects of truck operating weight on emissions. Consequently, the basic EPA emissions standards are expressed in units of brake-specific mass units (g/bhp-hr) and require emission testing over the transient federal testing procedure (FTP) engine dynamometer cycle. The FTP prescribed in the Code of Federal Regulations (CFR), Title 40, Part 86, Subpart N is a transient test used to establish engine certification to emissions standards, which are thus based solely upon the engine performance. There is no sophisticated accounting for the application of that engine in the vehicle, or the nature of vehicle behavior.

For the past few decades, the United States has experienced steady and significant growth in heavy-duty vehicle transport on its highway system (ARB, 1998). Emissions inventories use existing data from different emissions sources, and the existing data for heavy-duty vehicle emissions is not comprehensive, which makes accurate inventories difficult when limited by this data. Also, precise tracking and monitoring of heavy-duty vehicle emissions, specifically NO_X, HC, CO and PM, is extremely difficult in comparison with other types of vehicles.

There is a number of parameters that affect diesel vehicle emissions, which include vehicle class and weight, driving cycles, terrain traveled, and vehicle age [Clark et al., 2002]. In addition, the effects of engine control strategies employed play a vital role. Since the early 1990s, the engine manufacturers used engine control software that caused some engines to switch to a more fuel-efficient (but higher NO_X) driving mode during highway cruising. The higher NO_X emissions resulting from this control strategy are referred to as the “Off-Cycle” emissions. The off-cycle operation affects the emissions from the heavy-duty diesel vehicles.

There is a need for a detailed analysis on the effect of various parameters including the off-cycle operation on heavy-duty vehicle emissions to improve the emissions inventory prediction.

2 Objectives

Objectives of this research are to understand the extent to which various parameters affect the exhaust emissions from heavy-duty diesel vehicles, review different methods used for heavy-duty diesel vehicle emissions inventory prediction and to develop a methodology based on the speed-acceleration approach to accurately predict the emissions from heavy-duty diesel vehicles for emissions inventory purpose.

The objectives include:

1. Incorporating the effects of various parameters that affect the emissions in the model such as vehicle class/weight, vehicle model year, driving schedules (cycles and routes) and injection strategies employed. The effects of each of these parameters on emissions will be discussed in detail in Chapter 3.
2. Gathering emissions data at high speeds typical of highway operation to augment the existing data available from the WVU database.
3. Conducting tests on heavy-duty diesel vehicles to understand the off-cycle operation and the extent to which the off-cycle operation affects the emissions.
4. Finally, examining the validity of the speed-acceleration based approach for emissions prediction by gathering additional emissions data and also using emissions data available from previous research completed at WVU.

To meet these objectives, data available from the WVU database were used for the model development. Most of the data available in the WVU database do not cover high speeds typical of highway operation, although there is an extensive data set on emissions at low speed operations. Also, some of these data were found to include the "off-cycle" operation resulting from the injection timing strategies employed by the engine manufacturers.

Additional data were gathered, on two different trucks representing two different model year groups, to augment the existing data set with higher speed operation. Some of the additional data were available to study the "off-cycle" emissions.

The effects of different parameters were studied in detail and incorporated in the methodology proposed for predictions for inventory purpose. The methodology for emissions predictions were validated using measured emissions data from chassis dynamometer testing available in the WVU database.

3 Literature Survey

3.1 Vehicle Emissions Inventory Modeling

A fundamental requirement in the effort to control pollution in any form is to quantify the emissions being released. To determine the contribution of heavy vehicles to overall loss of atmospheric quality, an emissions inventory is employed. National emission inventories are computed in the United States by the Environmental Protection Agency (EPA) and are published in the periodically updated "Emission Trends Document" (EPA, 2001). To enable a complete and accurate inventory of mobile emissions, each vehicle would need to be tested for emissions using a test cycle that exactly reproduces its real world use, and have the total vehicle miles traveled (VMT) recorded. This is obviously impractical, so a simplified inventory model is used.

3.1.1 EMFAC 2002

The Air Resources Board (ARB) has maintained the Motor Vehicles Emissions Inventory, which are the product of population, activity, and emissions for over 25 years. The on-road emission inventory data reflects new vehicle testing information and the latest vehicle registration data from the California Department of Motor Vehicles. The activity-related data are updated by the regional transportation agencies.

The ARB developed an EMission FACtors (EMFAC) model to calculate emission rates from all motor vehicles, from passenger cars to heavy-duty trucks, operating on highways, freeways and local roads in California. EMFAC 2002 is the latest version of emissions inventory model that calculates emissions inventory for motor vehicles operating on roads in California. It supercedes EMFAC 2000, which was released in November 2000. In the EMFAC model, the emission rates are combined with vehicle activity data provided by regional transportation agencies to calculate statewide or regional emissions inventories [ARB, 2001].

An emission inventory (e.g., mass of pollutant emitted per day) can be summarized as the product of an emission rate (e.g., grams of pollutant emitted over a mile) and vehicle activity (e.g., miles driven per day) summed over vehicle type and vehicle model year.

EMFAC 2002 uses vehicle chassis dynamometer based emissions data as compared to the earlier versions that used engine dynamometer data to develop the emissions factors. EMFAC 2002 estimates HC, CO, NO_X, PM, CO_2 and SO_X for different emission processes. It should be noted that SO_X is attributed to the sulfur content of the diesel fuel. PM estimates are provided for total suspended particulate. PM is the general term used for a mixture of solid particles and liquid droplets found in the air. Some particles are large or dark enough to be seen as soot or smoke. Others are so small they can be detected only with an electron microscope. These particles, which come in a wide range of sizes ("fine" particles are less than 2.5 micrometers in diameter and coarser-size particles are larger than 2.5 micrometers), originate from many different stationary and mobile sources as well as from natural sources. Fine particles ($PM_{2.5}$) result from fuel combustion from motor vehicles, power generation, and industrial facilities, as well as from residential fireplaces and wood stoves. Coarse particles (PM_{10}) are generally emitted from sources such as vehicles traveling on unpaved roads, materials handling, and crushing and grinding operations, as well as windblown dust [EPA 2003]. Diesel particulates typically have sizes below 1 micrometers [Dieselnet, 2002]. Although fuel consumption is not a pollutant, in EMFAC 2002 it is calculated based on the emissions of CO, CO_2, and THC using the carbon balance equation.

The EMFAC 2002 supports calculation of emissions for three modes; Burden, Emfac, and Calimfac.

3.1.1.1 Burden mode

The Burden mode is used for calculating regional (area-specific) emission inventories. In this mode, the model reports total emissions as tons per weekday in the region of interest for each pollutant, by vehicle class and the total number of vehicles in a fleet The burden mode uses emission factors that have been corrected for ambient conditions and speeds combined with vehicle activity to calculate emissions in tons per day. Vehicle activity includes the number of vehicles, how many miles are driven per day and the number of daily trips. The Burden mode offers the user the option of selecting either an hourly or daily total output.

3.1.1.2 Emfac mode

The Emfac mode generates emission factors in terms of grams of pollutant emitted per vehicle activity. Vehicle activity can be expressed in terms of grams/mile or grams per hour or grams per start and depends on the emissions process. The emission factors depend on basic scenario data options for geographic area, calendar year and month or season. In the Emfac mode the model calculates a matrix of emission factors at specific values of temperature (-20^{o}F to 120^{o}F), relative humidity (0% to 100%), and vehicle speed (idle and 1 mph to 65 mph) for each vehicle class/technology combination. In the Emfac mode, an additional input form allows users to customize their output and select specific temperature, relative humidity and speed values.

3.1.1.3 Calimfac mode

The Calimfac mode is used to calculate very detailed emission rates (basic emission rates or BER) for each vehicle class and model years from 1965 to the scenario calendar year. As a vehicle ages its emissions increase with vehicle mileage. In the Calimfac mode a linear regression equation is obtained by employing a linear curve fit between the emissions data and the vehicle mileage. This linear fit results in a zero mile rate (emissions when the vehicle is new) and deterioration rate (emissions increase for every 10,000 miles) with a flex point where the deterioration rate changes for higher odometer values. These BER are based on standardized driving tests. In addition, the user can elect to have the emission factors calculated with or without correction factors, which account for ambient and driving conditions not encountered during standardized testing.

In the Calimfac mode, emission factors are calculated using the same data and methodology as in the Burden or Emfac mode. When “constants for calculating emission factors” (zero-mile and deterioration constants) are reported, they are based on linear regressions on the modeled results.

3.1.2 Latest Updates for EMFAC

The ARB has recently proposed many modifications to its EMFAC model. These include the modifications to the heavy-duty diesel trucks used for the model, fuel correction factors, inspection and maintenance programs, and vehicle activity data. These modifications will be incorporated in the next version of its on-road emissions inventory model “EMFAC 2005” scheduled to be released in the Fall of 2005.

The main modifications as far as the trucks used will be to include emissions UDDSata, based on the CRC E-55/E-59 study, which cover vehicle model year groups: 1973/75 - 2003/2004. The main emphasis is laid on HHDDT's with GVW over 33,000 lb. So far, 75 HHDDT's have been tested on the Urban Dynamometer Driving Schedule and the ARB-developed Heavy-Duty Truck test cycles (ARB, 2004).

3.1.3 EPA - Mobile 6

The EPA updated the estimates of heavy-duty engine emission factors currently contained in MOBILE 5b. The same methodology employed in previous versions of the MOBILE model was followed, using updated inputs. The methodology for heavy-duty vehicles entails determination of a gram per mile (g/mile) emission factor by multiplying a work-specific emission level (in units of grams per horsepower-hour (g/bhp-hr)) by a conversion factor, which converts work units into mileage units (bhp-hr/mile).

$$EF = m * CF \qquad \text{Equation 3.1}$$

The bhp-hr/mile conversion factors (CF) are calculated from tabulated brake-specific fuel consumption (BSFC) in lb/bhp-hr, fuel density (ρ) in lb/gal, and fuel economy (FE) in mile/gal because it is difficult to measure bhp-hr/mile directly.

$$CF = \frac{\rho}{BSFC * FE} \qquad \text{Equation 3.2}$$

The fuel densities used in the program were collected from fuel surveys, the BSFC from previous conversion factor analysis and manufacturer information, and fuel economies from highway statistics for trucks and buses (Machiele, 1988). Speed correction factors for NO_X alone also exist, but their origin and efficacy remain obscure. These factors indicate that for certain speed, there is a minimum emissions rate and higher or lower speed operation increases the emissions.

Engine certification data consist of zero-mile level (ZML) emissions, which correspond to new engine emissions, and rates of deterioration at the end of useful life, typically given in grams of pollutant per brake horsepower-hour (g/bhp-hr). For heavy-duty diesel engines, the certification data sets also generally include an intended service class for each engine model (light heavy, medium heavy, heavy heavy, and bus). Useful life is defined as 110,000 miles for all heavy-duty gasoline engines and those engines with the intended service class of light heavy-duty diesel, 185,000 miles for medium heavy-duty diesel engines, 290,000 (model year 1987 – 2003) miles, and 435,000 (model year 2004 and later) miles for heavy heavy-duty diesel engines and buses.

3.1.3.1 MOVES

The EPA's Office of Transportation and Air Quality (OTAQ) is currently working on a new modeling system termed the Multi-scale mOtor Vehicle and equipment Emission System (MOVES). This new system will estimate emissions for on-road and off-road sources, cover a broad range of pollutants, and allow multiple scale analysis, from fine-scale analysis to national inventory estimation. When fully implemented MOVES will serve as the replacement for MOBILE6 and NONROAD [EPA, 2002]. The new model was initiated by several recommendations for improving the EPA's mobile source modeling tools provided by the National Research Council (NRC). MOVES will be a modeling framework, which can be applied from very fine scales (e.g., intersections) to national-scale inventories for generating estimates of green house gases, toxic pollutants from on and off-road mobile sources.

One of the main characteristics of the MOVES model is the use of Vehicle Specific Power (VSP) to characterize "modal" emission rates for the running exhaust emission process. The primary benefit of this is that it combines numerous physical factors that influence vehicle fuel consumption; vehicle speed, acceleration, road grade, and road load parameters such as aerodynamic drag and rolling resistance [EPA, 2002].

3.1.4 European Inventory Models

Emissions inventories in European countries are reported in source categories that do not always separate diesel from gasoline emissions. There is an increasing penetration of diesel-fueled vehicles in the passenger car market in Europe. The proportion of diesel cars sold in 1995 in Belgium and France approached 50% of all new automobiles in these countries [Walsh, 1999].

COmputer Programme to Calculate Emissions from Road Transport (COPERT) III is the third update of the initial methodology developed on the basis of the results of a working group, which was set up for this purpose (the initial version was COPERT 85 (1989) followed by COPERT 90 (1993) and COPERT II (1997)). The current version draws its main principles from several European activities: COST and MEET [COPERT, 2003]. In principle, COPERT has been developed to estimate emissions from road transport to be included in official annual national inventories.

COPERT estimates emissions of all regulated air pollutants (CO, NO_X, HC, PM) produced by different vehicle categories (passenger cars, light duty vehicles, heavy duty vehicles, mopeds and motorcycles) as well as CO_2 emissions on the basis of fuel consumption. Furthermore, emissions are calculated for an extended list of non-regulated pollutants. Estimated emissions estimated are generally distinguished in three sources: Emissions produced during thermally stabilized engine operation (hot emissions); emissions occurring during engine start from ambient temperature (cold-start and warming-up effects); and HC emissions due to fuel evaporation. The total emissions are calculated as a product of activity data provided by the user and speed-dependent emission factors calculated by the software [Hickman, 1998].

In the UK, the emissions from road transport are calculated either from a combination of total fuel consumption data and fuel properties or from a combination of drive related emission factors and road traffic data [AEAT website, 2003].

Emissions of the pollutants HC, NO_X, and CO are calculated from measured emission factors expressed in grams per kilometer and road traffic statistics from the United Kingdom's Department of Environment, Transport and the Regions [DETR, 2000]. The emission factors are based on experimental measurements of emissions from in-service vehicles of different types driven under test cycles with different average speeds. The road traffic data used are vehicle kilometer estimates for the different vehicle types and different road classifications in the UK road network. These data are further broken down by composition of each vehicle fleet in terms of the fraction of diesel- and petrol-fuelled vehicles on the road and in terms of the fraction of vehicles on the road made to the different emission regulations which applied when the vehicle was first registered. Emissions from motor vehicles are classified into three different types, each of which is calculated in a different manner. Exhaust emissions of PM from vehicles are also calculated from emission factors and traffic data, but different procedures are used for estimating emissions from petrol and diesel vehicles. Particulate emissions from tire and brake wear are also estimated from emission factors and traffic data.

3.2 Factors Affecting Heavy-Duty Vehicle Emissions

Heavy-duty diesel vehicle emissions are affected by a number of parameters. These parameters include vehicle class, driving test cycle, vehicle age, and terrain traveled [Nine et al., 2000; EPA, 1999; Clark et al., 2002, Yanowitz et al., 2000]. In addition, the effects of injection timing strategies on measured emissions are discussed [Kwan et al., 1997, Clark et al., 2002]. Driving cycles are employed to evaluate vehicle emissions using chassis dynamometer based testing. Since driving cycles are usually proposed with vehicle class, driving activity and vehicle vocation in mind, the categories mentioned above are not independent of one another.

3.2.1 Vehicle Class/Weight

Vehicle class/weight has a significant effect on the exhaust emissions but not much information is available on its effect on emissions. Vehicle classes are defined by several entities, including the American Automotive Manufacturers Association (AAMA) and are usually based upon the Gross Vehicle Weight Rating (GVWR) as shown in Table 3.1. The GVWR is the maximum weight a vehicle is allowed to achieve, including the vehicle, driver, payload, and fuel.

Table 3.1 Vehicle classes as defined by the American Automotive Manufacturers Association (AAMA).

Class	GVWR (lbs.)
1	6,000 and less
2	6,001 – 10,000
3	10,001 – 14,000
4	14,001 – 16,000
5	16,001 – 19,500
6	19,501 – 26,000
7	26,001 – 33,000
8	33,001 and over

The effect of vehicle class on emissions can be best understood from an analytical point of view. The three main factors that cause a vehicle to demand engine power are speed/acceleration, weight, and the terrain traveled. As the required power increases, the amount of fuel burned to produce that power also increases, and the rate of regulated emissions produced will generally increase. (Note, however, that brake specific emissions levels of some constituents, such as hydrocarbons, may be high at low power ratings.) This implies that emissions will directly vary with truck weight, and thus heavier vehicles produce more regulated emissions. The power demanded at the wheels can be obtained by using a road load equation (Equation 3.3).

$$P = M * v * \left(\frac{dv}{dt}\right) + 0.5 * C_D * \rho * A * v^3 + \mu * M * g * v + M * g * Sin(\theta) \qquad \text{Equation 3.3}$$

It can be argued from Equation 3.3 that the power demand at the rear wheels is proportional to the vehicle weight at low speeds. This energy, required at the rear wheels, differs from the energy at the engine by the factor of transmission efficiency. Such variations would be accounted for if emissions variations were linear with power, as is NO_X in most cases, and if differences in the demanded energy were appropriately modeled. By this argument, even if the emissions in g/ahp-hr (or g/bhp-hr) were similar for the two vehicles, the emissions in g/mile would vary by a factor of the ratio of the ahp-hr/mile used by each vehicle [Clark et al., 2002].

Oxides of nitrogen are produced by diesel engines primarily by the combination of nitrogen and oxygen to form nitric oxide in the hot burned gas mixture that is still plentiful in oxygen. In this way, all else being equal, the quantity of NO_X produced is roughly proportional to the quantity of fuel injected, and so varies fairly linearly with engine power. Also, NO_X is generally insensitive to engine transient behavior, and can be modeled closely based on steady state engine operating data [Ramamurthy and Clark, 1999]. Hence, the NO_X emissions will vary nearly linearly with vehicle weight at low speeds, and a quadratic relationship may be observed at higher speeds. Unlike NO_X emissions, PM emissions are a strong function of transients; hence they cannot be treated in the same way as NO_X emissions. In particular, PM will arise during rapid increases in torque demand as well as during and immediately after gear changing. HC and CO emissions are very low in diesel engines. HC emissions can be erratic, but CO emissions follow similar trends to PM, because they depend on in-cylinder air-fuel ratio [Clark et al, 1999].

Ramamurthy and Clark (1999) examined the relationship between NO_X production (in units of g/sec.) and rear axle power of vehicles undergoing chassis dynamometer testing. Data were recorded on a second-by-second basis. The processing of these data required techniques to account for analyzer measurement delay and diffusion [Ganesan and Clark, 2001]. The analysis yielded relationships for several vehicles.

Kern (2000) compared the emissions from two different heavy vehicles with the same engine, noting that these two vehicles had different vocations, transmissions, and horsepower ratings. Tables 3.2 and 3.3 show the vehicle information and chassis dynamometer based emissions results for a TB and a TT with the same engine. These vehicles had different engine power ratings and were tested on a different test cycle. The two different cycles were the most similar test conditions available from the WVU database for two different vehicles with the same engine. The bus was tested on the CBD cycle, while the TT was tested on the Truck-CBD cycle (also called the Modified CBD cycle). The Truck-CBD cycle has slower acceleration ramps so that a vehicle with a lower power-to-weight ratio and an unsynchronized manual transmission (TT) can follow the scheduled speed.

It was found that the TT exhibited lower emissions in NO_X, HC, and PM of 26%, 8.2% and 30% respectively (Kern, 2000). Furthermore, the total emissions of CO (carbon monoxide) were higher for the TT by 12%. It is evident from these data that conclusions based upon vehicle class alone are not reliable, and that vocation (as mimicked by the test cycle) must be considered.

Table 3.2. Engine data for class comparison [Kern, 2000].

Engine	Detroit Diesel Corp. 6V-92TA
Displacement	9.05 liters
No. of Cylinders	6
Fuel	D2

Table 3.3. Test results for two different vehicles with the same engine (with different power ratings) [Kern, 2000].

Vehicle Type	Transit Bus	Tractor Truck	
Model Year	1993	1992	
Rated Power (hp.)	277	300	
GVW (lbs.)	39,600	80,000	
Test Weight (lbs.)	33,175	42,000	
Transmission	4-Speed Automatic	9-Speed Manual	
Test Cycle	CBD	Truck-CBD	
			Difference*
NO_x (g/mile)	25.0	19.3	- 26%
CO (g/mile)	6.44	7.24	+ 12%
HC (g/mile)	3.54	3.26	- 8.2%
PM (g/mile)	1.71	1.27	- 30%

* Difference/average as a percentage.

Research by Graboski et al. (1998) for the Northern Front Range Air Quality Study (NFRAQS) reported emissions testing on 21 different heavy-duty vehicles using the WVU Truck (i.e. 5-Peak) Cycle, the EPA Urban Dynamometer Driving Schedule for Heavy Duty Vehicles (UDDS), and the CBD Cycle as described in SAE J1376. Results of the NFRAQS included comparisons of the GVWR of the vehicles against the emission results. The conclusion by Graboski et al. was that a heavier vehicle uses more fuel (lower fuel economy) and thus produces more exhaust gas on a g/mile basis. It was also noted that, as a vehicle following a cycle exhibited lower fuel economy, higher emissions were produced in units of g/mile. For example, the CBD cycle yielded the lowest average fuel economy, and also the highest emissions as compared to the other cycles.

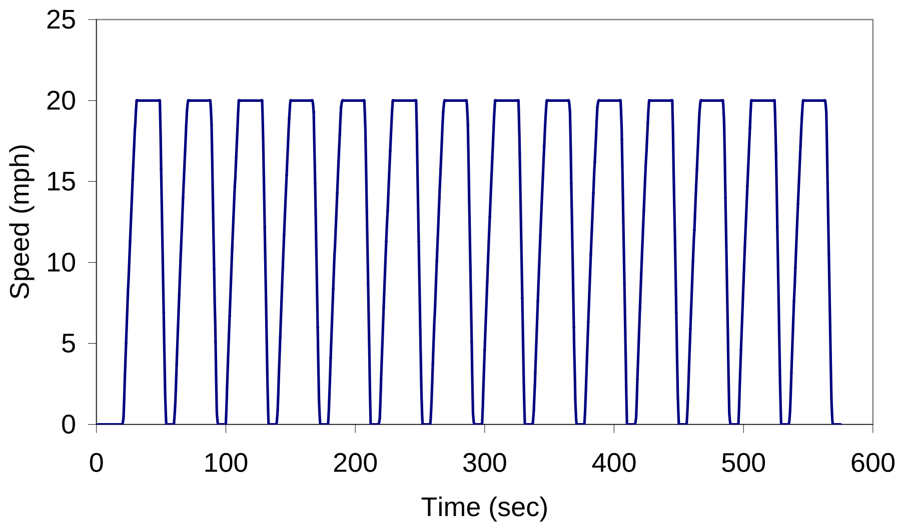
3.2.2 Driving Cycle

Driving test schedules are used in the measurement of vehicle emissions with a chassis dynamometer. The driving operation of a vehicle is affected by the traffic conditions and the routes traveled. Driving cycles or the test schedules vary widely in that they attempt to mimic specific driving behavior. Consequently, measured vehicle emissions are largely affected by the driving schedule. Some of the commonly used driving schedules are discussed here. Most chassis test schedules are defined by a speed versus time trace, with load implied by a road load equation with no gradient assumed. Some test schedules are defined by speed versus distance. These are called “Routes.” Routes allow sections of the schedule to demand full power operation from the vehicle. Speed versus time plots of every test cycle and routes discussed are included for visual comparison. Emissions testing are conducted on engines for EPA certification and so chassis driving schedules do not play a direct role in current emissions regulation. The test schedules for engine testing are commonly defined by speed and torque traces over a period of time. The actual speeds and torques are derived using the maximum torque curve and the rated and idle speeds of the engine.

3.2.2.1 Central Business District Cycle

The Central Business District (CBD) cycle is a synthesized driving cycle originally created for performance verification and fuel economy measurement of transit buses. This cycle is a portion of the Transit Coach Design Operating Duty Cycle, (SAE J1376, 1993), which also includes arterial and commuter phases. A modified CBD cycle (which is referred to as the Truck-CBD Cycle) has lower acceleration rates to suit heavy trucks with manual transmissions, but is no longer in regular use by any chassis dynamometer laboratory. Figure 3.1 shows a target speed versus time plot of the entire CBD cycle.

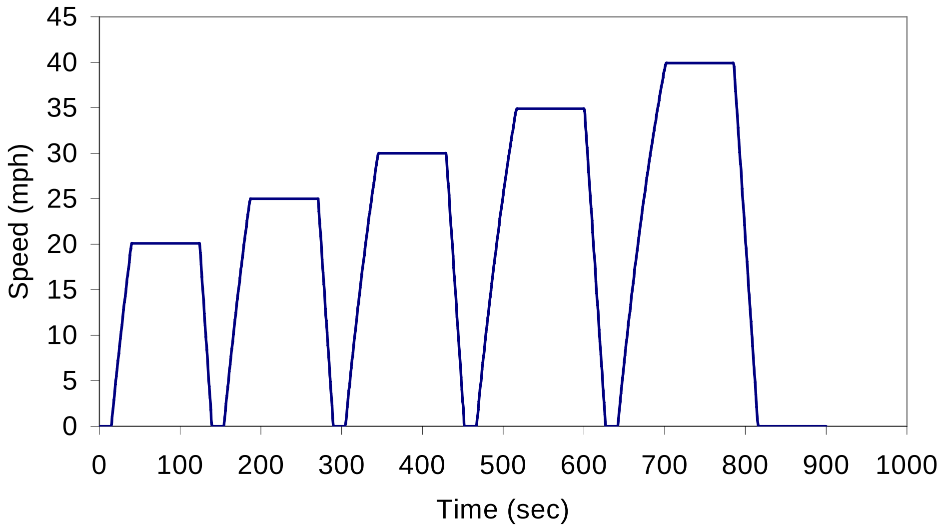
Figure 3.1 Central Business District Cycle Target speed versus time plot.



3.2.2.2 WVU 5-Peak Cycle

The WVU 5-Peak Cycle is also called the WVU Truck Cycle. This cycle was developed by the research group at the Transportable Heavy Duty Vehicle Emissions Testing Laboratory in West Virginia University in 1994 (Clark et al., 1994). The WVU 5-Peak cycle was designed for general truck chassis testing for comparison of diesel and alternate fuels. The target speed versus time plot for this cycle is shown in Figure 3.2. The cycle consists of five segments, each with acceleration to a peak speed, followed by a brief steady state operation and then a deceleration back to idle. The five peak speeds are 20, 25, 30, 35, and 40 mph.

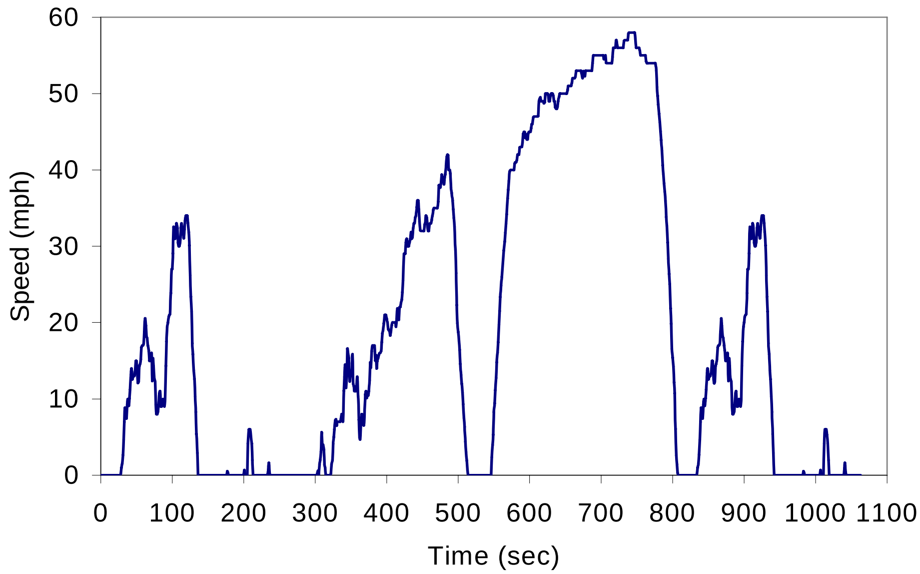
Figure 3.2 Target speed versus time plot for the WVU 5-Peak cycle.



3.2.2.3 EPA Urban Dynamometer Driving Schedule (UDDS) for Heavy-Duty Vehicles

The EPA Urban Dynamometer Driving Schedule for Heavy-Duty Vehicles is also referred to as "UDDS." It is a cycle developed from the CAPE-21 database and is presented in the Code of Federal Regulations, Title 40, Part 86, Subpart N, as a conditioning cycle for heavy-duty vehicle evaporative emissions testing. This cycle was developed from the freeway and non-freeway data collected in the survey, and it is meant to represent heavy-duty driving in all United States urban areas (40 CFR Part 86 Subpart M). This speed-time cycle is arduous to follow with a heavy truck having a low power-to-weight ratio and an unsynchronized transmission. Although it is intended to reflect the same operation as the present day engine certification test, Dietzmann and Warner-Selph (1985) found poor emissions correlation between the two. This cycle has been employed occasionally as a "best attempt" basis to simulate vehicle activity and emissions by most heavy-duty chassis emissions laboratories in North America. Figure 3.3 shows the scheduled speed versus time plot for UDDS.

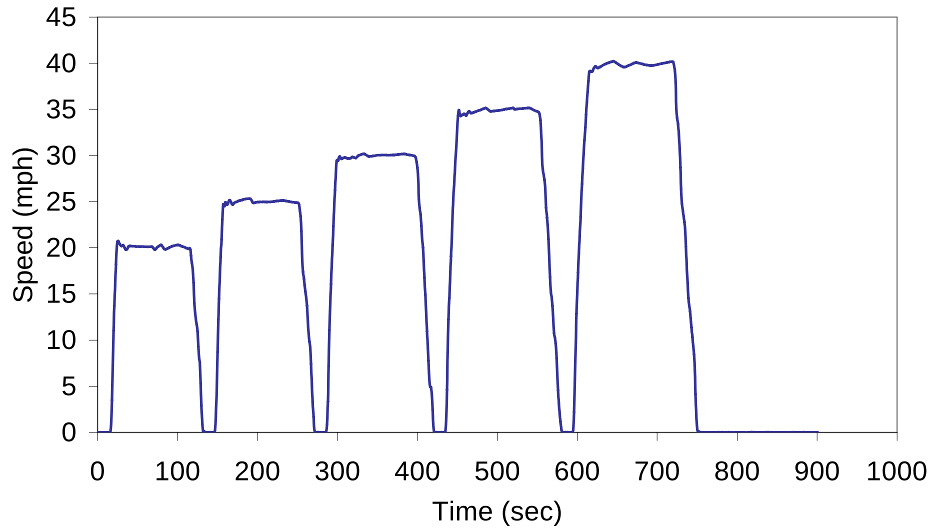
Figure 3.3 EPA Urban Dynamometer Driving Schedule for heavy-duty vehicles (UDDS) target speed versus time plot.



3.2.2.4 WVU 5-Mile Route

The WVU 5-Mile Route is also called the Modified WVU Truck Cycle although it is a route, by definition. A route, as opposed to a cycle, utilizes the vehicle's maximum acceleration to the peak speed followed by a steady-state operation before decelerating to an idle. The total distance is always controlled to equal five miles, regardless of the acceleration the vehicle can attain. This causes the speed versus time schedule to vary from one vehicle to another. Consequently, a more powerful vehicle will be able to complete the driving portion in less time. An example of a TB driving this schedule is shown in Figure 3.4 and because the bus can accelerate relatively quickly, the extended idle period at the end of the cycle for this bus is to match the total driving time of 900 seconds. Clark and Lyons (1999) have given details of the 5-Mile Route. The target cycle cannot be illustrated on a speed-time plot, but can be illustrated on a speed-distance plot.

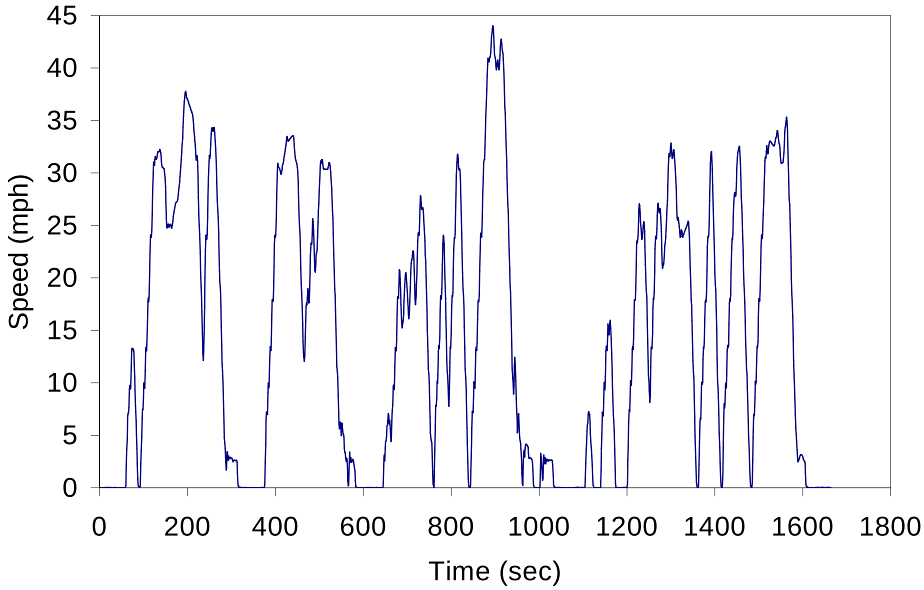
Figure 3.4 Plot of actual speed versus time for a TB driving the WVU 5-Mile Route. The simulated test weight was 33,000lbs. The vehicle was powered by a 275 hp. DDC Series 50 engine and was equipped with a 5 speed automatic transmission.



3.2.2.5 City Suburban Heavy Vehicle Route (CSHVR)

The City Suburban Heavy Vehicle Route was developed at WVU by concatenating microtrips (defined as one delivery stop to the next) from data collected in the field from trucks operating in Richmond, Virginia and Akron, Ohio [Clark et al., 1998]. A speed versus time plot of a TT driving the CSHVR is shown in Figure 3.5.

Figure 3.5 Actual speed-time plot of a 1996 TB driving the City Suburban Heavy Vehicle Route.



3.2.2.6 Effect of Driving Schedule on Emissions

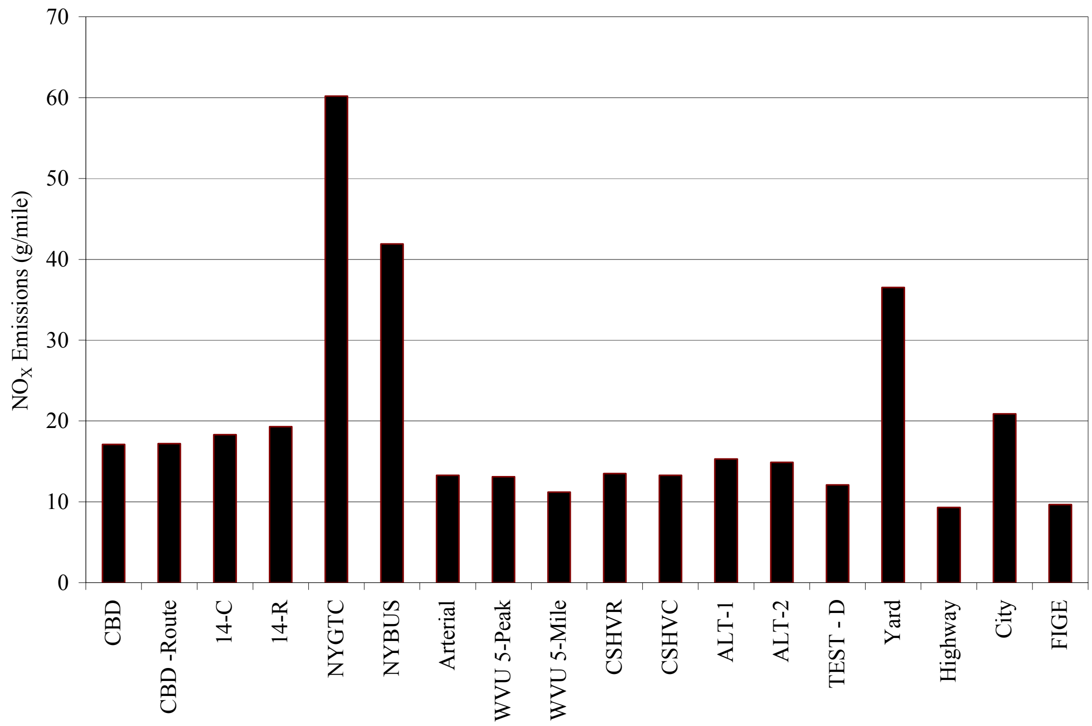
It is certain that the test cycle used has profound effect on the emissions yielded [Nine et al., 2000]. As an example, consider steady speed operation of a truck. At low speeds, the emissions are dominated by the tire rolling losses, while at high freeway speeds, wind losses may start to dominate.

PM emissions depend strongly on transients. In particular, PM will arise during rapid increases in torque demand as well as during and immediately after gear changing. PM will also be produced in disproportionately high quantity close to or at the engine maximum torque rating at any given engine speed. Consideration suggests that the engine is likely to undergo a similar number of shift transients regardless of test weight, whereas prolonged high loads may be dependent on test weight. Beyond these concerns over transients, the same logic on road and wind load may be applied to the PM production as well.

HC and CO emissions are usually low for diesel engines. HC emissions may be quite erratic, while CO emissions follow similar trends to PM, because they depend on in-cylinder air-fuel ratio [Clark et al, 1999].

A portion of testing conducted at WVU under a contract for the National Renewable Energy Laboratory (NREL) involved testing of a single truck on many different test cycles. The NO_X emissions data in grams/mile are shown in Figure 3.6. Figure 3.7, and Figure 3.8 show the CO and PM emissions in grams/mile for the same vehicle. The vehicle was a 1995 GMC box truck with a Caterpillar 3116 engine rated at 170 hp. The fuel used was number 2 diesel and the vehicle had a test weight of 22,000 pounds. It can be seen that the NO_X emissions from this truck varied with the type of test cycle used. The New York Garbage Truck Cycle (NYGTC), New York Bus Cycle (NYBUS) and the Yard cycle with very low average speeds exhibit very high emissions levels.

Figure 3.6 NO_X emissions of various test schedules on a box truck [Nine et al., 2000, Clark et al., 2002].



The NO_X emissions varied by a factor of seven, being highest for a low speed, high idle content cycle, and lowest for a highway cycle. It is evident that cycles with long period of idle resulted in high values of NO_X emissions. This was also true for cycles with high percentage of idle operation for which the distance traveled were shorter than a similar cycle with less idle. This resulted in higher distance-specific emissions. PM and CO emissions are more variable than the NO_X emissions.

Figure 3.7 CO emissions of various test schedules on a box truck [Nine et al., 2000, Clark et al., 2002].

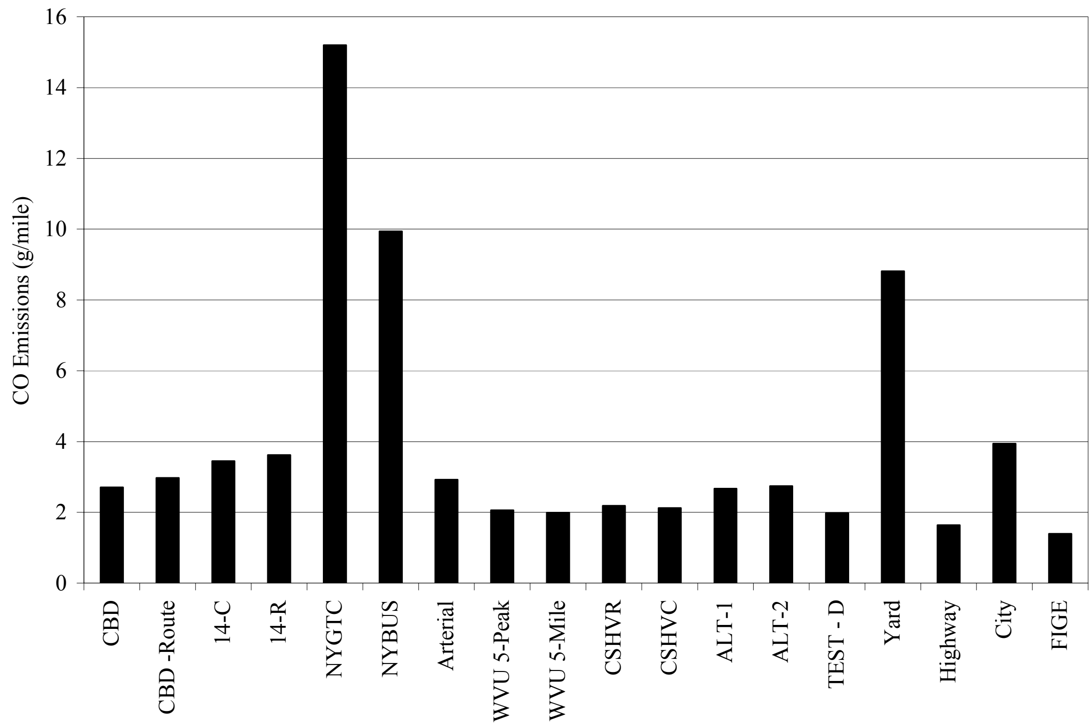
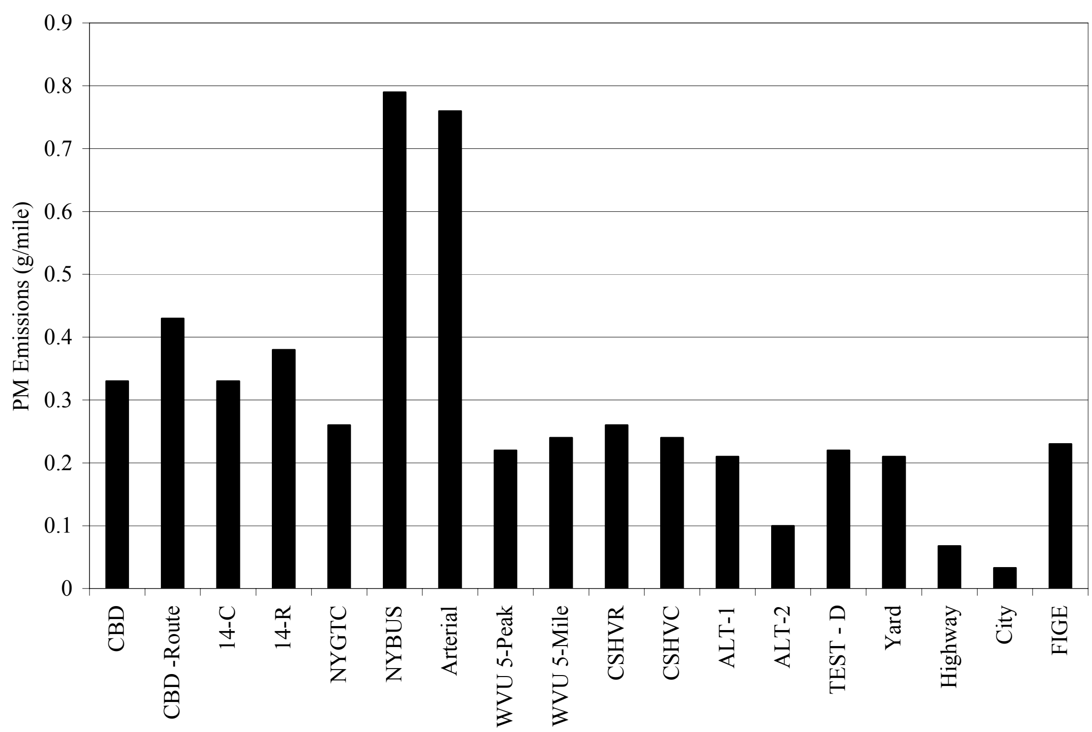


Figure 3.8 PM emissions of various test schedules on a box truck [Nine et al., 2000, Clark et al., 2002].



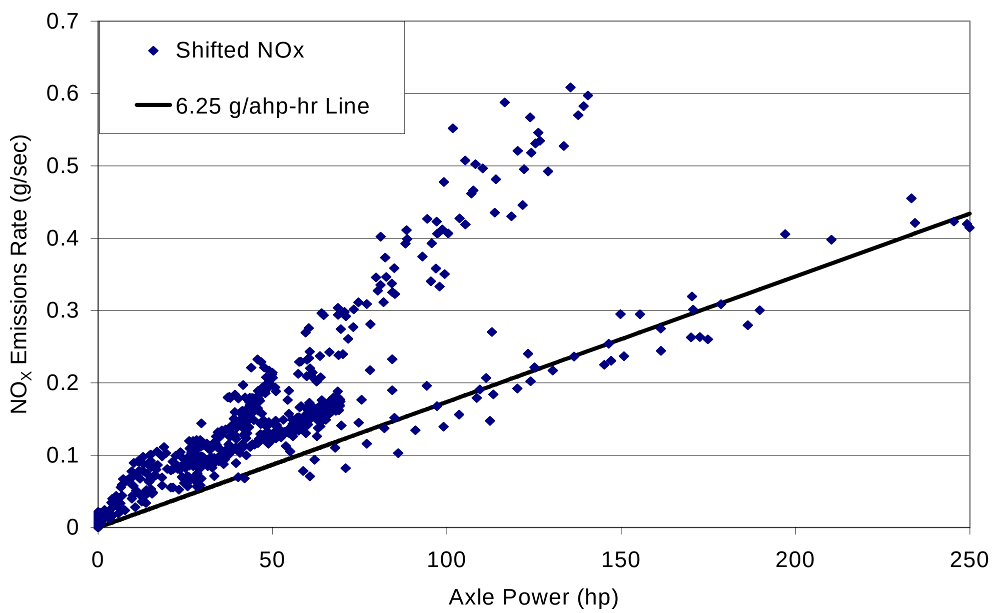
3.2.3 Injection Timing Variances

NO_X production does depend strongly on in-cylinder temperature and the time available for NO formation until the expansion stroke cools and "freezes" the reactions. In this way injection timing can have a profound effect on the NO_X level. PM emissions are also known to be affected strongly by the timing of the in-cylinder fuel injection. Advanced injection timing will result in a longer mixing time for the injected fuel and in-cylinder air. This will result in better mixing of the fuel and air and hence better combustion of the fuel-air mixture and hence lower PM emissions. It is common to present a hyperbolic "NO_X-PM tradeoff" curve for an engine, with more advanced timing leading to higher NO_X, and lower PM. Within a reasonable operating range, there is also a tradeoff between NO_X and efficiency, with advanced timing leading to a higher NO_X levels and higher thermal efficiency (less fuel consumed).

Many modern electronically controlled engines do not embody timing throughout their operating range that reflects the timing employed during the engine certification test. These deviations in timing during "off-cycle" operation may lead to emissions of NO_X in grams/mile that are higher than those that would occur during the certification test at the same engine speed and load. In other words, a vehicle with an engine that complies with the certification may still result in higher fuel-specific or brake-specific NO_X emissions over large parts of the operating envelope in real world operation. The vehicle component or software that allows excess emissions to be produced has been termed a "defeat device" by regulators. In the case of a heavy-duty NO_X defeat device, the device (software) was active during steady-state operating modes such as cruising down the freeway, but was mostly inactive during transient operation [EPA, 1999]. According to a report by the EPA, these devices were built into heavy-duty diesel vehicles beginning in the 1988 model year, and completely removed by the 2000 model year.

Figure 3.9 presents a plot of chassis-based NO_X emissions versus power output at the rear axle for a late model diesel truck (Kern, 2000). These data were obtained by West Virginia University as part of its field research funded by the U.S. Department of Energy, Office of Transportation Technologies. The lower NO_X data set, when plotted versus axle power, corresponds well to the line of 6.25-g NO_X/ahp-hr (where ahp is horsepower measured at the rear axle). A certification rate of 5 g/bhp-hr, coupled with an assumed drivetrain efficiency of 80% yields a 6.25 g/ahp-hr value. The 80% value is offered as an approximation because precise records of transmission and drivetrain efficiency are not commonly available. Also, loads on the engine due to accessories are incorporated in the 20% loss. In the figure, the higher NO_X values represented by the upper "arm" of the bifurcation represent the "off cycle" operating points.

Figure 3.9 Smoothed axle power versus shifted NO_X showing bifurcation of data.



Injection timing variations influence the overall emissions inventory in two ways. Firstly, the timing variations cause the actual NO_X inventory to be higher than predicted based upon certification data, and secondly, the timing variations cause the actual PM inventory to be lower than predicted based upon certification data. It is widely acknowledged that the NO_X effect is far more significant than the PM effect. Timing variations in electronically controlled diesel engines present the single greatest obstacle to present day emissions inventory prediction. Clark et al. (2002) found the injection timing strategy to be a significant factor in influencing diesel emissions. Neural network model prediction performed on engine-dynamometer emissions UDDSata showed that NO_X emissions can be predicted reasonably accurately using a simple 3-layer model. PM and CO could not be predicted to the same extent due to their complicated formation mechanism (Tehranian, 2003). The author however believes that avoiding too many inputs from engine map and adding some other input as oxygen concentration may lead to some improvements in CO predictions.

3.3 Methods of Generating Emissions Factors

Various approaches exist for the prediction of heavy-duty vehicle emissions contributions to the national or to a regional inventory. In the absence of accurate measurement of emissions from every vehicle performing every task, all approaches must be an approximation and it may prove impossible with current data to develop a highly accurate approach. Following are some of the approaches that can be used for emissions prediction [Kern, 2000, Clark et al., 2003].

1. Use of Certification Data
2. Direct Use of Chassis Dynamometer Data
3. Use of Power Based Emissions Factors
4. Use of NO_X / CO_2 Ratios
5. Use of Modal Approaches
6. Use of Speed-Acceleration Data

3.3.1 Use of Certification Data.

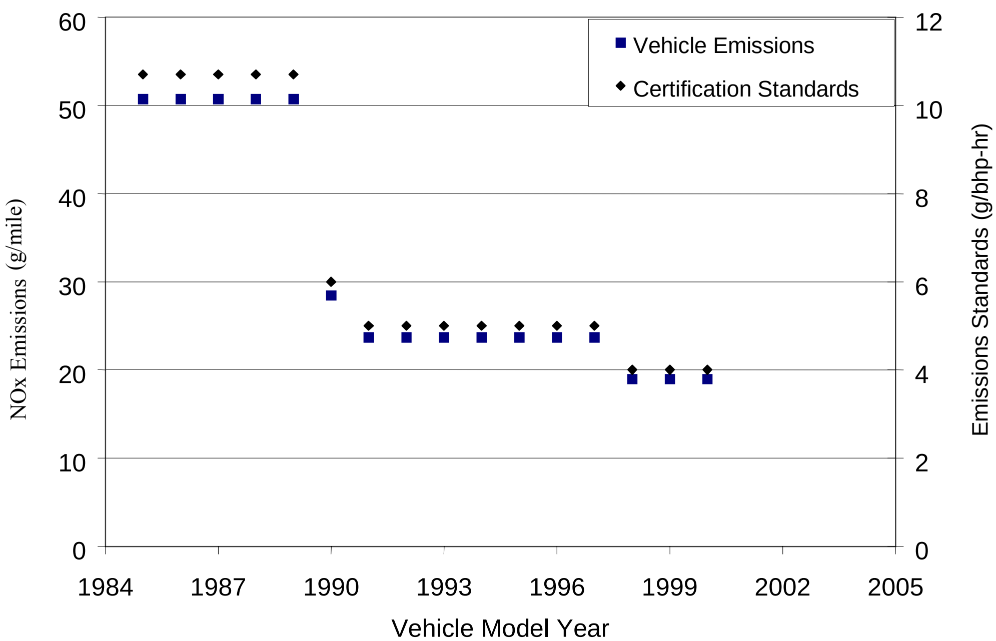
The present Environmental Protection Agency's (EPA) approach to prediction of emissions output from heavy-duty vehicles relies on the use of emissions certification data to yield, for each species, an emissions factor with units of g/bhp-hr. This is the approach used in the EPA's MOBILE 5 and it was continued in MOBILE 6. This approach is also used in the California Air Resources Board's (CARB) previous model EMFAC 7. The Federal Testing Procedure (FTP) is a transient stationary dynamometer test used to evaluate an engine's emission production level for federal certification and is used to provide emissions input for MOBILE. The target values (engine speed and load values) were arrived at through the use of a Monte Carlo simulation of data collected in Los Angeles, CA and New York, NY in the early 1970's. The vehicles represented in the study had a lower power-to-weight ratio than current highly turbocharged diesel powered heavy-duty vehicles.

Emissions factors for heavy-duty vehicles for use in models such as MOBILE are usually expressed in grams/mile. However, the emissions certification data for the engines that power these vehicles are available in units of grams per brake horsepower-hour (g/bhp-hr). Machiele (1988) has proposed a method to convert the certification data to vehicle emissions. To use this method, the conversion factor of brake horsepower-hour per mile (bhp-hr/mile) of the vehicle is needed. The conversion factor is obtained using the fuel density, fuel energy content, engine fuel conversion efficiency and fuel economy of the vehicle. The formula for vehicle emissions in g/mile is given earlier in this chapter.

Figure 3.10 shows the trend through two decades of emissions of a vehicle that achieves a fuel economy of 3.0 miles per gallon and has a brake specific fuel consumption of 0.5 pounds per brake horsepower-hour (Kern, 2000). These values are from the representative data given in

Machiele's report for a 1980's vintage heavy-duty diesel vehicle. The emissions factors in g/mile are then multiplied by vehicle miles traveled (VMT) to yield the mass of emissions released into the environment. The emissions factors can also be expressed in terms of grams per second (g/sec) if the speed of the vehicle is known. Emissions in g/sec are determined by multiplying the g/mile data by miles/second. A speed correction factor exists for emissions of NO_X in the MOBILE approach.

Figure 3.10 Plot of vehicle NO_X emissions versus model year using the data from Machiele (1988) (Kern, 2000).



The main problem with using this method is that the FTP emissions certification test is based on vehicle behavior that is probably not relevant to the average real world vehicle usage. Also, it does not properly represent the extremes of freeway cruising and stop-and-go city service vehicle behavior. The emissions tests were conducted under closely controlled conditions with respect to intake air temperature and the engine intake and exhaust manifold pressures. In reality, engines are subject to the vagaries of weather and the influence of altitude and maintenance. Certification data may also not reflect emissions in the field if "off-cycle" injection timing strategies are employed in the engine controller. The EPA's emissions inventory model MOBILE 6, and ARB's EMFAC 2002 incorporate corrections for off-cycle operation.

Also there is little information as to how the emissions vary with accumulated engine mileage. Even though manufacturers provide these factors, they do not account for the tampering and/or malfunction. Some effects of tampering have been described by McKain et al. (1998). Concerns over the effect of vehicle condition will rise as exhaust aftertreatment devices become prevalent in use.

3.3.2 Direct Use of Chassis Dynamometer Data

Heavy-duty vehicles can be tested on a chassis dynamometer for emissions characterization, as is the present approach for light duty vehicles [Clark et al., 1995, Graboski et al., 1998, Deitzman et al., 1985]. The emissions results can be obtained directly in g/mile for each emissions constituent. A simple approach for prediction therefore involves taking the product of these emissions factors and the vehicle miles traveled. This approach is at least as valid as the FTP-based approach and offers the advantage that fuel economy need not be considered in the process. All else being equal, a vehicle with a less efficient drivetrain would simply yield higher emissions factors in units of grams/mile.

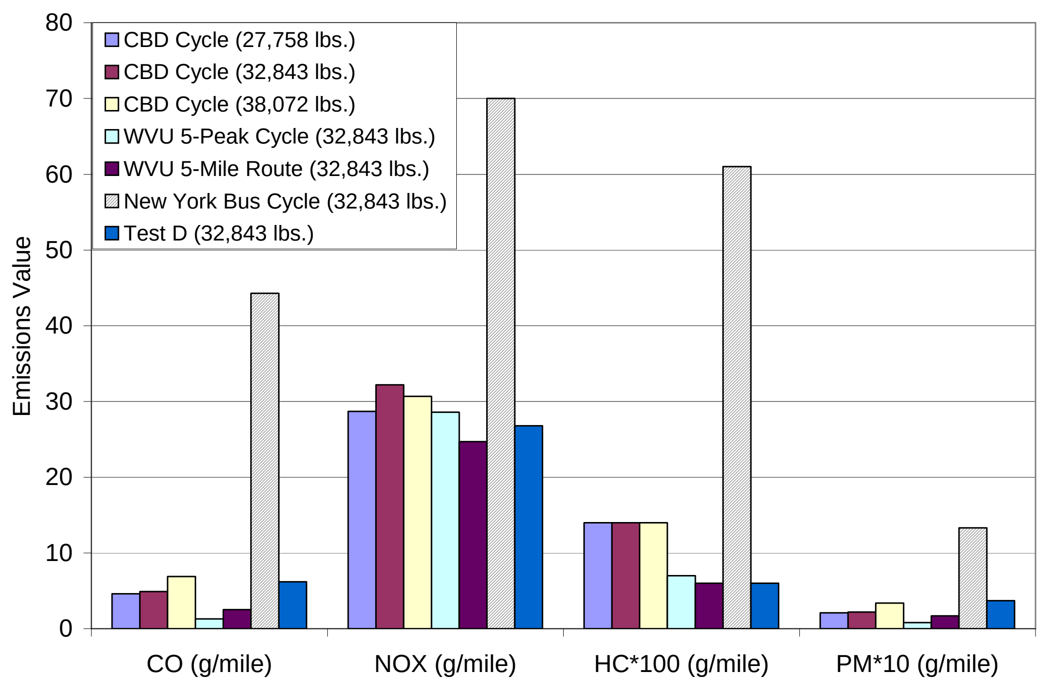
One advantage of chassis testing is that the vehicles can be tested as received, including influences of tampering or malfunction that might be lost if the engine were first removed from the vehicle. There is also the advantage that vehicles are more readily tested using chassis dynamometer systems than by removing the engine from the vehicle, so that data more representative of the whole fleet, rather than new vehicles.

There is no single cycle that mimics the real world spectrum of vehicle activities. Although the Urban Dynamometer Driving Schedule (40 CFR, Part 86) exists as a companion to the engine certification test, it does not correlate well with the FTP engine certification test [Deitzman and Warner-Selph, 1985] and does not represent all behaviors.

The California Air Resources Board is now employing direct chassis based emissions measurements from either a cycle or a route for the new EMFAC 2002 model. Based on these data, the approach of using direct chassis dynamometer data for emissions inventory has appeal only for future testing following the development of a suite of cycles that are acceptably representative of fleet behavior, considering regional and vocational differences.

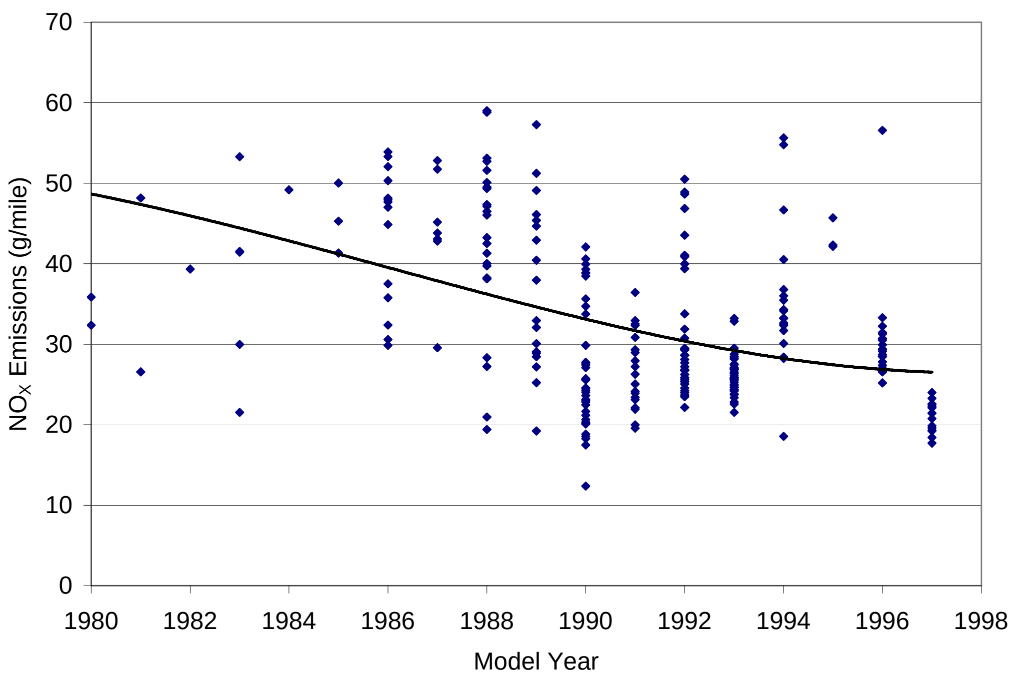
Figure 3.11 shows the results from a chassis test performed on a 1996 TB. The effect of test weight and test cycle used on resulting emissions can also be seen.

Figure 3.11 Emissions data from the 1996-TB on different test weights and test cycles (Clark et al. (1997)).



The chassis-testing laboratory at WVU reports results for a vehicle driving a test schedule in g/mile of an emissions species. These data can be used directly as an emissions factor for that vehicle providing that the test cycle used was representative of the vehicle's actual use. Figure 3.12 shows the results of testing of full size transit buses. Testing was performed by WVU on diesel-powered buses driving the CBD test cycle described in SAE J1376. The line shown on the plot represents the trend of bus emissions factors, but this is specific to the CBD behavior. Further data, showing trends of emissions of Detroit Diesel powered buses have been published by Clark et al. (2000).

Figure 3.12 Vehicle NO_X emissions versus model year for CBD cycle using data from chassis laboratory testing [Kern, 2000].

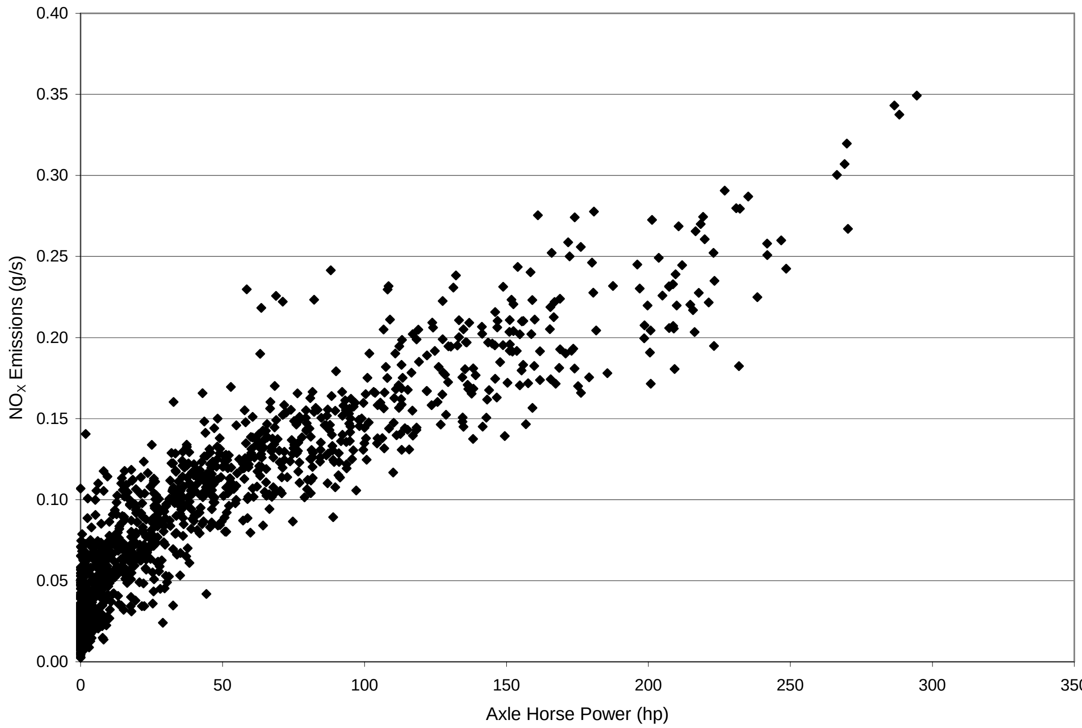


3.3.3 Power Based Emissions Factors

Chassis dynamometer data can be used to obtain the emissions factors in a different way. Continuous emissions data from chassis dynamometer are acquired for NO_X, CO and HC. These data can be considered in the development of models that can then be used to project the emissions from the vehicle under a broad range of operating conditions. The data gathered by the WVU Translabs were acquired by the laboratories in units of parts per million for each of the species in diluted exhaust, but are readily converted to units of grams per second using the dilution tunnel mass flow rates. The dilution tunnel mass flow rate varies over the cycle depending on the engine speed and power requirements, and is also affected by the exhaust gas mass flow rate from the vehicle.

It is possible, if a successful model can be developed to relate the emissions from a vehicle to its operating parameters, that the emissions may be predicted for any other cycle for which the operating conditions are known. Ramamurthy and Clark (1998) have proposed an approach where the emissions are related to the instantaneous power output from the vehicle rear axle. Instantaneous chassis dynamometer emissions data for a particular vehicle were processed to yield the instantaneous emissions in grams per second as a function of the single variable of rear axle power, as shown in Figure 3.13. In using these factors, one must employ correct time alignment of instantaneous power and the emissions constituent [Messer and Clark, 1995]. Work has been completed at WVU to understand the time alignment of instantaneous power and its resulting emission production. The axle power was measured instantaneously yet the resulting emissions are measured after a time delay of the gas traveling from the engine to the analysis bench. An effect defined as "smearing" has also been observed and is when a spike of emissions from the engine is smeared into a bell-shaped curve (in time) when it reaches the analyzers [Ramamurthy and Clark, 1998, Ganesan and Clark, 2001].

Figure 3.13 Continuous NO_X versus power for a 1995 TT tested on the CSHVR.



Ramamurthy and Clark (1998) have found this approach of relating emissions to axle power to be successful for modeling of NO_X emissions (and for carbon dioxide, which is not regulated) from diesel vehicles but difficulties arise for the cases of CO and HC. Modern turbocharged diesel engines yield CO and HC emissions, which are highly dependent on transient engine behavior, so that additional variables beyond axle power must be considered in a model.

Although modeling of gaseous emissions is possible because continuous data are available, PM is measured gravimetrically as a composite for the whole test, so that instantaneous PM is not known. Clark et al. (1998) have argued that the best available tool at present involves proportioning the lumped PM over the duration of the cycle in linear proportion to the CO. There is sympathy in PM mass production and CO production although lubricant contribution, heavy HC contribution, sulfate contribution and varying PM formation mechanisms all render this as an approximate approach. Data from devices such as the Tapered Element Oscillating Microbalance are being used with more accurate estimates of instantaneous PM emissions.

Once an acceptable model has been formulated, vehicle activity data can be used to project as many cycles as are needed to describe the vocations of the fleet The model can be used to predict emissions from each of those cycles in g/mile without direct experimentation. This approach is considered to have great potential, but will require further effort in model development.

3.3.4 Use of NO_X / CO_2 Ratios

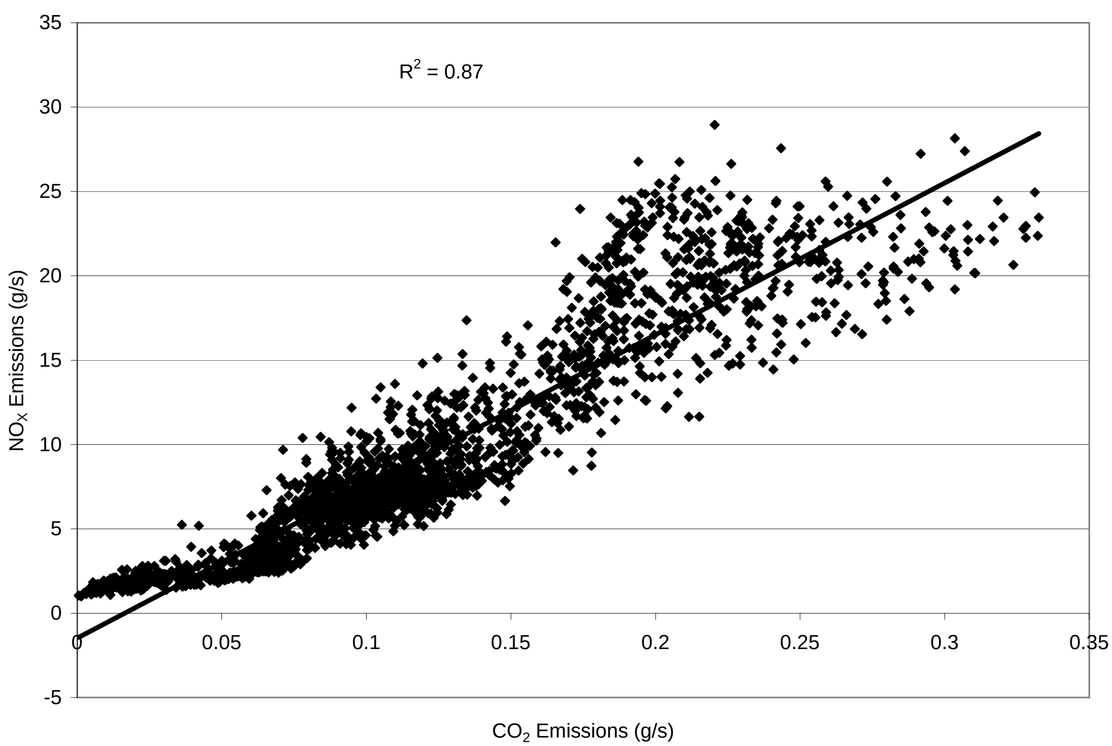
NO_X and CO_2 values on a mass basis (grams) can easily be reported as a NO_X over CO_2 ratio. Fuel usage on a volume basis (gallons) can be inferred from the CO_2 mass production thus giving a predictor of NO_X emissions produced on a per gallon of fuel basis. The CO_2 production, or mass of CO_2 produced per mass of fuel used, can be obtained by using a carbon balance. It should be noted that CO and HC have very little effect on the carbon balance, as they are very low for diesel engines. This results in 44 grams of CO_2 produced for (approximately) every 13.8 grams of diesel used (based on a C:H ratio of 1:1.8). It may be noted that the fuel density and carbon content vary a little, hence, this method will be a good approximation unless the exact composition is known. Again, the database values are subject to the characteristics of the driving cycle followed on the chassis dynamometer.

Figure 3.14 shows the continuous data of NO_X plotted against CO_2 for 5 consecutive test runs on the CBD Cycle. The vehicle was a 1996 TB powered by a Cummins M-11 engine rated at 280 hp. Data scatter arises due to the "smearing" of instantaneous values by the two analyzers coupled with the presence of severe transients in the cycle. The average value of the ratio throughout this testing was determined to be 0.014 grams of NO_X per gram of CO_2. To predict vehicle emissions in grams/mile, the fuel mileage of the vehicle, density of the fuel, and CO_2 production per amount of diesel need to be determined. Then Equation 3.4 can be used to obtain the emissions value in grams/mile.

$$\frac{gNO_x}{mile} = \left(\frac{0.014\, gNO_x}{gCO_2}\right)\left(\frac{44\, gCO_2}{13.8 g\ diesel}\right)\left(\frac{gallon}{miles}\right)\left(\frac{3217\ g\ diesel}{gallon}\right) \qquad \text{Equation 3.4}$$

This approach will not prove sufficiently accurate if the engine timing varies substantially over the operating envelope. It will also be unreliable for other emissions species, which do not vary in proportion to CO_2.

Figure 3.14 Variation of NO_X with CO_2 for 5 consecutive test runs on the CBD cycle for a 1996 model year 40-foot TB powered with 280 hp Cummins M11 engine.



3.3.5 Modal Approaches

In addition to the continuous data approach, segments of the test may be considered, yielding modal emissions factors. It is argued that any vehicle behavior can be viewed as a collection of modes such as “cruising at high speed,” “idling” or “accelerating.” This approach exists as a simplification of the modeling approach, but it is argued that it will at best be approximated when considering response of PM, CO and HC to transient engine behavior.

3.3.6 Use of Speed-Acceleration Data

This approach is closely related to the modeling and modal approaches and is the approach favored in this research. It is common in reviewing light-duty vehicle emissions data to consider the speed and acceleration of the vehicle to be governing independent variables. For a given vehicle, the speed governs the road load losses, and the product of speed and acceleration governs the instantaneous inertial power demand. Emissions for a vehicle can be binned according to its speed and acceleration characteristics in the post processing of cycle data. There is a question as to whether vehicle speed and acceleration offer advantage over the single variable of power in heavy-duty applications, since the engine responds solely to power demand, and vehicle acceleration rates are low in heavy-duty vehicles. However, since more gear shifting occurs at lower speeds, speed is likely to add value as a variable. The objective of the emissions model is therefore to provide an emissions value, in the units of g/mile or g/sec, for each species as a function of speed and acceleration. This is accomplished by placing measured instantaneous emissions data into pre-determined speed and acceleration bins, and averaging the data in each bin.

These averaged emissions values can then be combined with the vehicle activity data to obtain emissions factors for inventory application. The vehicle activity data is the percentage of the time the vehicle spends in a particular speed and acceleration value (bin) in real world operation, for the entire range of speed and acceleration encountered by the vehicle. The vehicle activity data can be converted to the speed-acceleration form similar to the emissions data. Then, the emissions value in each bin can be multiplied by the activity data, which is the percentage of time of operation in a particular bin, in the corresponding bin and summed over the whole range of bins to obtain an average value. This procedure is explained in detail in Chapter 5.

Problems in using a speed-acceleration approach for prediction arise when the speed-acceleration profile of the vehicle for which an emissions factor is to be determined encounters hills, or grades. The extent to which a grade affects the emissions is not well known because the test schedules used to date on chassis dynamometers have no provisions for simulating hills. The WVU chassis dynamometers do not have the ability to motor the vehicle to simulate downhill driving and are limited in their ability to absorb full power at low speeds. This presents a problem when correlating the emissions to the speed-acceleration profile of the actual activity of a vehicle. As a vehicle is traveling uphill, the rate of change of speed (acceleration) is low while the axle power demand is high as compared when the vehicle is traveling on level ground, as simulated on the dynamometer. The only full-power emissions data that are gathered on the dynamometer are at a high rate of change of speed. This means that the predicted emissions of the vehicle ascending the grade will be lower than the actual emissions produced. This will hold true for emissions species that correlate well with axle power, such as NO_X. Likewise, the emissions predicted when the vehicle descends a hill will be higher than the actual emissions produced because the vehicle can attain a relatively high rate of change of speed, for which there are emissions data at full power.

As discussed earlier, not all existing cycles cover the speed-acceleration envelope thoroughly. Figures 3.15 and 3.16 show the speed vs. acceleration plots for a 1996 TB powered by 280 hp Cummins M-11 engine over a CBD cycle and a the same vehicle tested over the City-Suburban Heavy Vehicle Route (CSHVR) respectively. The CBD has all acceleration rates defined, whereas the CSHVR is a speed-distance based route, and at certain points requires maximum vehicle acceleration. It can be seen that the CBD cycle fails miserably in covering the envelope, although the CSHVR has better coverage. In real world operation a vehicle may be able to achieve acceleration rates that are higher than those demanded by a test schedule. In order to develop a model that can predict the emissions with reasonable accuracy for the real world operation, the UDDSata must be obtained for a wide range of acceleration and speed values that are typical of day-to-day vehicle operation. Real world emissions are affected by atmospheric conditions, altitudes, driving terrain, and nature of driving and engine thermal history. Aggressive driving with frequent braking or clutch riding can have a serious effect on emissions.

Figure 3.15 Speed versus acceleration for a 1996 model year TB driving the CBD Cycle.

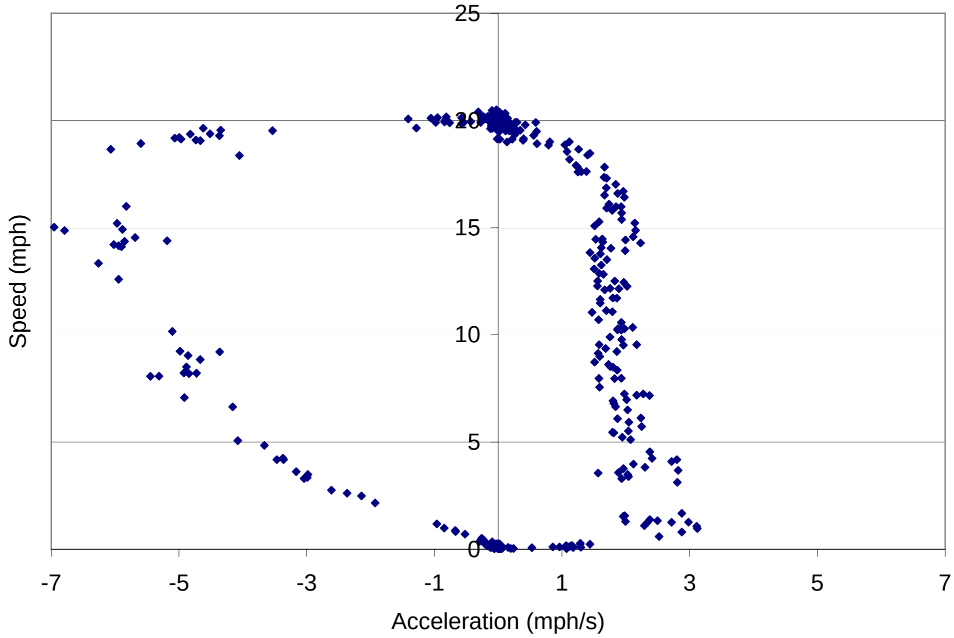


Figure 3.16 Speed versus acceleration for a 1996 model year TB driving the CSHVR.

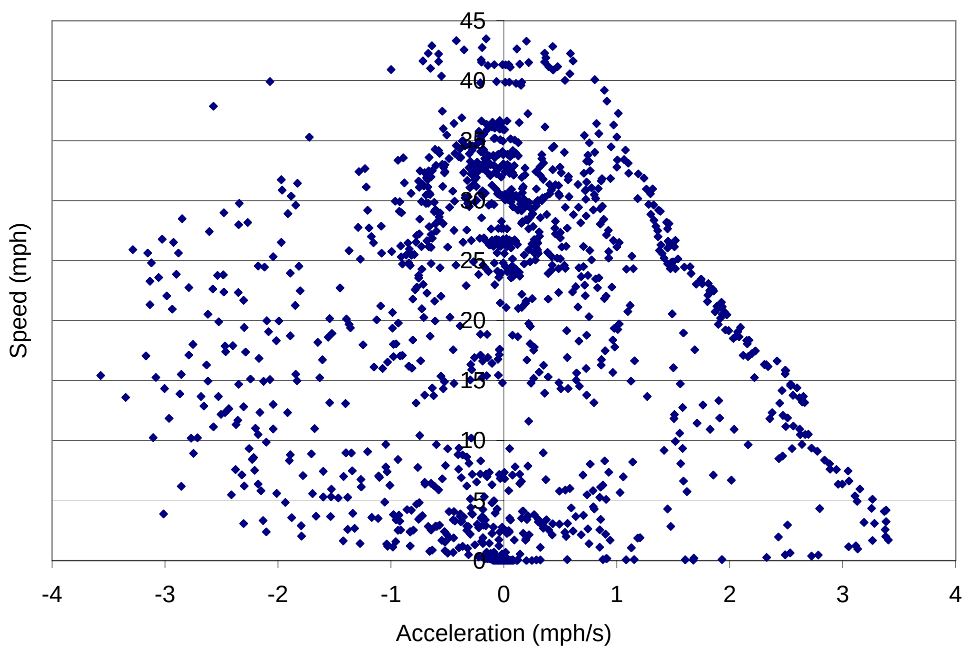


Table 3.4 Speed-acceleration based NO_X emissions (g/s) matrix for the 1994-97 model year tractor trucks. ND represents cells with no data.

Speed Bin	Heavy Acceleration	Medium Acceleration	Light Acceleration	Cruise	Light Deceleration	Medium Deceleration	Heavy Deceleration
0 - 2.5	0.1120	0.0645	0.0564	0.0291	0.0281	0.0196	0.0354
2.5 - 7.5	0.1684	0.1267	0.0837	0.0551	0.0220	0.0175	0.0397
7.5 - 12.5	0.1713	0.1896	0.1151	0.0660	0.0166	0.0147	0.0402
12.5 - 17.5	0.1822	0.2475	0.1804	0.0949	0.0142	0.0104	0.0536
17.5 - 22.5	0.3235	0.2864	0.2741	0.1018	0.0049	0.0077	0.0534
22.5 - 27.5	0.4505	0.3115	0.3405	0.1060	0.0022	0.0058	0.0537
27.5 - 32.5	0.4391	0.3805	0.3544	0.1148	0.0041	0.0048	0.0614
32.5 - 37.5	ND	0.3440	0.3893	0.1656	0.0124	0.0055	0.0615
37.5 - 42.5	ND	0.3977	0.4255	0.1959	0.0398	0.0080	0.0545
42.5 - 47.5	ND	0.4042	0.4214	0.2748	0.0633	0.0094	0.0639
47.5 - 52.5	ND	ND	0.2585	0.2827	ND	ND	0.1168
52.5 - 57.5	ND	ND	ND	ND	ND	ND	ND

As an example, Table 3.4 shows the speed-acceleration based emissions factor table for the 1994-97 model year tractor trucks available in the WVU database. This table was obtained from the continuous NO_X emissions data for all the tests performed on the 1994-97 model year tractor trucks. The analysis was performed as a part of a research project sponsored by NCHRP. The NO_X emissions were grouped according to a speed-acceleration based matrix. Each speed bin was 5 mph wide except for the first bin. The acceleration ranges were divided into seven bins; heavy acceleration (> 2 mph/s), medium acceleration (> 1 mph/s and < 2 mph/s), light acceleration (> 0.3 mph/s and < 1 mph/s), cruise (> -0.3 mph/s and < 0.3 mph/s), light deceleration (> -1 mph/s and < -0.3 mph/s), medium deceleration (> –2 mph/s and < -1 mph/s), heavy deceleration (< -2 mph/s). The value in each bin represents the average value obtained from all the UDDSata in the 1994-97 model year group. The bins that have a “ND” have no data available for that speed and acceleration conditions. It can be seen that the existing database does not provide emissions values at speeds above 52.5 mph.

It can be concluded that the existing models do not take into consideration all of the parameters that affect the emissions from heavy-duty diesel vehicles. There is a need for a model that can predict the emissions accurately and at the same time incorporate the effects of different parameters that have profound effect on the exhaust emissions. It is evident that the driving schedule used has a significant effect on emissions from a vehicle. Clearly, none of the present day driving schedules covers the entire speed-acceleration range that is representative of real world operation. Additional data covering high-speed operation typical of highway operation is needed to augment the existing database.

The extent to which vehicle weight/load affects the emissions needs to be studied in detail. There is a need for an emissions prediction methodology that fully explores and incorporates the various parameters that affect the emissions.

4 Experimental Set Up and Details of Tests Conducted

4.1 Experimental Set-Up

Specific data have been gathered to characterize and study the effects of various parameters on heavy-duty diesel vehicle emissions. Emissions data were obtained using various test schedules, which consisted of cycles or routes. Data were gathered using the West Virginia University Transportable Heavy Duty Emissions Testing Laboratories (Translabs) [Clark et al., 1999 and Lyons et al., 1995]. Figure 4.1 shows a truck being tested on one of the transportable laboratories. The two West Virginia University Translabs are heavy-duty chassis dynamometer systems that can be moved from site to site with a dedicated semi-trailer and a laboratory trailer. The cycle-averaged emissions data gathered by the laboratories are added to a database. Each laboratory consists of a mobile chassis test bed and an emission analyzer trailer. The test vehicle was driven onto the test bed via ramps and chained down with the drive wheels supported on four pairs of free-spinning rollers. Right and left sets of flywheel weights and eddy-current power absorbers load the vehicle through drive shafts connected to the vehicle's right and left hubs respectively. Road load (wind and rolling resistance) is simulated by two Mustang air-cooled eddy-current power absorbers. The power absorber load was varied by electric current flow controlled by Dyn-loc IV power absorber controllers. Irreversible (frictional) dynamometer losses were considered during system calibration. Axle torque was measured using two Eaton torque transducers with a 22,600 N-m (16,669-ft -$lb_{f.}$) rating. Vehicle exhaust was ducted to a full flow dilution tunnel with nominal flow rate options of 0.47, 0.71, 1.0, or 1.2 m^3/s (1000, 1500, 2000, or 2500 standard cubic feet per minute [scfm]) controlled by a critical flow venturi. Sample probes near the end of the dilution tunnel delivered diluted exhaust gas samples to the analyzer bench for continuous concentration measurement of HC, CO, CO_2 and NO_x. Analyzer output was collected using an RTI-815 analog to digital data acquisition board that delivered an ADC signal (0-4000), depending on the selection of a particular channel, to a computer at a frequency of 10Hz. Data were readily converted to a frequency of 1 Hz and available in continuous second-by-second format.

The data collected during the tests were available as continuous records of vehicle speed, vehicle power, and emissions of CO, NO_X, and HC. Data were also available for CO_2, and PM emissions from TEOM.

Figure 4.1 A historical photograph showing one of the WVU Transportable Laboratories testing a New York city Department of Sanitation truck at Brooklyn Union Gas site.

4.2 Development of a High Speed Cycle

The existing data in the WVU database do not provide emissions data for heavy-duty trucks at high speeds typical of highway operation. Since typical highway operation represents longer period of cruise at highway speeds, there is a need for emissions data at these speeds in order to obtain an emissions factors table for an inventory prediction model. To augment the existing WVU database with high-speed data, a cycle was developed with typical highway operation. This cycle was created using the second-by-second data available from the Battelle study of truck activity in California [Battelle, 1999]. The cycle was created using truck trips from activity data collected by Battelle Memorial Institute, limited to Class 8 vehicles, and limited to trips that included high speed driving.

For the development of a cycle, the most important parameter is vehicle speed as a function of time. In the present effort, speed-time data from the Battelle database were used for that purpose. The speed-time data were divided into microtrips. A microtrip was defined as a period of driving activity typically commencing from an idle condition and ending at an idle condition.

Acceleration data were obtained from the first derivative of the speed-time data. Then the acceleration and speed data were separated into vehicle acceleration (VA), vehicle deceleration (VD), vehicle cruise (CR), and idle segments. Idle was defined as any time that the speed equals 0 mph and acceleration equals 0 mph/s. The VA, VD, and CR were differentiated by using different values of the acceleration as cutoff values discussed in Section 3.3.6 of Chapter 3. Cruise occurred when, according to the criteria set, the vehicle was not accelerating, decelerating or idling.

The above process reduced the second-by-second distance data to speed, VA, VD, CR, idle times, acceleration times, deceleration times, and cruise times. Next, two separate sets of statistics were generated: one set for each individual microtrip, and a second for the whole Battele database.

All statistics used in the development of the cycle excluded idle times. Idle times vary widely among heavy-duty vehicles. Some trucking companies have devices that shut down a vehicle when it idles for a certain length of time, hence, it was decided that the idle time would be added to the cycle after the active portions were developed in proportion to the idle time in the database. This does not affect the statistics of the cycle, because the idle times were excluded during the evaluation of the statistics.

Four main criteria that were considered for the cycle development were the degree to which the cycle was representative of the entire set of microtrips (the database) in terms of: average vehicle velocity (mph), standard deviation of velocity, the average value of velocity^2 (proportional to specific energy), and the standard deviation of velocity^2.

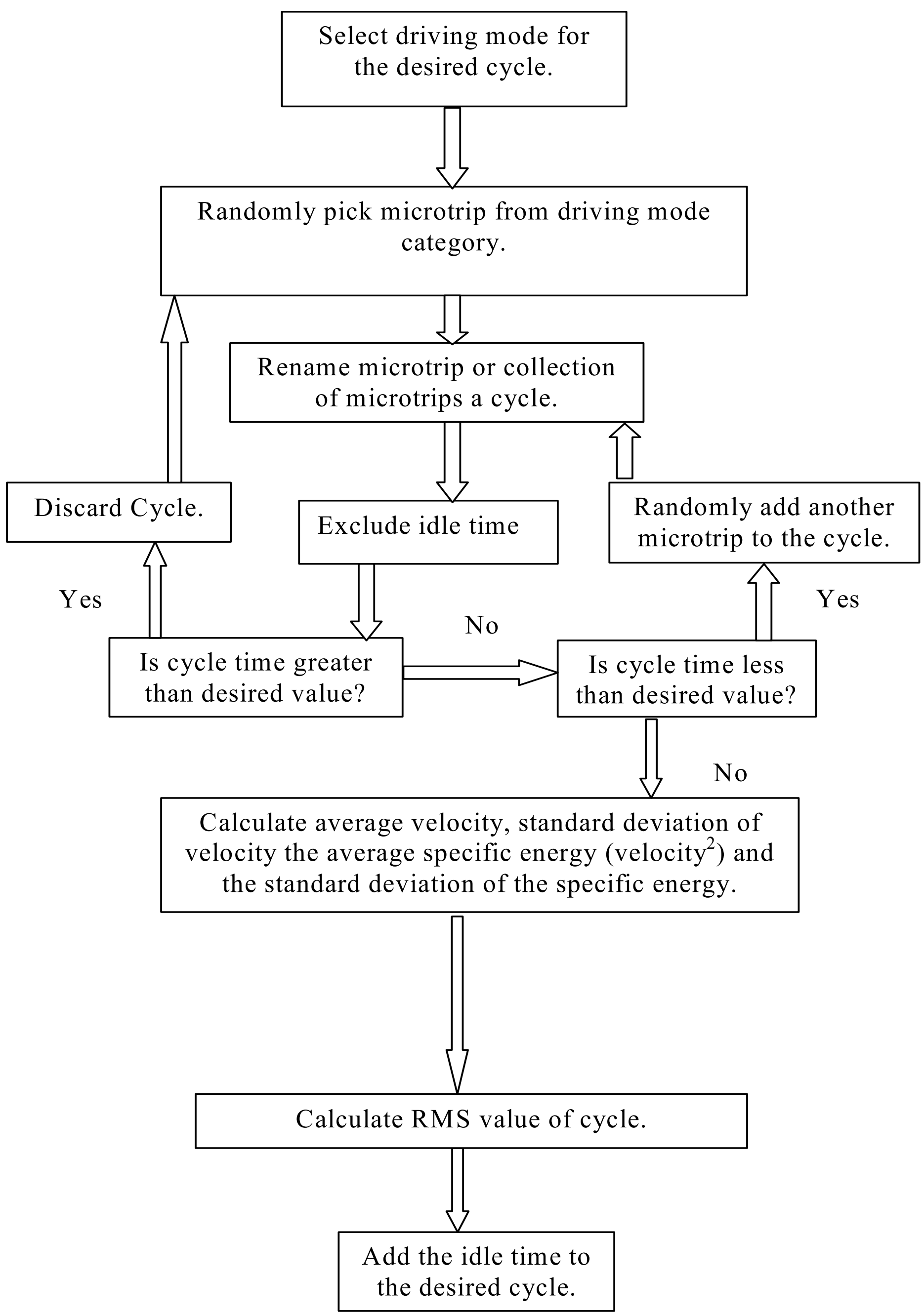
A cycle was developed by randomly adding together one or more microtrips until the total time of the microtrips reached a desired value. These combinations of microtrips (termed a "cycle") were examined to determine how well the above criteria were met

For each of the cycles thus formed, the average velocity (mph), standard deviation of velocity (mph), average velocity^2, and standard deviation of velocity^2 were determined. These values were then compared to the average values of the entire database using a root mean square (RMS) formula. The RMS value is given by

$$RMS = \left[\left(\frac{AS_{DB} - AS_{CYC}}{AS_{DB}} \right)^2 + \left(\frac{SS_{DB} - SS_{CYC}}{SS_{DB}} \right)^2 + \left(\frac{AE_{DB} - AE_{CYC}}{AE_{DB}} \right)^2 + \left(\frac{SE_{DB} - SE_{CYC}}{SE_{DB}} \right)^2 \right]^{0.5} \qquad \text{Equation 4.1}$$

where, AS is the average speed, SS is the standard deviation of average speed, AE is the average velocity^2, and SE is the standard deviation of velocity^2. The subscripts CYC and DB refer to the cycle and the database respectively. Figure 4.2 shows the flow chart used for the methodology used to develop the high-speed cycle.

Figure 4.2 Flow chart depicting the methodology used to develop the high-speed test cycle.



Each combination of microtrips or cycles had a RMS value. The goal was to pick a cycle with a low RMS value. Once the desired cycle was identified, the idle times were added back to form the final cycle. A cycle was developed using this method and its details are given below.

Decelerations were limited, by altering the cycle, to 2.5 mph/sec. Higher decelerations were encountered in original activity data, but these may have been associated with uphill grades coupled with braking or emergency stops, and high rates of deceleration are a safety issue during dynamometer testing. The resulting cycle was 1900 seconds long. The new cycle, termed the "Inventory Highway Cycle" (IHC) offered good coverage of speeds and accelerations typical of tractor-trailer operation. The maximum acceleration in the driver's target trace was 7.82 mph/sec and the highest speed attained was 68.08 mph. Table 4.1 gives the statistical information for this cycle. Figure 4.3 shows the actual speed-time performance of a 1995 model year TT over the new cycle (IHC). Figure 4.4 and Figure 4.5 show the plots of speed versus acceleration and distribution of operating points along speed and acceleration bins for the IHC. It can be seen that this cycle covers more fully the speed-acceleration envelope typical of tractor-trailer operation. It can be noted that the decelerations have been limited to –2.5 mph/s. Small differences existed between the target trace and actual performance due to the need to change gears and due to power limitations of the vehicle during transients.

Table 4.1 Statistical information for the Inventory Highway Cycle (IHC).

Data	Value
Maximum Speed (mph)	68.08
Average Speed (mph)	36.94
Total Duration (seconds)	1900
Total Distance (miles)	19.50
Maximum Acceleration (mph/s)	7.82
Total Idle Time (seconds)	124
Average Speed without Idle considered (mph)	39.5

Figure 4.3 Speed-time trace of the Inventory Highway Cycle (IHC).

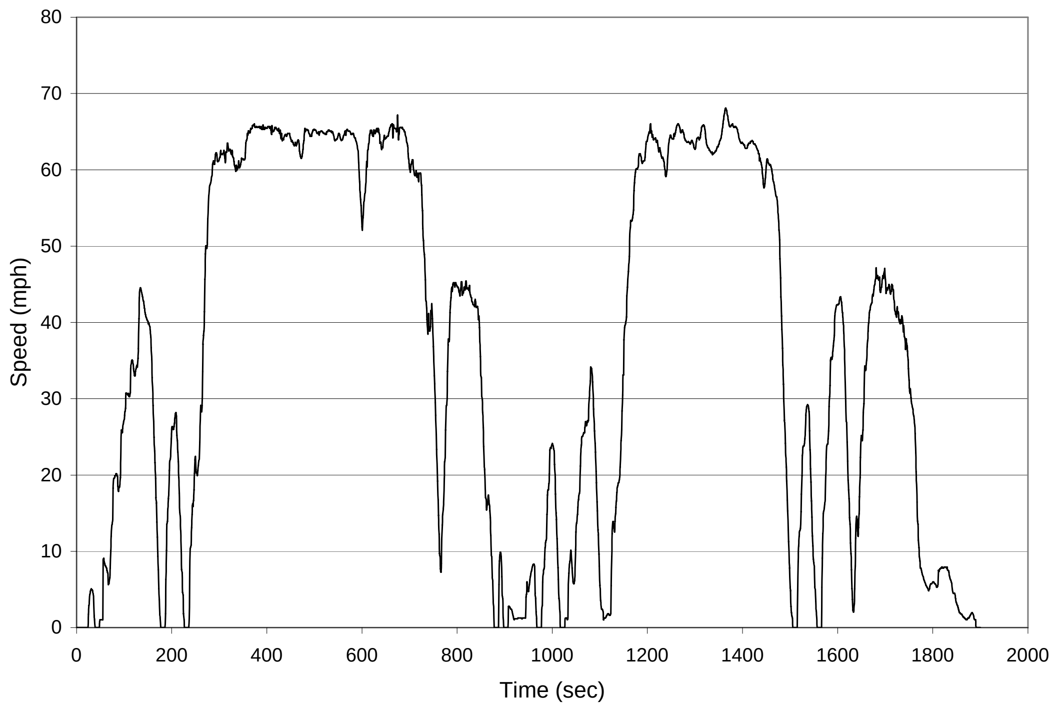


Figure 4.4 Speed-acceleration trace of the Inventory Highway Cycle (IHC).

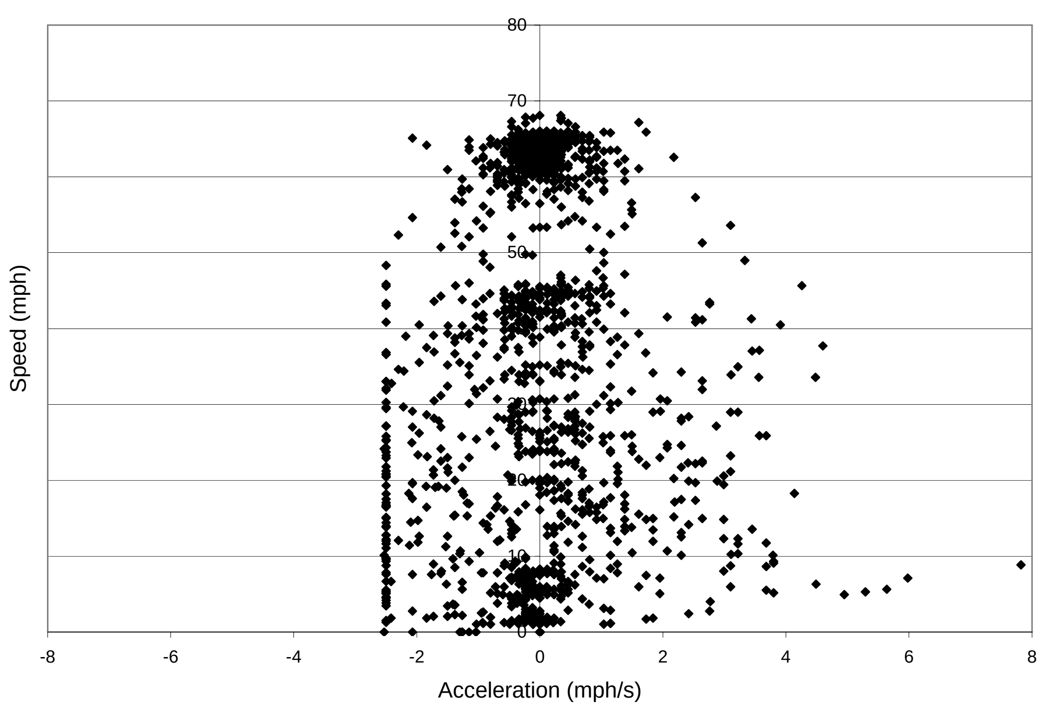
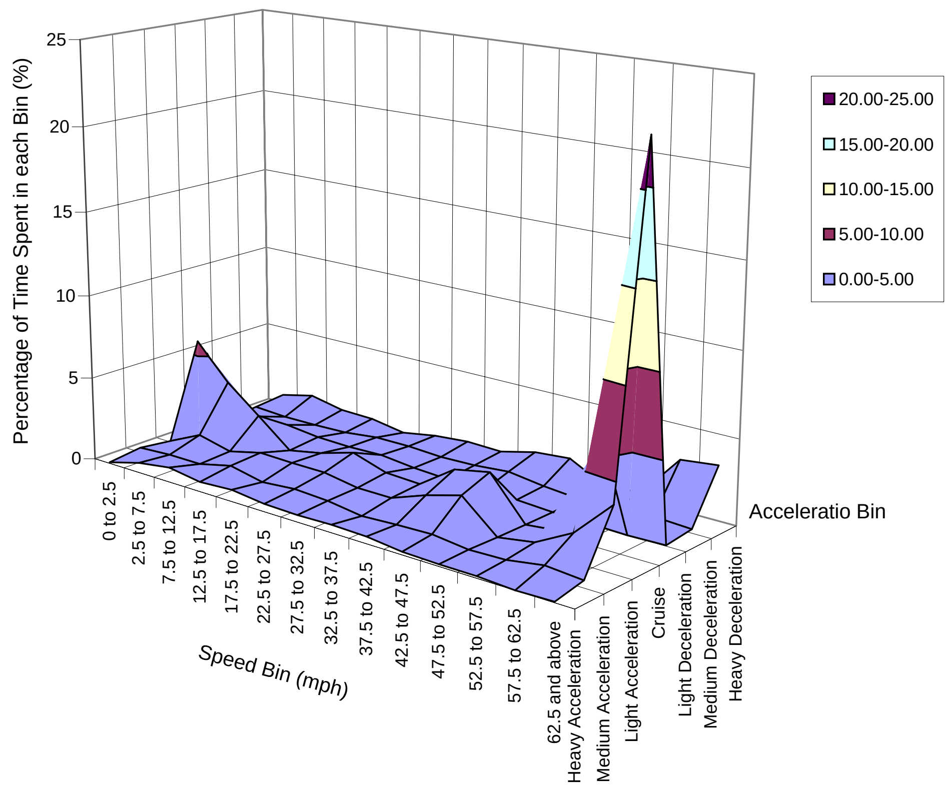


Figure 4.5 Distribution of operating points along speed and acceleration bins for the Inventory Highway Cycle (IHC).



4.3 Details of Vehicles Tested

Additional emissions data were obtained from two over the road trucks representing two different model year groups on two different cycles. The tested vehicles include “Test Vehicle 1,” which was a 1995 model year TT with a GVWR of 56,000 lb. and “Test Vehicle 2,” which was a 1982 model year truck with a GVWR of 80,000 lb. These vehicles were tested on the IHC and the CSHVR. The CSHVR provided coverage at lower speeds typical of urban stop and go traffic condition. The older model year truck was tested at a test weight of 60,000 lb. The newer model year truck was tested at test weights of 56,000 lb. and 42,000 lb. respectively.

The Test Vehicle 1 was tested on two different configurations. The first configuration was the as sold mode with off-cycle emissions and from here on is referred to as a "dual map" truck. In the dual map mode, the vehicle is capable of operating in the off-cycle mode (high NO_X). The same vehicle was also configured to operate with no off-cycle emissions. This is termed as "single map" and leads to lower NO_X emissions overall. This enabled the study of the effect of off-cycle emissions.

A detailed analysis was performed on the emissions data gathered from the two Test Vehicles and Table 4.2 gives the details of tests conducted on these two trucks.

Table 4.2 Tests conducted on the two over-the-road tractor trucks.

Test weight (lbs.)	**Test Schedule**	**Single/Dual Map**	**No. of Repeats**
Tests on the "Test Vehicle 1" - 1995 model year TT			
42,000	IHC	Dual Map	2
42,000	CSHVR	Dual Map	3
56,000	IHC	Dual Map	3
56,000	CSHVR	Dual Map	4
56,000	IHC	Single Map (Low NO_X mode)	4
56,000	CSHVR	Single Map (Low NO_X mode)	2
Tests on "Test Vehicle 2" - 1982 model year truck			
60,000	CSHVR	Mechanical	3
60,000	IHC	Mechanical	4

To cover the range of model year groups, emissions data available from Phase I of a research project conducted for Coordinating Research Council (CRC) were used. This study involved the testing of 25 different Class 8 trucks on 6 different driving schedules at two different test weights. Multiple test runs were available for each of the driving schedule. Table 4.3 gives the distribution of the trucks according to the model year groups. Details of the vehicles tested and the test schedules used are tabulated in Table 4.4. Emissions data from these tests enabled the study of the effects of model year groups and test weight on vehicle emissions.

Table 4.3 Distribution of vehicles according to model year group.

Vehicle Model Year Group	Number of Vehicles
1974 - 1977	2
1978 -19 81	2
1982 – 1985	3
1986 – 1989	3
1990 – 1993	6
1994 – 1997	4
1998 and Newer	5

Table 4.4 Details of test vehicles from the CRC Study

E55CRC (Truck)	Engine Manufacturer	Engine Model	Engine Model Year	Vehicle Model Year
E55CRC-1	Detroit Diesel Corp.	Series 60	1994	1994
E55CRC-2	Caterpillar	3406B	1995	1995
E55CRC-3	Cummins	NTCC-300	1985	1985
E55CRC-4	Caterpillar	C-10	2000	2000
E55CRC-5	Cummins	N14-435E1	2000	2000
E55CRC-6	Cummins	M11-300	1995	1995
E55CRC-7	Detroit Diesel Corp.	Series 60	1990	1990
E55CRC-8	Cummins	M11-300	1996	1996
E55CRC-9	Caterpillar	C12	1998	1998
E55CRC-10	Detroit Diesel Corp.	Series 60	1998	1998
E55CRC-11	Cummins	ISM-11	2000	2000
E55CRC-12	Cummins	300	1986	1986
E55CRC-13	Cummins	350	1978	1978
E55CRC-14	Cummins	LTA10	1985	1986
E55CRC-15	Cummins	NTC-350	1986	1973
E55CRC-16	Caterpillar	3208	1979	1979
E55CRC-17	Cummins	L-10	1993	1993
E55CRC-18	Cummins	L-10	1991	1991
E55CRC-19	Cummins	L-10	1987	1987
E55CRC-20	Detroit Diesel Corp.	Series 60	1992	1992
E55CRC-21	Caterpillar	3406B	1990	1990
E55CRC-22	Cummins	L10-280	1993	1993
E55CRC-23	Cummins	Plate Not Available	N/A	1983
E55CRC-24	Cummins	NTCC-350	1975	1975
E55CRC-25	Cummins	Plate Not Available	1983	1983

The vehicles listed in Table 4.3 were tested on the following six test schedules: UDDS (UDDS), AC5080, CARB Idle3 Cycle, CARB Cruise3 Cycle, CARB Trans3 Cycle, and CARB Creep Cycle.

Additional data were available from prior tests conducted by the WVU Translabs on five different vehicles at different test weights. These data were used to study the effects of test weight during initial part of this research. The new data available from the 25 Class 8 trucks were augmented to enable complete understanding of the effect of test weights on heavy-duty vehicle emissions.

The following vehicles were examined during this study and have been reported in prior papers [Clark et al., 1997,1999] covering individual studies.

1) A 1989 model year transit Bus (TB), powered by a DDC 6V-92TA engine, and with an automatic transmission. This vehicle was tested at 19,429 lb. and 32,042 lb. over the Central Business District (CBD) cycle.
2) A 1989 model year transit Bus (TB), powered by a DDC 6V-92TA engine, and with an automatic transmission. This vehicle was tested at 19,429 lb. and 32,042 lb. over the NY composite cycle.
3) A 1996 model year transit bus (TB), powered by DDC Series 50 engine, and with an automatic transmission. This vehicle was tested at 27,650 lb., 32,825 lb. and 38,000 lb. over the CBD cycle.
4) A 1998 model year tractor truck (TT), powered by a Cummins N14 Celect engine, and with a manual transmission. This vehicle was tested at 26,000 lb., 36,000 lb. and 46,400 lb. over the CSHVR.

5) A 1994 model year tractor truck (TT), powered by a Cummins M11-330E engine, and with a manual transmission. This vehicle was tested at 29,000 lb., 42,000 lb. and 61,000 lb. over the CSHVR.

To study the effect of test schedule on the vehicle emissions, data from a prior study where a single vehicle was tested on 16 different cycles were used engine [Nine et al., 2001, Clark et al., 2002] The vehicle was a 1995 model year GMC Box Truck powered by a 170 hp, 6.6 liter Caterpillar. The vehicle was tested at 22,000 lbs. In prior research, the data from this truck have been used to train and predict emissions using Artificial Neural Network (ANN) [Tehranian, 2003]. Emissions data from this truck were used to compare the speed-acceleration approach with the ANN. Detailed analysis was conducted on the data from all the vehicles, including the two test vehicles and the results are presented and discussed in detail in the following chapters.

Table 4.5 Details of test schedules for the 1995 Box Truck.

Chassis Test Schedule	Length (seconds)	Distance (miles)	Maximum Speed (mph)	Average Speed (mph)
CDB	600	2.0	20.0	12.6
CBD Route	566	2.1	20.0	13.1
14-C	600	2.0	20.0	11.8
NYBUS	600	0.6	30.8	3.7
Arterial	291	2.0	40.0	24.8
5-Peak Cycle	900	5.0	39.9	20.0
5-Mile Route	759	5.0	39.9	23.7
CSR	1605	6.9	43.8	15.5
CSC	1700	6.4	43.8	13.5
ALT-1	1722	6.4	51.3	13.4
ALT-2	1590	6.3	38.7	14.2
Test_D	1060	5.6	58.0	18.9
Yard	1168	1.1	16.8	3.3
Highway	1648	15.5	60.7	34.0
City	1430	3.4	35.8	8.5
FIGE	1722	17.5	56.6	36.6

5 Development of Speed-Acceleration Based Emissions Factors Tables

This chapter describes the methodology that was used to generate the speed-acceleration based emissions factors tables from the continuous emissions data obtained from chassis dynamometer testing. Detailed analyses involved in generating emissions factor tables for the HC, NO_X, and CO are discussed. Results from the analysis are tabulated and are presented in a form that can be used for the emissions inventory prediction method that is favored in this dissertation.

A basic assumption used in constructing Heavy Duty Diesel Vehicle (HDDV) emission factors from the WVU chassis dynamometer data was that the second-by-second emissions at any given speed-acceleration point were independent of the overall speed-time profile over which the vehicle was being driven. In other words, it was assumed that a vehicle would have the same emissions (in grams per second) if it accelerates from 18 to 20 mph in one second regardless of the previous driving history during the trip. Given this assumption, emissions over a particular driving cycle can be estimated by applying the dynamometer-based emission rate at each speed-acceleration point in the cycle being evaluated. Summing the gram per second emissions over the entire cycle and dividing that total by the distance of the cycle then gives emissions in terms of grams/mile.

The WVU database, which was used in this research, consisted of individual test runs of heavy-duty vehicles that were driven on different test sequences. The term “test sequences” encompasses both routes and cycles that are present in the database.

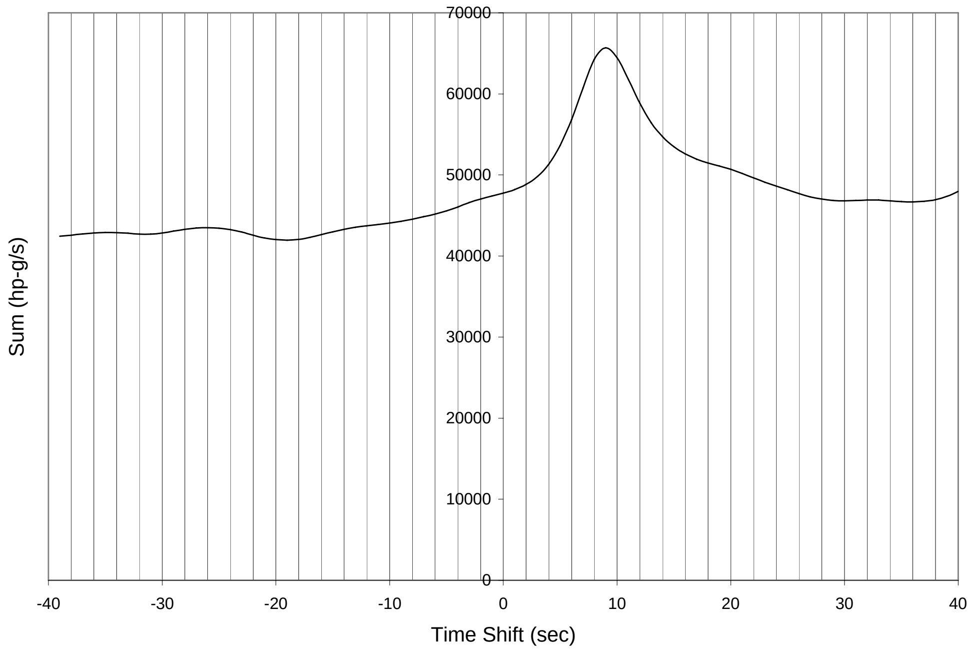
5.1 Time Alignment of Emissions Data

The test run data were available as continuous records of vehicle speed, vehicle power, and emissions of CO, NO_X and HC. As the exhaust gas leaves the vehicle, it travels through a transfer pipe, into the dilution tunnel, and then to the analyzers where the emissions were measured. The vehicle speed and load were measured instantaneously at the axle, and there was a delay time between the measurement of speed and load at the axle and the measurement of the exhaust gas produced from that speed and load. This time delay was observed in the emissions data for each emission species, and represents the residence time of the exhaust in the transfer pipe and dilution tunnel from the vehicle's engine to the analysis bench. The time shift of the emissions data must be corrected to be able to correlate a particular speed-acceleration of the vehicle to an emissions event. This was accomplished using a cross-correlation method employing Equation 5.1.

$$S = \sum \frac{d\left(P(t)\right)}{dt} * \frac{d\left(m\left(t + \Delta t\right)\right)}{dt} \qquad \text{Equation 5.1}$$

where P is power in hp and m is emission species in grams/sec, they represent the continuous data recorded from the test. A time shift was chosen and the sum (S) was calculated using Equation 5.1. It was assumed that emissions are higher at higher power demand as it directly relates to the energy required and hence the amount of fuel burnt. The sum was calculated for different values of the time shift, Δt, and the time shift that produced the largest sum was used as the best correlation. This method has been used previously by Messer and Clark (1995). As an example, the plots of time shift vs. sum for NO_X, CO and HC emissions for the Test Vehicle 1 operating on the dual map are shown in Figure 5.1 through 5.3.

Figure 5.1 Plot of sum vs. time shift (Δt) for the NO_X emissions from the Test Vehicle 1 on dual map over IHC. Time shift in this case was 9 sec.



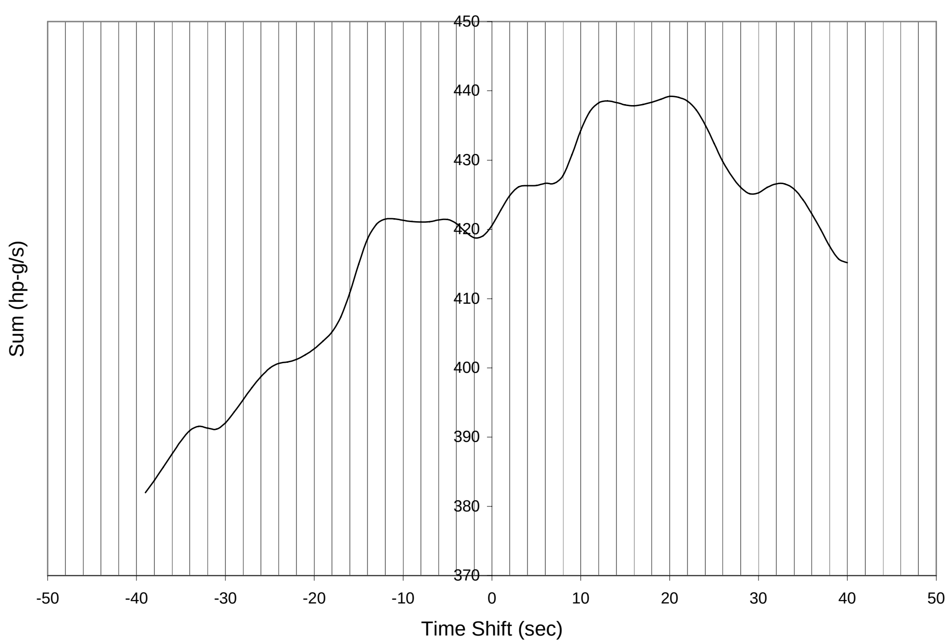
The time-shifted emissions were then grouped according to the speed-acceleration bins as a two-dimensional matrix in the units of grams per second. The speed and acceleration bin ranges were chosen to be same as those for the heavy-duty activity data obtained from Battelle Memorial Institute. The speed values were grouped into 14 bins with a width of 5 mph and the acceleration values were divided into 7 bins, namely: high acceleration, medium acceleration, light acceleration, cruise, light deceleration, medium deceleration, and heavy deceleration. Table 5.1 shows the acceleration ranges for each of these bins. A suite of tables was created according to the vehicle class and model year grouping for the UDDSata used in this research.

Table 5.1 Acceleration bin ranges

Bin label	Acceleration range
Heavy Acceleration	> 2 mph/s
Medium Acceleration	1 to 2 mph/s
Light Acceleration	0.3 to 1 mph/s
Cruise	-0.3 to 0.3 mph/s
Light Deceleration	-0.3 to –1 mph/s
Medium Deceleration	1 to 2 mph/s
Heavy Deceleration	< -2 mph/s

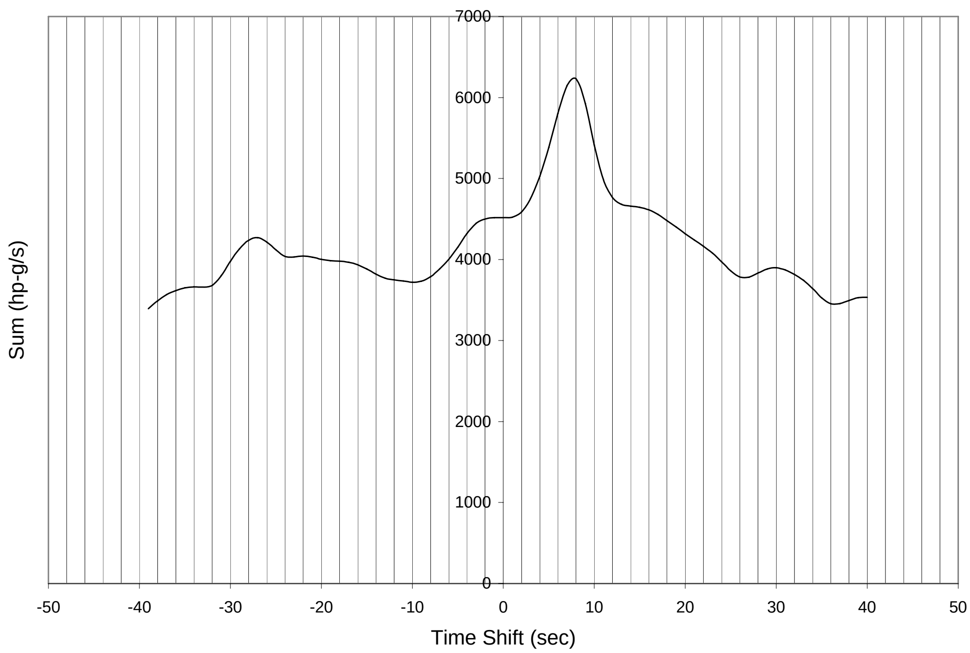
The continuous NO_X emissions for the test runs on Test Vehicle 1 and Test Vehicle 2 on two different cycles are shown in Figures 5.4 through 5.8. These figures all have the same axis scales to permit visual comparison.

Figure 5.2. Plot of sum vs. time shift (Δt) for the HC emissions from the Test Vehicle 1 on dual map over IHC. Time shift in this case is 20 sec. HC emissions do not correlate as well with power as do CO or NO_X emissions. There is some uncertainty in using this method for estimating delay time for HC emissions.



It can be seen in Figure 5.2 that the HC emissions does not correlate well with the power. This may be because the HC emissions may not be proportional to the power. HC emissions may be high at light loads due to incomplete (or poor) combustion. However, these are still relatively low compared to gasoline engines.

Figure 5.3. Plot of sum vs. time shift (Δt) for the CO emissions from the Test Vehicle 1 on dual map over IHC. Time shift in this case is 8 sec.



5.2 Presentation of Continuous Emissions Data

The continuous emissions data from the two over-the-road tractor trucks that were tested on the chassis dynamometer as a part of this research are presented in this section. These two trucks (discussed in Chapter 4) were tested on the CSHVR and the IHC. Test Vehicle 1 was tested at two different test weights of 56,000 lb. and 42,000 lb., and Test Vehicle 2 was tested at 60,000 lb. Figures 5.4 through 5.6 show some example plots of NO_X emissions in g/s vs. time. In the continuous plots for each of the emissions species, the y-axis uses the same scale to enable better visual comparison.

Figure 5.4 Continuous NO_X emissions in g/s for the Test Vehicle 1 operating on dual map over the City Suburban Heavy Vehicle Route (CSHVR) at 42,000 lbs.

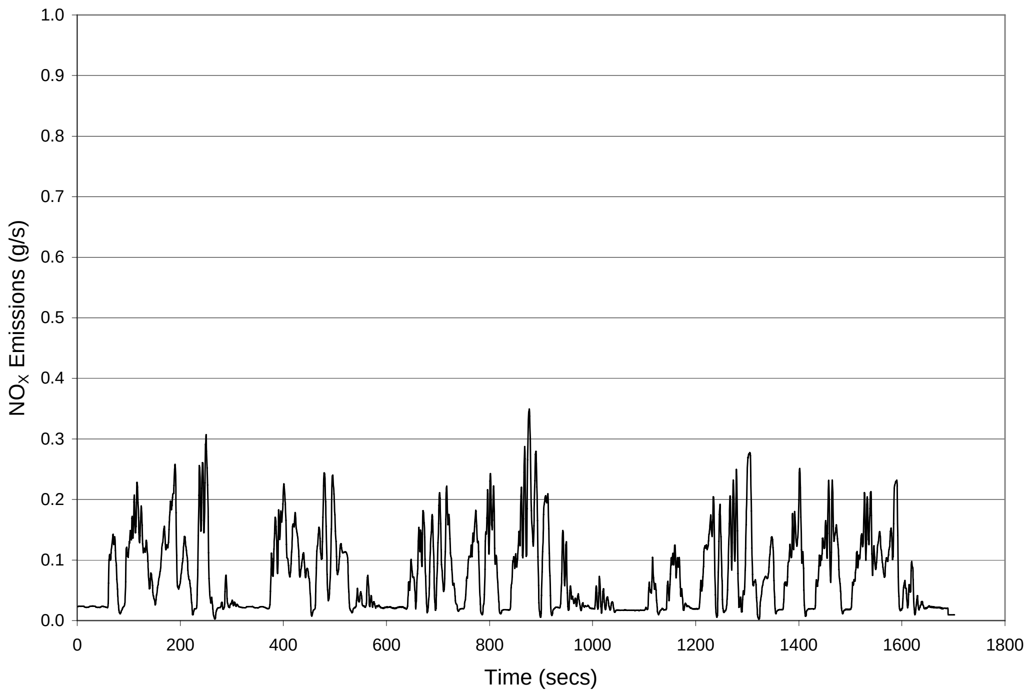


Figure 5.5 Continuous NO_X emissions in g/s for the Test Vehicle 2 on the City Suburban Heavy Vehicle Route (CSHVR) at 60,000 lbs.

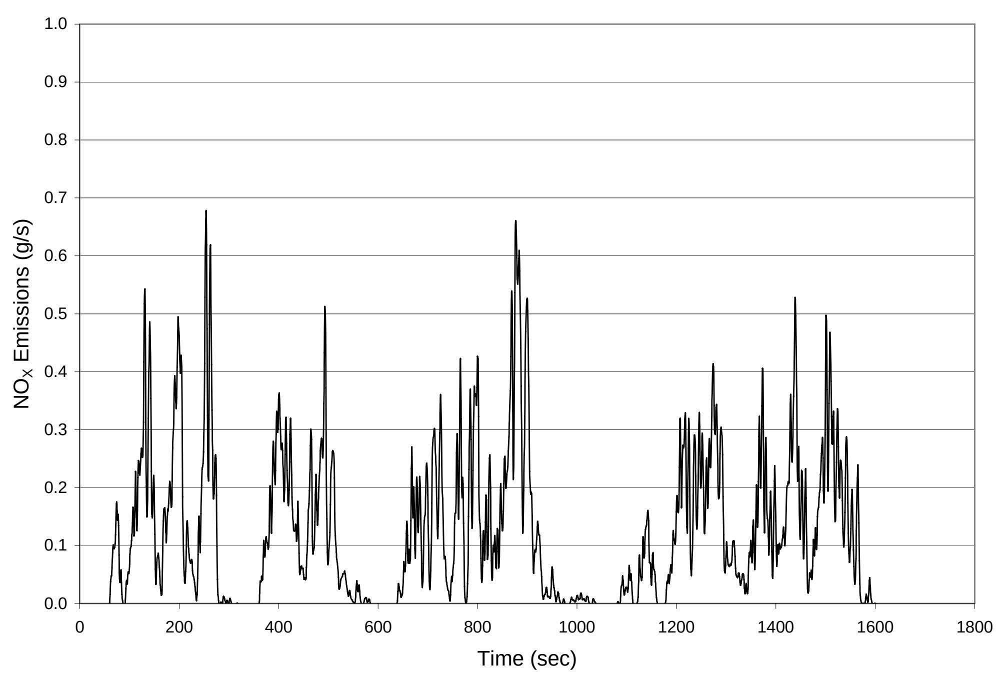


Figure 5.6 Continuous NO_X emissions in g/s for the Test Vehicle 2 on the Inventory Highway Cycle (IHC) at 60,000 lbs.

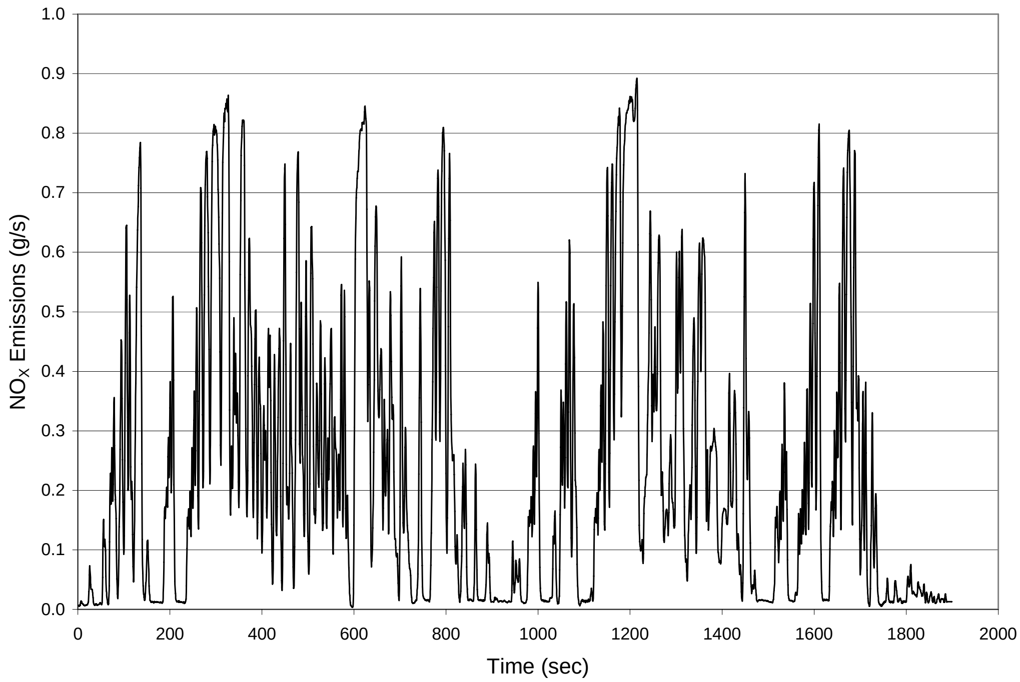


Figure 5.7 Continuous NO_X emissions in g/s for the Test Vehicle 1 operating on single map over the Inventory Highway Cycle (IHC) at 56,000 lbs.

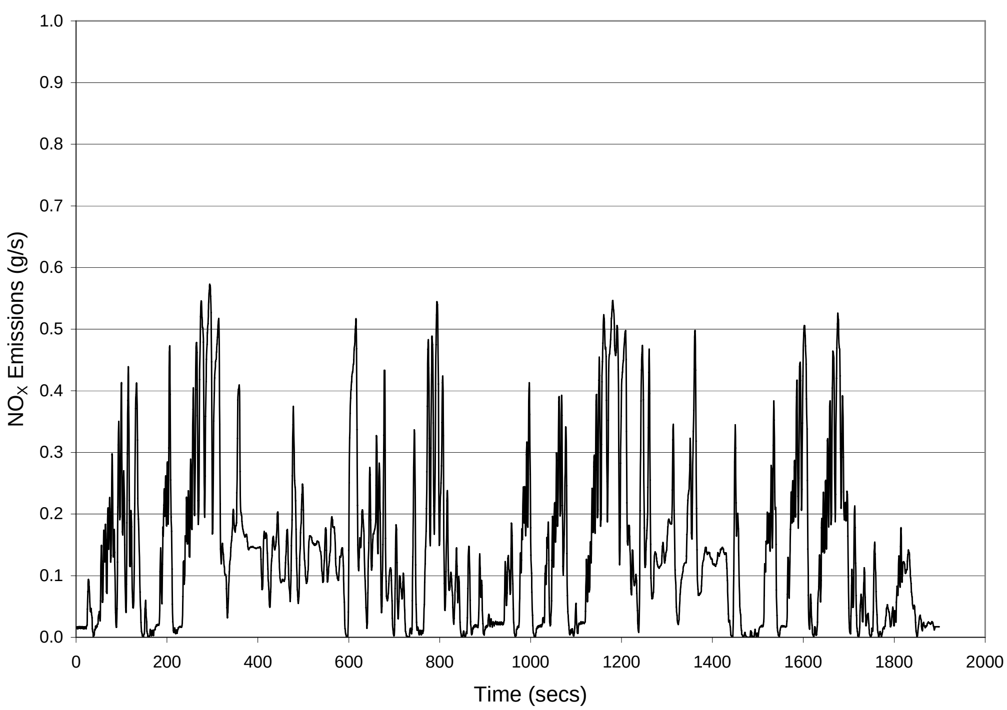
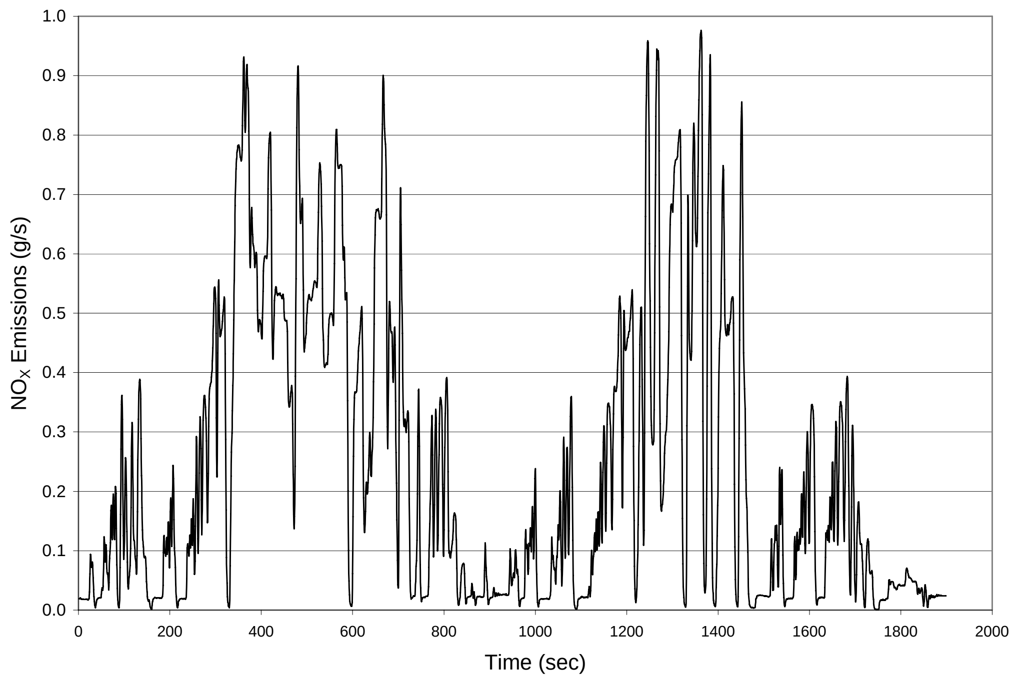


Figure 5.8 Continuous NO_X emissions in g/s for the Test Vehicle 1 operating on dual map over the Inventory Highway Cycle (IHC) at 56,000 lbs.



Figures 5.7 and 5.8 show the NO_X emissions for the Test Vehicle 1 operating on the single and dual maps respectively. It can be observed that the NO_X emissions are higher for the dual map (Figure 5.8). The NO_X emissions increased from a value of 14.61 g/mile for single map to 24.75 g/mile for the dual map operation. This increase in NO_X emissions (almost double) is attributed to the presence of off-cycle operation.

5.3 Generating the Speed-Acceleration based Emissions Factors Tables

Emissions values were grouped according to the speed-acceleration based tables for all the tests conducted on the two test vehicles. UDDSata were available on a second-by-second basis that is the data were available at 1Hz. In each cell, representing a particular speed and acceleration range, the emissions value is the weighted average. A detailed analysis was performed on all the emissions species. The emissions factors in g/s for all the species were tabulated and the values are presented in this section. For each test configuration, the tests were performed on two cycles (CSHVR and IHC). The emissions data from these two cycles were blended together to form composite speed-acceleration matrices. Tables 5.2 and 5.3 show the NO_X emissions data (raw, or "unsmoothed") and the number of occurrences as a population matrix for the Test Vehicle 1 operating on the single map over the CSHVR. The population matrix represents the number of occurrences in each bin; this is essentially the number of seconds the vehicle spent in a particular speed-acceleration bin. These are examples of the speed-acceleration based emissions tables that were discussed earlier in this chapter. Tables 5.4 and 5.5 show the NO_X emissions and the population matrix for the same truck on the IHC. The truck was operated at a test weight of 56,000 lbs. As can be seen, the CSHVR does not cover high-speed operation and this is augmented by the IHC data resulting in the blended matrix that has a better coverage over a wide range of speed and acceleration values. Table 5.6 shows the blended matrix for the NO_X emissions and Table 5.7 shows the resulting population matrix.

Table 5.2 NO_X emissions data in g/s for the Test Vehicle 1 on the single map over the CSHVR – 56,000 lbs.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.01733	0.01813	0.01902	0.01892	0.04862	0.07833	ND
2.5 To 7.5	0.01405	0.01935	0.02696	0.06721	0.09961	0.10809	0.10426
7.5 To 12.5	0.01146	0.01951	0.03904	0.16434	0.15192	0.18194	0.13639
12.5 To 17.5	0.01250	0.02117	0.03243	0.19525	0.17302	0.23250	0.39705
17.5 To 22.5	0.01246	0.01959	0.04585	0.15138	0.24675	0.30824	0.37151
22.5 To 27.5	0.01232	0.01903	0.02970	0.14271	0.26876	0.34784	ND
27.5 To 32.5	0.00819	0.01938	0.03245	0.14802	0.25356	0.36110	ND
32.5 To 37.5	ND	0.01495	0.06803	0.10465	0.24598	0.38937	ND
37.5 To 42.5	ND	0.02432	0.03583	0.22320	0.29479	ND	ND
42.5 To 47.5	ND	ND	0.07325	0.11689	0.22821	ND	ND
47.5 To 52.5	ND	ND	ND	ND	ND	ND	ND
52.5 To 57.5	ND	ND	ND	ND	ND	ND	ND
57.5 To 62.5	ND	ND	ND	ND	ND	ND	ND
62.5 and above	ND	ND	ND	ND	ND	ND	ND

Table 5.3 Population matrix for the Test Vehicle 1 on the single map over the CSHVR - 56,000 lbs.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	4	14	30	427	19	16	0
2.5 To 7.5	13	21	18	92	39	29	7
7.5 To 12.5	15	21	4	18	23	29	1
12.5 To 17.5	19	15	14	35	29	38	2
17.5 To 22.5	13	24	19	19	24	33	6
22.5 To 27.5	5	30	22	81	34	35	0
27.5 To 32.5	4	18	24	80	42	21	0
32.5 To 37.5	0	4	16	77	17	9	0
37.5 To 42.5	0	4	6	13	14	0	0
42.5 To 47.5	0	0	3	4	4	0	0
47.5 To 52.5	0	0	0	0	0	0	0
52.5 To 57.5	0	0	0	0	0	0	0
57.5 To 62.5	0	0	0	0	0	0	0
62.5 and above	0	0	0	0	0	0	0

Table 5.4 NO_X emissions data in g/s for the Test Vehicle 1 on the single map over the IHC - 56,000 lbs.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.01288	0.01287	0.02011	0.02294	0.05766	0.10150	ND
2.5 To 7.5	0.01673	0.01908	0.04077	0.06931	0.11729	0.12588	0.11398
7.5 To 12.5	0.01092	0.01013	0.03479	0.11740	0.17861	0.18139	0.18463
12.5 To 17.5	0.00610	0.01266	0.02435	0.16255	0.20069	0.25033	0.38345
17.5 To 22.5	0.00769	0.01102	0.02219	0.15685	0.23174	0.34579	0.44804
22.5 To 27.5	0.00537	0.01037	0.01688	0.15921	0.26934	0.38557	ND
27.5 To 32.5	0.00487	0.01314	0.01451	0.17841	0.26973	0.38942	ND
32.5 To 37.5	0.00506	0.01262	0.01501	0.12607	0.25243	0.49362	ND
37.5 To 42.5	0.01245	0.01236	0.02031	0.11810	0.35414	0.45454	ND
42.5 To 47.5	0.00452	0.00598	0.02323	0.10623	0.32182	0.51157	ND
47.5 To 52.5	0.00370	0.00428	0.01438	0.13084	0.55198	ND	ND
52.5 To 57.5	0.00263	0.00853	0.02361	0.26720	0.42853	ND	ND
57.5 To 62.5	ND	0.00937	0.02540	0.14224	0.42942	ND	ND
62.5 and above	ND	ND	0.03032	0.14205	0.33900	ND	ND

Table 5.5 Population matrix for the Test Vehicle 1 on the single map over the IHC - 56,000 lbs.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	5	11	18	178	17	5	0
2.5 To 7.5	12	11	27	101	23	19	11
7.5 To 12.5	15	9	8	35	18	27	1
12.5 To 17.5	14	7	7	17	13	28	1
17.5 To 22.5	11	11	11	19	13	25	2
22.5 To 27.5	8	8	7	21	15	20	0
27.5 To 32.5	7	9	8	24	24	16	0
32.5 To 37.5	7	6	6	9	5	23	0
37.5 To 42.5	3	5	21	47	31	9	0
42.5 To 47.5	4	1	16	48	27	2	0
47.5 To 52.5	2	4	3	1	13	0	0
52.5 To 57.5	1	6	7	15	23	0	0
57.5 To 62.5	0	4	29	94	34	0	0
62.5 and above	0	0	19	449	41	0	0

Figure 5.9 and Figure 5.10 show the plots of NO_X emissions in g/s for cruise and medium acceleration bins for Test Vehicle 1 on single map over IHC and CSHVR as a function of speed bin. It can be observed from Figures 5.9 and 5.10 that there are some deviations from the general trend for the cruise bin. This can also be clearly seen from Tables 5.2 and 5.4 respectively. The corresponding population matrices show that there is very low activity in these cells. These deviations may exist due to measurement errors and thus bring the need for smoothing of data, which is discussed in detail in Section 5.5 of this chapter. It can also be observed that extrapolation is very sensitive to the form of smoothing equation employed. Proper care must be taken when choosing a smoothing equation.

Figure 5.9 Variation of NO_X emissions (g/s) with speed for cruise and medium acceleration bins for Test Vehicle 1 on single map over IHC tested at 56,000 lb.

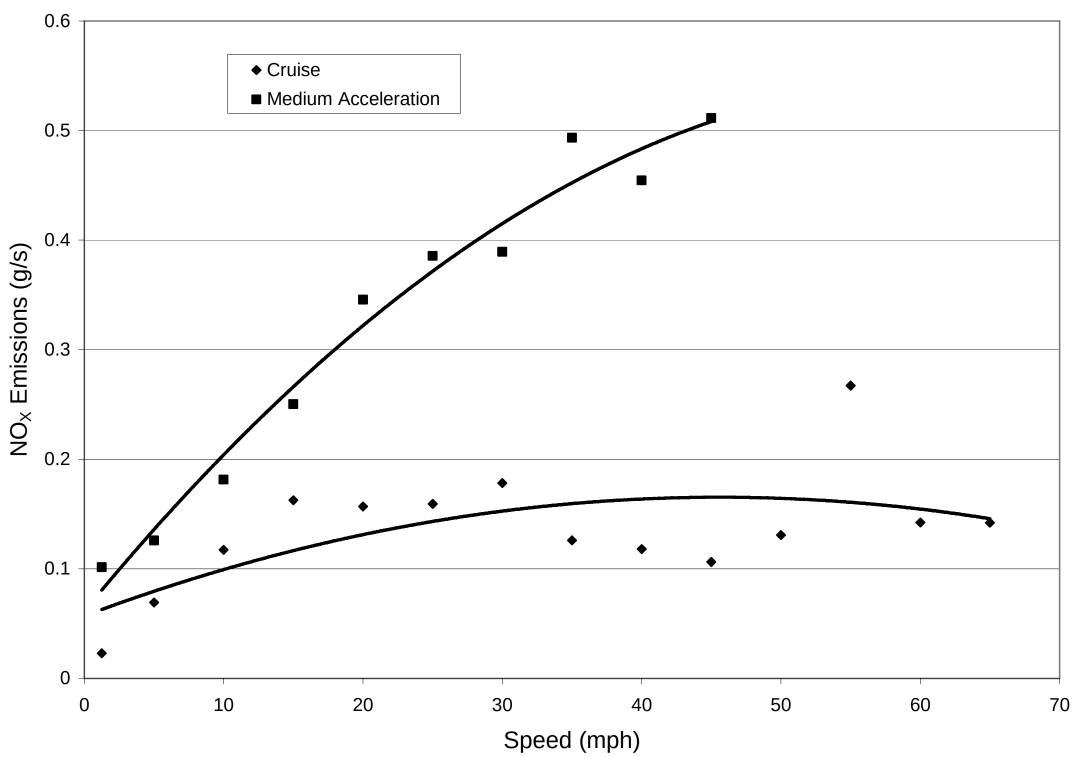
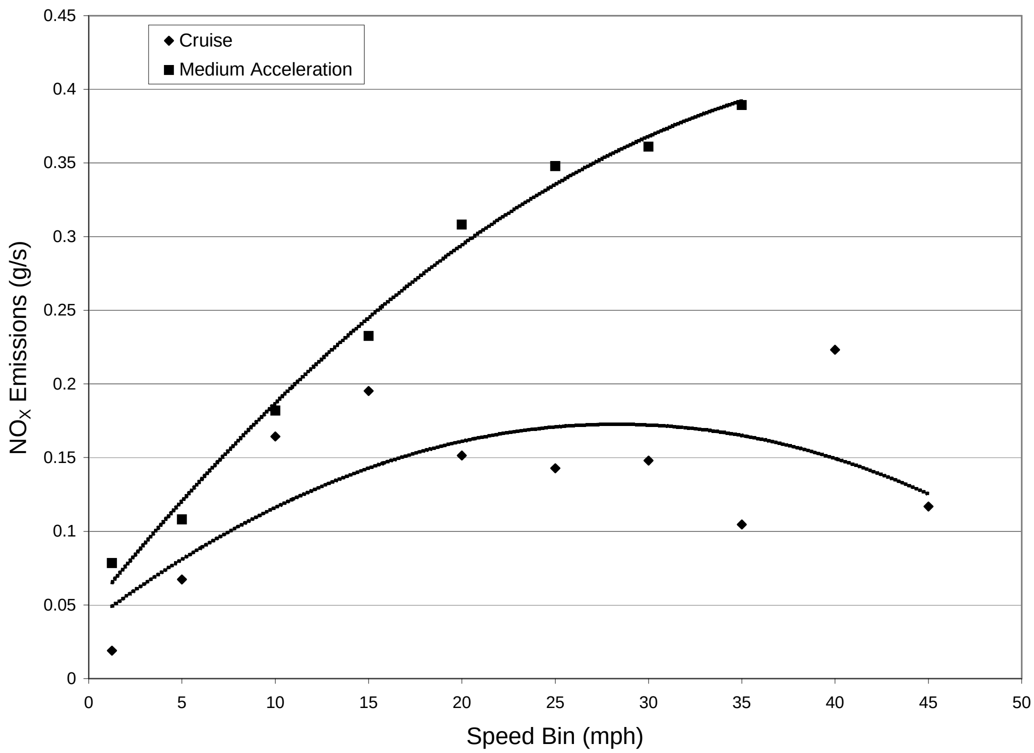


Figure 5.10 Variation of NO_X emissions (g/s) with speed for cruise and medium acceleration bins for Test Vehicle 1 on single map over CSHVR tested at 56,000 lb.



The blended matrices were obtained by obtaining the average for the emissions values in each bin resulting from the two test cycles. In the tables presented, the cells that contain a "ND" (zero valued cells in the population matrix) represent operating points that the tested vehicles did not achieve during the chassis dynamometer operation. These cells can exist because of two reasons. The first reason is that the vehicle could not achieve the performance represented by some cells, and second is that the test cycle did not require the vehicle to operate at the performance level represented by some cells. Of course, operation in some cells, representing combinations of high speed and high acceleration, are unrealistic on flat terrain because the implied engine power demand would exceed the engine rating. These cells can be filled with values using an extrapolation method in the interests of obtaining a more complete matrix. The extrapolation methods used to fill in the zero valued cells are discussed in detail later in this chapter. Figure 5.11 shows the plot of percentage difference between the NO_X emissions for IHC and CSHVR as a function of speed for the Test Vehicle 1 on single map in the overlap area corresponding to the blended matrix. It can be seen that the NO_X emissions values are within 20% for most of the operation in all four acceleration bins (cruise, light acceleration, medium acceleration, and heavy acceleration). The unusually high value corresponding to 40 mph is believed to be caused due to gear shifting and is discussed later in this dissertation.

Figure 5.11 Variation of percentage difference of NO_X emissions (g/s) between IHC and CSHVR for Test Vehicle 1 on single map – 56,000 lbs.

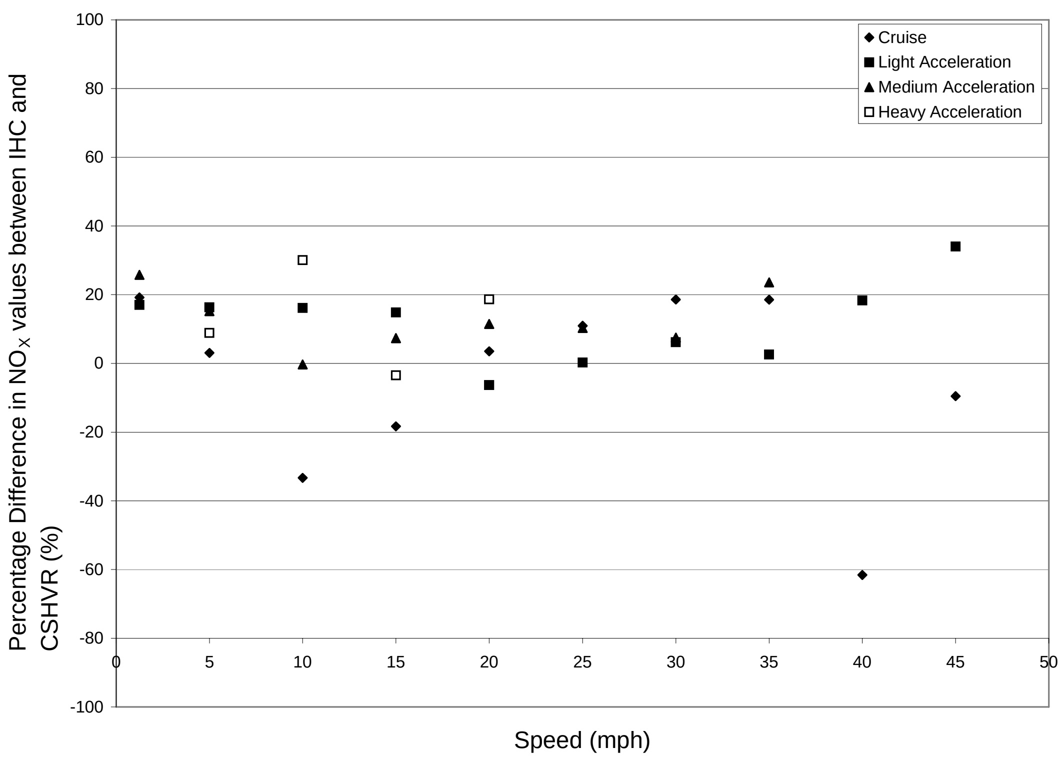


Table 5.6 Blended NO_X emissions data in g/s for the Test Vehicle 1 on the single map – 56,000 lbs.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.01687	0.01751	0.02177	0.02270	0.05453	0.09655	ND
2.5 To 7.5	0.01892	0.02121	0.03673	0.06396	0.10169	0.11490	0.11684
7.5 To 12.5	0.01566	0.01763	0.03450	0.11005	0.15117	0.15767	0.15995
12.5 To 17.5	0.01400	0.01686	0.02538	0.12598	0.16346	0.20842	0.41020
17.5 To 22.5	0.01304	0.01613	0.02136	0.14076	0.21229	0.27392	0.33223
22.5 To 27.5	0.00969	0.01433	0.02320	0.11373	0.22283	0.32857	ND
27.5 To 32.5	0.00663	0.01173	0.01989	0.12267	0.22752	0.32173	ND
32.5 To 37.5	0.00522	0.01496	0.02245	0.09924	0.22915	0.44720	ND
37.5 To 42.5	0.01089	0.01488	0.02271	0.12991	0.33107	0.45454	ND
42.5 To 47.5	0.00452	0.01098	0.02472	0.10397	0.31157	0.51157	ND
47.5 To 52.5	0.00370	0.00428	0.01438	0.13084	0.55198	ND	ND
52.5 To 57.5	0.00263	0.00853	0.02361	0.26720	0.42853	ND	ND
57.5 To 62.5	ND	0.00937	0.02540	0.14224	0.42942	ND	ND
62.5 and above	ND	ND	0.03032	0.14205	0.33900	ND	ND

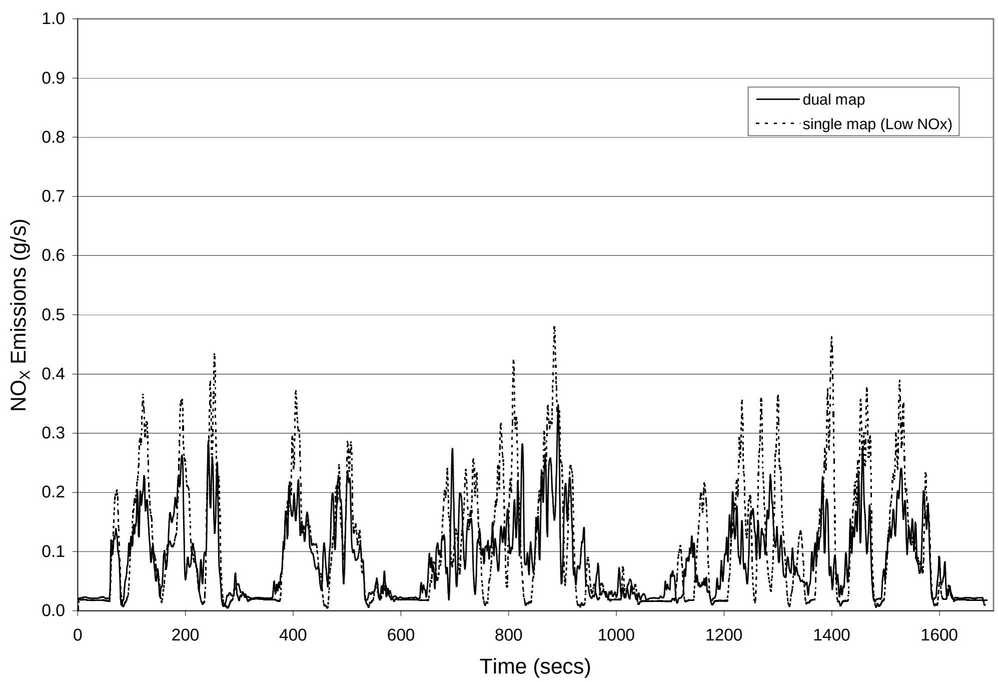
Table 5.7 Population matrix for the blended data for the Test Vehicle 1 on the single map – 56,000 lbs..

Speed Bin	Heavy Deceleration	Medium Acceleration	Light Acceleration	Cruise	Light Deceleration	Medium Deceleration	Heavy Acceleration
0 To 2.5	8	26	47	608	36	18	0
2.5 To 7.5	25	33	51	179	57	53	17
7.5 To 12.5	31	30	13	54	45	58	2
12.5 To 17.5	32	21	18	50	46	65	2
17.5 To 22.5	25	32	26	38	38	61	6
22.5 To 27.5	16	35	28	97	52	55	0
27.5 To 32.5	10	26	32	105	67	37	0
32.5 To 37.5	7	11	21	84	25	32	0
37.5 To 42.5	4	8	25	58	44	9	0
42.5 To 47.5	4	2	18	52	31	1	0
47.5 To 52.5	1	4	3	1	13	0	0
52.5 To 57.5	1	6	7	15	23	0	0
57.5 To 62.5	0	4	29	94	34	0	0
62.5 and above	0	0	19	449	41	0	0

As mentioned in Chapter 4, Test Vehicle 1 data were available for both dual and single maps of operation. Test results showed that the CSHVR did not invoke off-cycle behavior even in the dual map mode. However, there was some difference in the NO_X emissions values between the two modes (for the CSHVR), which can be seen clearly from Figure 5.12. The cycle averaged NO_X emissions values (in grams/mile) varied by 16%. This difference can be attributed to the day-to-day variations in environmental conditions such as the relative humidity and the ambient temperature as well as the sensitivity of NO_X to driving style. In addition, in the experience of the experimental researchers, run-to-run variations of NO_X are of the order of 5%.

To overcome this variation, the CSHVR data for the (Test Vehicle 1 at 56,000 lb.) tests performed in single map and dual map modes were averaged and no difference between single and dual modes for the CSHVR were considered further. NO_X values given in Table 5.6 were obtained using the averaged CSHVR data along with the IHC data for the single map.

Figure 5.12 Comparison of continuous NO_X emissions in g/s for the Test Vehicle 1 at 56,000 lbs between the dual and single map operation over the CSHVR.



Tables 5.8 through 5.13 present the NO_X emissions values in grams/second and the corresponding population matrices for the Test Vehicle 1 at 56,000 lbs. on the dual map, Test Vehicle 1 at 42,000 lbs. on the dual map and the Test Vehicle 2 at 60,000 lbs. respectively.

Table 5.8 Blended NO_X emissions data in g/s for the Test Vehicle 1 at 56,000 lbs. on the dual map.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.01876	0.01821	0.02122	0.02176	0.04847	0.09203	ND
2.5 To 7.5	0.01935	0.01958	0.03011	0.05323	0.08787	0.10507	0.11628
7.5 To 12.5	0.01834	0.01996	0.02803	0.07765	0.12481	0.13020	0.14086
12.5 To 17.5	0.01769	0.01686	0.03165	0.10885	0.14852	0.17706	0.41318
17.5 To 22.5	0.01686	0.01605	0.02363	0.11450	0.19614	0.21755	0.26893
22.5 To 27.5	0.01508	0.01523	0.02484	0.09842	0.20396	0.30061	ND
27.5 To 32.5	0.01085	0.01147	0.02268	0.10921	0.21787	0.28112	ND
32.5 To 37.5	0.00712	0.01183	0.01953	0.09611	0.24346	0.35204	ND
37.5 To 42.5	0.00388	0.01712	0.02370	0.12828	0.30843	0.35877	ND
42.5 To 47.5	ND	0.01573	0.01994	0.11898	0.34194	ND	ND
47.5 To 52.5	ND	0.00799	0.06170	0.21253	0.49494	ND	ND
52.5 To 57.5	ND	0.00994	0.01193	0.27773	0.41814	ND	ND
57.5 To 62.5	ND	0.02900	0.06613	0.36629	0.58501	ND	ND
62.5 and above	ND	ND	0.07493	0.52728	0.76010	ND	ND

Table 5.9 Population matrix for the blended data for Test Vehicle 1 at 56,000 lbs. on the dual map.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	6	30	45	620	34	18	0
2.5 To 7.5	20	40	58	150	61	66	9
7.5 To 12.5	28	37	11	55	58	57	4
12.5 To 17.5	29	30	13	48	60	63	2
17.5 To 22.5	21	39	21	35	42	67	3
22.5 To 27.5	14	38	24	81	51	55	0
27.5 To 32.5	4	33	29	102	71	36	0
32.5 To 37.5	1	20	23	82	35	28	0
37.5 To 42.5	1	12	23	60	54	1	0
42.5 To 47.5	0	7	18	40	31	0	0
47.5 To 52.5	0	6	2	1	14	0	0
52.5 To 57.5	0	8	6	10	27	0	0
57.5 To 62.5	0	7	21	98	41	0	0
62.5 and above	0	0	22	430	40	0	0

Table 5.10 Blended NO_X emissions data in g/s for the Test Vehicle 1 at 42,000 lbs. on the dual map.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.01639	0.01815	0.02259	0.02193	0.04503	0.08048	ND
2.5 To 7.5	0.01760	0.02118	0.02488	0.05320	0.08500	0.10343	0.11409
7.5 To 12.5	0.01825	0.01845	0.02793	0.08370	0.11593	0.12567	0.12446
12.5 To 17.5	0.01795	0.01949	0.03754	0.10322	0.13787	0.13831	0.18700
17.5 To 22.5	0.01653	0.01558	0.02804	0.10865	0.16136	0.17718	0.16354
22.5 To 27.5	0.01563	0.01383	0.02054	0.08987	0.16680	0.22926	0.11792
27.5 To 32.5	0.01588	0.01038	0.02616	0.10719	0.17565	0.21258	ND
32.5 To 37.5	0.01373	0.01492	0.03256	0.09174	0.20440	0.30309	ND
37.5 To 42.5	0.01411	0.01710	0.03135	0.11113	0.21875	0.26692	ND
42.5 To 47.5	0.01243	0.01738	0.03029	0.10246	0.19685	0.37704	ND
47.5 To 52.5	0.00944	0.03639	0.01308	0.12754	0.40705	0.46195	ND
52.5 To 57.5	0.02290	0.02480	0.05243	0.20929	0.39868	ND	ND
57.5 To 62.5	0.00430	0.02500	0.08432	0.36716	0.49800	ND	ND
62.5 and above	ND	ND	0.08336	0.43163	0.69106	ND	ND

Table 5.11 Population matrix for the blended data for the Test Vehicle 1 at 42,000 lbs. on the dual map.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	13	25	55	646	32	20	0
2.5 To 7.5	32	27	55	154	67	64	14
7.5 To 12.5	41	17	21	33	50	57	5
12.5 To 17.5	38	16	18	42	50	58	7
17.5 To 22.5	39	20	16	40	35	61	4
22.5 To 27.5	28	18	26	88	50	55	1
27.5 To 32.5	14	16	32	109	60	37	0
32.5 To 37.5	9	9	23	98	23	32	0
37.5 To 42.5	3	9	21	58	31	16	0
42.5 To 47.5	2	4	16	62	15	12	0
47.5 To 52.5	4	3	1	1	6	4	0
52.5 To 57.5	1	7	7	11	22	0	0
57.5 To 62.5	0	5	24	101	32	0	0
62.5 and above	0	0	29	457	41	0	0

Table 5.12 Blended NO_X emissions data in g/s for the Test Vehicle 2 at 60,000 lbs.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.00743	0.00531	0.00477	0.00415	0.03240	0.06765	ND
2.5 To 7.5	0.00639	0.00820	0.01625	0.03040	0.08498	0.11899	0.13190
7.5 To 12.5	0.00499	0.01031	0.03011	0.11671	0.15199	0.15770	ND
12.5 To 17.5	0.00371	0.00946	0.03469	0.16396	0.23833	0.27006	ND
17.5 To 22.5	0.00562	0.00966	0.02561	0.18781	0.28770	0.40043	ND
22.5 To 27.5	0.00449	0.00846	0.04353	0.14537	0.35785	0.48731	ND
27.5 To 32.5	0.00780	0.00750	0.03967	0.17661	0.36362	0.61139	ND
32.5 To 37.5	0.01151	0.01465	0.03735	0.12555	0.56283	0.73076	ND
37.5 To 42.5	0.00990	0.02153	0.04154	0.17403	0.58025	ND	ND
42.5 To 47.5	0.01525	0.01462	0.04243	0.20224	0.64459	ND	ND
47.5 To 52.5	0.00488	0.01325	ND	0.31468	0.76483	ND	ND
52.5 To 57.5	ND	0.02248	0.03713	0.33079	0.76339	ND	ND
57.5 To 62.5	ND	0.02321	0.06872	0.24478	0.77361	ND	ND
62.5 and above	ND	0.01755	0.10173	0.30120	0.65141	ND	ND

Table 5.13 Population matrix for the blended data for the Test Vehicle 2 at 60,000 lbs.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	6	28	28	562	18	18	0
2.5 To 7.5	16	42	45	199	49	50	16
7.5 To 12.5	16	42	13	85	56	57	0
12.5 To 17.5	17	46	11	47	45	63	0
17.5 To 22.5	14	50	16	47	53	70	0
22.5 To 27.5	4	54	28	97	66	58	0
27.5 To 32.5	4	34	32	80	60	46	0
32.5 To 37.5	2	18	28	77	68	3	0
37.5 To 42.5	1	10	27	53	54	0	0
42.5 To 47.5	1	4	12	46	29	0	0
47.5 To 52.5	1	5	0	5	18	0	0
52.5 To 57.5	0	7	5	10	30	0	0
57.5 To 62.5	0	4	29	75	48	0	0
62.5 and above	0	1	47	401	49	0	0

It can be seen from the tables presented above that the blended matrix has an overall good coverage of the speed-acceleration envelope for the Test Vehicle 1 at both test weights. Test Vehicle 2 has good coverage for all the acceleration bins except for the heavy acceleration bin. This vehicle was an older model year vehicle (1982) tested at 60,000 lbs.

It can be observed from Tables 5.8, 5.10, and 5.12 that for a given acceleration bin, the NO_X emissions (g/s) increases with an increase in speed. For example, in Table 5.8 the NO_X emissions increases from a value of 0.022 g/s for the 0-2.5 mph speed bin to a value of 0.527 g/s for the 62.5 and above speed bin. This is consistent with the assumption that emissions increase with increase in power demand. The product of speed and acceleration is representative of the power demand and for a given acceleration bin, the power required at the rear axle increases with increase in speed. Similarly, if we look at a particular speed bin (row), the emissions increase from the left most column, which is heavy deceleration, to the right most column, which is the heavy acceleration bin. Considering the same example (Table 5.8), it can be seen that for the 2.5-7.5 mph speed bin, NO_X emissions increases from a value of 0.0194 for heavy deceleration to a value of 0.1163 g/s for the heavy acceleration bin. This trend is expected, as the power demand increases in this direction, being the maximum for the heavy acceleration bin and minimum for the heavy deceleration bin.

The speed-acceleration based blended emissions matrices for CO and HC emissions are presented in the following tables. Since the population matrices for the HC and CO emissions are essentially the same as the population matrices for NO_X emissions presented in this section, the population matrices are not repeated in the following tables (Tables 5.14 – 5.21).

Table 5.14 Blended CO emissions data in g/s for the Test Vehicle 1 at 56,000 lb. on the single map.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.00543	0.00661	0.00919	0.00947	0.02249	0.01938	ND
2.5 To 7.5	0.00841	0.01060	0.02285	0.03409	0.02906	0.02515	0.02477
7.5 To 12.5	0.00871	0.00983	0.03267	0.05515	0.03962	0.03826	0.02752
12.5 To 17.5	0.00749	0.00978	0.01347	0.03828	0.03599	0.06047	0.14797
17.5 To 22.5	0.00705	0.00849	0.01284	0.05275	0.05703	0.05721	0.13244
22.5 To 27.5	0.00440	0.00885	0.01017	0.03263	0.05732	0.06879	ND
27.5 To 32.5	0.00454	0.01111	0.01154	0.03504	0.05518	0.06181	ND
32.5 To 37.5	0.00584	0.01051	0.01451	0.02532	0.05352	0.06687	ND
37.5 To 42.5	0.00576	0.01215	0.02556	0.07890	0.08718	0.06339	ND
42.5 To 47.5	0.00250	0.02175	0.02327	0.05489	0.14187	ND	ND
47.5 To 52.5	0.00001	0.00066	0.00700	0.06687	0.02865	ND	ND
52.5 To 57.5	ND	0.01326	0.03607	0.12904	0.05579	ND	ND
57.5 To 62.5	ND	0.01295	0.02979	0.07723	0.08790	ND	ND
62.5 and above	ND	ND	0.02289	0.05336	0.10203	ND	ND

Table 5.15 Blended CO emissions data in g/s for the Test Vehicle 1 at 56,000 lb. on the dual map.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.00500	0.00435	0.00466	0.00519	0.00460	0.00999	ND
2.5 To 7.5	0.00502	0.00596	0.00786	0.01312	0.01672	0.01811	0.02958
7.5 To 12.5	0.00507	0.00723	0.01030	0.01907	0.02419	0.03131	0.06401
12.5 To 17.5	0.00634	0.00539	0.01155	0.02120	0.02396	0.04865	0.31020
17.5 To 22.5	0.00739	0.00563	0.01227	0.02271	0.04113	0.04658	0.23165
22.5 To 27.5	0.00466	0.00672	0.00869	0.02029	0.04143	0.06175	ND
27.5 To 32.5	0.00521	0.00602	0.01171	0.02231	0.03828	0.05750	ND
32.5 To 37.5	0.00133	0.00585	0.01090	0.02048	0.04517	0.04811	ND
37.5 To 42.5	0.00197	0.00710	0.01090	0.02981	0.06333	0.11828	ND
42.5 To 47.5	ND	0.00321	0.01031	0.01681	0.05264	ND	ND
47.5 To 52.5	ND	0.00087	0.01766	0.10977	0.07621	ND	ND
52.5 To 57.5	ND	0.00126	0.00315	0.05019	0.09335	ND	ND
57.5 To 62.5	ND	0.00177	0.00363	0.01357	0.07974	ND	ND
62.5 and above	ND	ND	0.00527	0.00980	0.05147	ND	ND

Table 5.16 Blended CO emissions data in g/s for the Test Vehicle 2 at 42,000 lb. on the dual map.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.00196	0.00215	0.00173	0.00133	0.00332	0.00650	ND
2.5 To 7.5	0.00183	0.00404	0.00572	0.01374	0.01551	0.01486	0.01786
7.5 To 12.5	0.00209	0.00267	0.00809	0.01940	0.02250	0.02452	0.02983
12.5 To 17.5	0.00105	0.00155	0.00636	0.01669	0.02334	0.02531	0.05798
17.5 To 22.5	0.00181	0.00107	0.00761	0.01876	0.02838	0.03075	0.04130
22.5 To 27.5	0.00215	0.00206	0.00430	0.01582	0.02315	0.03682	0.06500
27.5 To 32.5	0.00286	0.00234	0.00768	0.01873	0.02483	0.03389	ND
32.5 To 37.5	0.00481	0.00835	0.01000	0.01954	0.03662	0.03671	ND
37.5 To 42.5	0.00281	0.00639	0.00972	0.02125	0.03961	0.05283	ND
42.5 To 47.5	0.00360	0.00125	0.01079	0.02310	0.03353	0.05823	ND
47.5 To 52.5	0.00294	0.01847	0.00895	0.05781	0.05089	0.05895	ND
52.5 To 57.5	0.00622	0.00803	0.02245	0.04341	0.06983	ND	ND
57.5 To 62.5	0.00486	0.00437	0.00820	0.01290	0.04969	ND	ND
62.5 and above	ND	ND	0.00921	0.01129	0.02900	ND	ND

Table 5.17 Blended CO emissions data in g/s for the Test Vehicle 2 at 60,000 lb.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.01921	0.01599	0.01843	0.01843	0.02694	0.05113	ND
2.5 To 7.5	0.02006	0.01907	0.03600	0.04128	0.10091	0.17688	0.31313
7.5 To 12.5	0.01897	0.02054	0.05358	0.09249	0.13864	0.19211	ND
12.5 To 17.5	0.01974	0.02028	0.06390	0.11218	0.14553	0.22400	ND
17.5 To 22.5	0.02457	0.02270	0.05418	0.11326	0.16426	0.23695	ND
22.5 To 27.5	0.01454	0.02187	0.05529	0.07305	0.19642	0.22581	ND
27.5 To 32.5	0.01966	0.02318	0.04985	0.08060	0.17770	0.21576	ND
32.5 To 37.5	0.02299	0.02770	0.05335	0.06745	0.23896	0.29783	ND
37.5 To 42.5	0.00933	0.02948	0.05728	0.09242	0.23165	ND	ND
42.5 To 47.5	0.01170	0.01183	0.06555	0.10624	0.24206	ND	ND
47.5 To 52.5	0.02550	0.01935	0.00000	0.18041	0.21853	ND	ND
52.5 To 57.5	ND	0.03737	0.05267	0.14115	0.24406	ND	ND
57.5 To 62.5	ND	0.04439	0.06086	0.10022	0.18854	ND	ND
62.5 and above	ND	0.04810	0.06017	0.07645	0.14403	ND	ND

Table 5.18 Blended HC emissions data in g/s for the Test Vehicle 1 at 56,000 lb. on the single map.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.00216	0.00166	0.00157	0.00141	0.00207	0.00242	ND
2.5 To 7.5	0.00180	0.00172	0.00211	0.00241	0.00236	0.00258	0.00231
7.5 To 12.5	0.00170	0.00149	0.00229	0.00243	0.00233	0.00257	0.00192
12.5 To 17.5	0.00157	0.00152	0.00172	0.00233	0.00229	0.00231	0.00214
17.5 To 22.5	0.00142	0.00144	0.00203	0.00234	0.00240	0.00234	0.00203
22.5 To 27.5	0.00151	0.00133	0.00175	0.00200	0.00226	0.00238	ND
27.5 To 32.5	0.00147	0.00128	0.00182	0.00259	0.00249	0.00238	ND
32.5 To 37.5	0.00116	0.00134	0.00227	0.00314	0.00284	0.00262	ND
37.5 To 42.5	0.00086	0.00153	0.00150	0.00211	0.00256	0.00268	ND
42.5 To 47.5	0.00102	0.00195	0.00247	0.00249	0.00259	0.00315	ND
47.5 To 52.5	0.00109	0.00107	0.00116	0.00226	0.00219	ND	ND
52.5 To 57.5	0.00119	0.00179	0.00128	0.00295	0.00313	ND	ND
57.5 To 62.5	ND	0.00188	0.00236	0.00255	0.00338	ND	ND
62.5 and above	ND	ND	0.00301	0.00334	0.00366	ND	ND

Table 5.19 Blended HC emissions data in g/s for the Test Vehicle 1 at 56,000 lb. on the dual map.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.00170	0.00158	0.00136	0.00139	0.00239	0.00250	ND
2.5 To 7.5	0.00142	0.00153	0.00189	0.00235	0.00251	0.00277	0.00318
7.5 To 12.5	0.00127	0.00142	0.00153	0.00234	0.00243	0.00258	0.00327
12.5 To 17.5	0.00128	0.00140	0.00155	0.00215	0.00224	0.00233	0.00193
17.5 To 22.5	0.00126	0.00135	0.00238	0.00223	0.00234	0.00229	0.00182
22.5 To 27.5	0.00120	0.00138	0.00181	0.00208	0.00223	0.00257	ND
27.5 To 32.5	0.00111	0.00133	0.00201	0.00273	0.00256	0.00243	ND
32.5 To 37.5	0.00038	0.00126	0.00226	0.00307	0.00266	0.00217	ND
37.5 To 42.5	0.00032	0.00130	0.00170	0.00210	0.00246	0.00281	ND
42.5 To 47.5	ND	0.00160	0.00309	0.00308	0.00295	ND	ND
47.5 To 52.5	ND	0.00154	0.00145	0.00141	0.00222	ND	ND
52.5 To 57.5	ND	0.00160	0.00154	0.00195	0.00229	ND	ND
57.5 To 62.5	ND	0.00206	0.00252	0.00260	0.00335	ND	ND
62.5 and above	ND	ND	0.00283	0.00292	0.00352	ND	ND

Table 5.20 Blended HC emissions data in g/s for the Test Vehicle 1 at 42,000 lb. on the dual map.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.00133	0.00129	0.00114	0.00111	0.00168	0.00232	ND
2.5 To 7.5	0.00134	0.00169	0.00224	0.00291	0.00268	0.00276	0.00292
7.5 To 12.5	0.00126	0.00139	0.00191	0.00299	0.00394	0.00349	0.00347
12.5 To 17.5	0.00132	0.00145	0.00225	0.00286	0.00307	0.00325	0.00220
17.5 To 22.5	0.00124	0.00160	0.00230	0.00278	0.00286	0.00302	0.00171
22.5 To 27.5	0.00124	0.00167	0.00162	0.00245	0.00260	0.00285	0.00110
27.5 To 32.5	0.00153	0.00176	0.00237	0.00312	0.00307	0.00285	ND
32.5 To 37.5	0.00170	0.00181	0.00285	0.00339	0.00308	0.00303	ND
37.5 To 42.5	0.00128	0.00188	0.00277	0.00283	0.00318	0.00305	ND
42.5 To 47.5	0.00169	0.00198	0.00309	0.00365	0.00337	0.00330	ND
47.5 To 52.5	0.00203	0.00176	0.00120	0.00190	0.00258	0.00260	ND
52.5 To 57.5	0.00126	0.00205	0.00194	0.00255	0.00293	ND	ND
57.5 To 62.5	0.00140	0.00250	0.00318	0.00306	0.00343	ND	ND
62.5 and above	ND	ND	0.00332	0.00331	0.00354	ND	ND

Table 5.21 Blended HC emissions data in g/s for the Test Vehicle 2 at 60,000 lb.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.01450	0.01451	0.01474	0.01604	0.02314	0.02315	ND
2.5 To 7.5	0.01457	0.01474	0.01915	0.01642	0.02339	0.02637	0.02934
7.5 To 12.5	0.01476	0.01480	0.02193	0.02631	0.02898	0.02947	ND
12.5 To 17.5	0.01385	0.01359	0.01858	0.02637	0.02651	0.02663	ND
17.5 To 22.5	0.01367	0.01428	0.02110	0.02683	0.02699	0.02728	ND
22.5 To 27.5	0.01273	0.01439	0.02058	0.02053	0.02360	0.02682	ND
27.5 To 32.5	0.01055	0.01509	0.02066	0.02226	0.02434	0.02676	ND
32.5 To 37.5	0.00739	0.01303	0.02372	0.02239	0.02539	0.02923	ND
37.5 To 42.5	0.00752	0.01479	0.02127	0.02081	0.02514	ND	ND
42.5 To 47.5	0.01215	0.01708	0.02266	0.02309	0.02234	ND	ND
47.5 To 52.5	0.00435	0.01258	ND	0.02412	0.02549	ND	ND
52.5 To 57.5	ND	0.01809	0.01870	0.02215	0.02287	ND	ND
57.5 To 62.5	ND	0.04115	0.03395	0.02771	0.02700	ND	ND
62.5 and above	ND	0.02845	0.03182	0.02876	0.02902	ND	ND

It can be seen from Tables 5.14 through 5.21 that HC and CO emissions exhibit similar trends; however, CO emissions tables show considerable variations unlike NO_X emissions. This illustrates the influence of transient activity on CO. Given the relatively low level of CO and HC emissions from diesel vehicles; the erratic behavior is not a particular concern with regard to emissions inventory.

5.4 Combining the Emissions Factors Table with Vehicle Activity Data

The main objective of an inventory prediction is to provide the average emissions value in grams/mile as a function of the average speed class over a period of travel, or over a road link. This method is discussed in detail in the next section of this chapter, but is also addressed briefly here to assist in understanding of the need for data smoothing and extrapolation. Emissions values can be obtained by combining the emissions factors (binned according to the speed and acceleration table) with the vehicle activity data. The vehicle activity data were available from a prior study by the Battelle Memorial Institute [Battelle, 1999] that was originated by the Planning and Technical Support Division of the California Air Resources Board (CARB) and jointly supported by the federal Highway Administration (FHWA). The activity data were collected using automated data collection equipment that included Global Positioning System (GPS) technology [Battelle, 1999]. The Battelle project database contains extensive data for heavy-duty trucks that accumulated over 53,000 vehicle miles of travel (VMT) during the data collection. The 99 trucks for which complete data were collected included 52 postal/parcel trucks, and 22 combination trucks.

The activity data were available as two-dimensional speed-acceleration matrices. Each such matrix represented the percentage time of operation for a particular vehicle class at a particular average speed. The two-dimensional speed-acceleration based emissions tables presented earlier in this chapter were intentionally binned according to the same speed and acceleration groups that were used for the activity data.

One such matrix was available for each of the average speed classes. The speed classes represented average speeds of operation of 0-10 mph, 10-20 mph, and so on. Two sets of these matrices were available, one for urban operation and the other for rural operation. Urban operation is defined as operation in areas with a population greater than 5000. All other areas were referred to as rural [Battelle, 1999].

The emissions tables were multiplied with the activity data for each of the average speed class resulting in speed-acceleration based two-dimensional product matrix. One such product matrix was obtained for each of the average speed classes. The values in each product matrix were summed to obtain a single value and then divided by the average speed to obtain a value in grams/mile. Table 5.22 below shows the activity data for the class 8 trucks for one particular average speed class (in this case 50-60 mph) in the urban mode of operation.

As an example, the mass emissions rates (the product matrix) obtained by multiplying the activity data for urban operation with the NO_X emissions data from the test Vehicle 1 at 42,000 lbs. on dual map are shown in Table 5.23. Of interest is the fact that almost 89% of the operation in Table 5.22 occurs in two speed-acceleration entries. This emphasizes the need for the smoothing of emissions values (such as those in Table 5.23) and shows that little operation occurs in the high acceleration, high speed zone.

Table 5.22 An example of activity data for Class 8 trucks for the average speed class of 50-60 mph (values in percentage of time of operation) – Urban operation. Note that 89% of activity occurs between 52.5 and 62.5 mph.

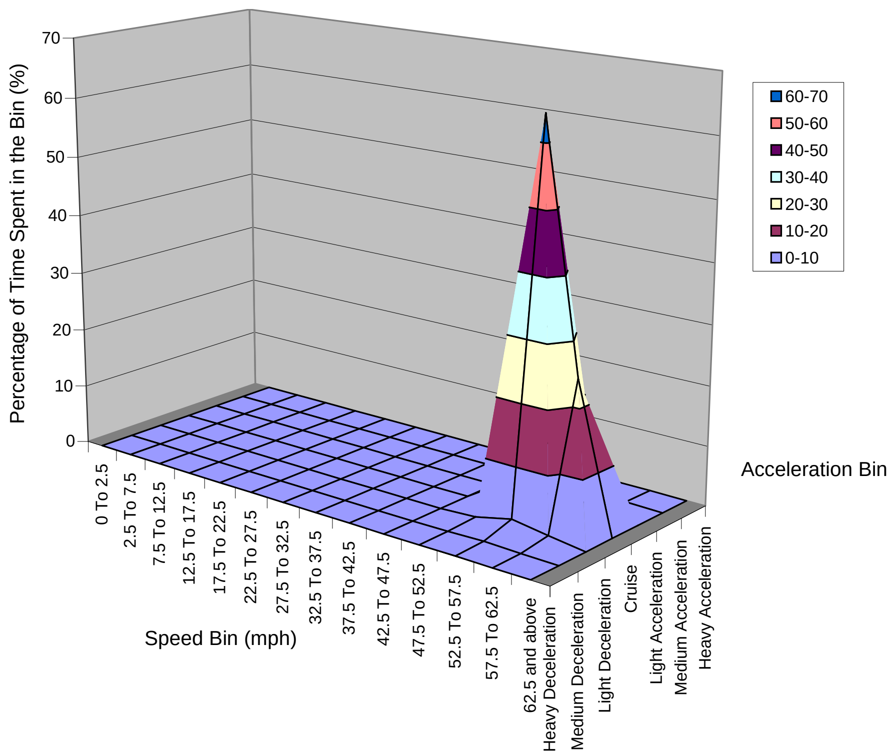
Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.0024%	0.0001%	0.0001%	0.0020%	0.0000%	0.0000%	0.0000%
2.5 To 7.5	0.0002%	0.0001%	0.0000%	0.0001%	0.0000%	0.0003%	0.0001%
7.5 To 12.5	0.0002%	0.0001%	0.0001%	0.0002%	0.0006%	0.0001%	0.0001%
12.5 To 17.5	0.0003%	0.0001%	0.0001%	0.0003%	0.0003%	0.0002%	0.0001%
17.5 To 22.5	0.0002%	0.0003%	0.0000%	0.0001%	0.0004%	0.0003%	0.0001%
22.5 To 27.5	0.0004%	0.0003%	0.0001%	0.0006%	0.0004%	0.0002%	0.0001%
27.5 To 32.5	0.0005%	0.0003%	0.0003%	0.0003%	0.0004%	0.0002%	0.0001%
32.5 To 37.5	0.0012%	0.0007%	0.0008%	0.0015%	0.0013%	0.0007%	0.0002%
37.5 To 42.5	0.0024%	0.0038%	0.0051%	0.0043%	0.0042%	0.0038%	0.0005%
42.5 To 47.5	0.0079%	0.0162%	0.0389%	0.0483%	0.0442%	0.0118%	0.0010%
47.5 To 52.5	0.0283%	0.0736%	0.3453%	3.9541%	0.3728%	0.0453%	0.0073%
52.5 To 57.5	0.0628%	0.2490%	1.7317%	64.4553%	1.6975%	0.1927%	0.0371%
57.5 To 62.5	0.0157%	0.0875%	0.8435%	24.2583%	1.0573%	0.1535%	0.0464%
62.5 and above	0.0003%	0.0013%	0.0072%	0.0392%	0.0155%	0.0039%	0.0066%

Table 5.23 Activity data multiplied with NO_X emissions data (g/s) for the Test Vehicle 1 at 42,000 lbs. for average speed class of 50-60 mph – Urban operation.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	3.91E-07	1.92E-08	2.39E-08	4.42E-07	0.00E+00	0.00E+00	ND
2.5 To 7.5	3.73E-08	1.12E-08	0.00E+00	2.82E-08	0.00E+00	2.74E-07	1.21E-07
7.5 To 12.5	2.90E-08	9.78E-09	1.48E-08	1.77E-07	6.76E-07	1.33E-07	1.32E-07
12.5 To 17.5	4.75E-08	2.07E-08	1.99E-08	2.73E-07	4.38E-07	2.93E-07	1.98E-07
17.5 To 22.5	3.50E-08	4.13E-08	0.00E+00	5.76E-08	5.98E-07	4.69E-07	1.73E-07
22.5 To 27.5	5.80E-08	4.40E-08	1.09E-08	5.71E-07	6.19E-07	3.64E-07	1.25E-07
27.5 To 32.5	7.57E-08	3.30E-08	8.32E-08	3.41E-07	6.51E-07	3.38E-07	ND
32.5 To 37.5	1.67E-07	1.03E-07	2.76E-07	1.41E-06	2.60E-06	2.09E-06	ND
37.5 To 42.5	3.44E-07	6.43E-07	1.61E-06	4.83E-06	9.16E-06	1.02E-05	ND
42.5 To 47.5	9.88E-07	2.81E-06	1.18E-05	4.95E-05	8.71E-05	4.43E-05	ND
47.5 To 52.5	2.67E-06	2.68E-05	4.52E-05	5.04E-03	1.52E-03	2.09E-04	ND
52.5 To 57.5	1.44E-05	6.17E-05	9.08E-04	1.35E-01	6.77E-03	ND	ND
57.5 To 62.5	6.74E-07	2.19E-05	7.11E-04	8.91E-02	5.27E-03	ND	ND
62.5 and above	ND	ND	5.96E-06	1.69E-04	1.07E-04	ND	ND

Figure 5.13 shows a 3-D plot of the activity data for class 8 trucks for the average speed class of 50-60 mph in the urban mode of operation. It can be observed that most of the activity for this average speed class occurs in the cruise bin.

Figure 5.13 3-D plot of activity data for Class 8 trucks for the average speed class of 50-60 mph (values in percentage of time of operation) – Urban operation. Note that 89% of activity occurs between 52.5 and 62.5 mph.



5.5 Extrapolation and Smoothing (Interpolation) of the NO_X Emissions Data – An Example

This section discusses the methodology used to fill in the zero valued cells (represented by a "ND" in Section 5.3) in the speed-acceleration based emissions factors tables and smoothing (interpolation) to eliminate anomalous values. The analyses performed on the emissions data for the Test Vehicles 1 and 2 are presented in this section. Extrapolation was used to fill in the zero valued cells in the emissions matrix outside the envelope. The zero valued cells in between cells that have emissions values were filled using interpolation (smoothing). It was observed from the emissions factors tables presented in Section 5.3 that some cells contain quirks and deviations resulting from monotonic behavior that can be attributed to the original cycles used to acquire data. For example, the data acquired at one specific speed-acceleration bin might be associated with more transient behavior in the cycle than a neighboring speed-acceleration bin, or a bin might include some history effects that cannot be eliminated even with time alignment. These cells represented cells with a very low activity population matrix (usually 1 or 2 data points).

As an example, one case of such deviation was analyzed in detail. Consider the blended NO_X emissions table for the Test Vehicle 1 on single map tested at 56,000 lb (Table 5.6). The cell corresponding to an average speed range of 52.5-57.5 mph in the cruise bin has a value of 0.2672, which falls out of the general trend considering the adjacent cells in the same cruise bin. A review of the raw data showed that this cell had 15 data points. For each of these data points, the actual speed values, acceleration values and the actual time of occurrence in the original cycle are presented in Table 5.24. These 15 data points resulted from the IHC, as the CSHVR did not have any operation in that speed and acceleration bin values.

Table 5.24 Actual speed, acceleration, and NO_X emission values for the 15 data points corresponding to 52.5-57.5 mph speed bin in the cruise bin for Test Vehicle 1 on single map tested at 56,000 lb.

Point of Occurrence	Speed (mph)	Acceleration (mph/s)	NO_X Emissions (g/s)
302	52.6	0.27	0.3653
602	52.9	0.19	0.2715
600	53.1	-0.97	0.0774
1188	53.7	0.26	0.3944
1189	53.9	0.21	0.4198
1190	54.1	0.24	0.4463
1191	54.4	0.27	0.4470
1192	54.7	0.29	0.4104
1193	54.9	0.21	0.3588
1194	55.1	0.21	0.2978
1195	55.3	0.16	0.2689
1196	55.4	0.15	0.2885
1197	55.7	0.28	0.3385
1473	56.4	-0.27	0.0200
1472	56.7	-0.17	0.0346
1471	56.9	-0.29	0.0390

The first column in Table 5.24 gives the actual location of the fifteen data points in the UDDSata collected. These numbers simply represent the time in seconds starting from the beginning of the cycle. Figure 5.14 shows a plot of the actual speed and measured NO_X emissions versus time. The data points corresponding to the 52.5-57.5 mph in the cruise bin are also indicated using arrow marks. It can be observed that these data points actually lie in a steady acceleration/deceleration operation. Data point corresponding to 602nd second lies in the region where there is a sudden change in the direction of speed. That is it lies at a point where the vehicle ends decelerating and starts to accelerate. Even though the vehicle is not cruising, due to change in the acceleration from a negative to positive value, the momentary acceleration value corresponds to the cruise bin and the emissions value is assigned to cruise bin. Data points from 1188-1197 seconds and 1471-1473 seconds fall in the acceleration and deceleration region respectively. An exploded view of the plot in these two regions show that there is a brief period of low acceleration and deceleration values in these two regions. These can be attributed to the gearshift effect due to driving style. The exploded view also reveals large spikes in NO_X emissions values for short periods of time. These result from changes in engine load during gearshifts. The exploded view shown in Figure 5.15 and 5.16 clearly shows this effect.

Figure 5.14 Continuous NO_X emissions and actual driving speed plotted against time for Test Vehicle 1 on single map tested at 56,000lb. Data points corresponding to 52.5-57.5 mph bin are indicated.

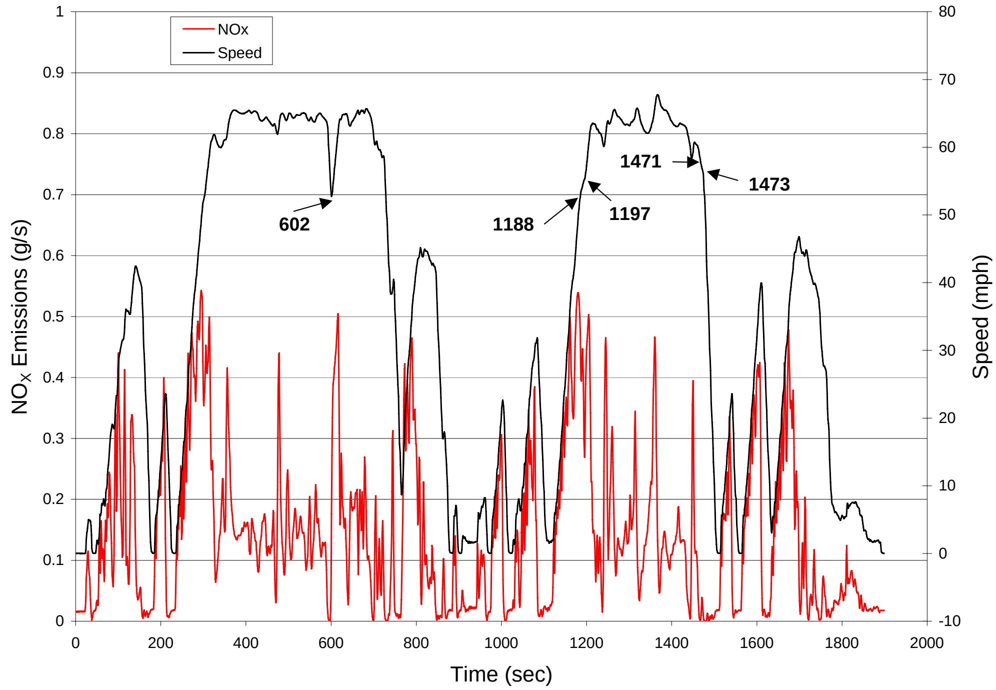


Figure 5.15 Exploded view showing points 1471-1473 for NO_X emissions and actual driving speed plotted against time for Test Vehicle 1 on single map tested at 56,000lb.

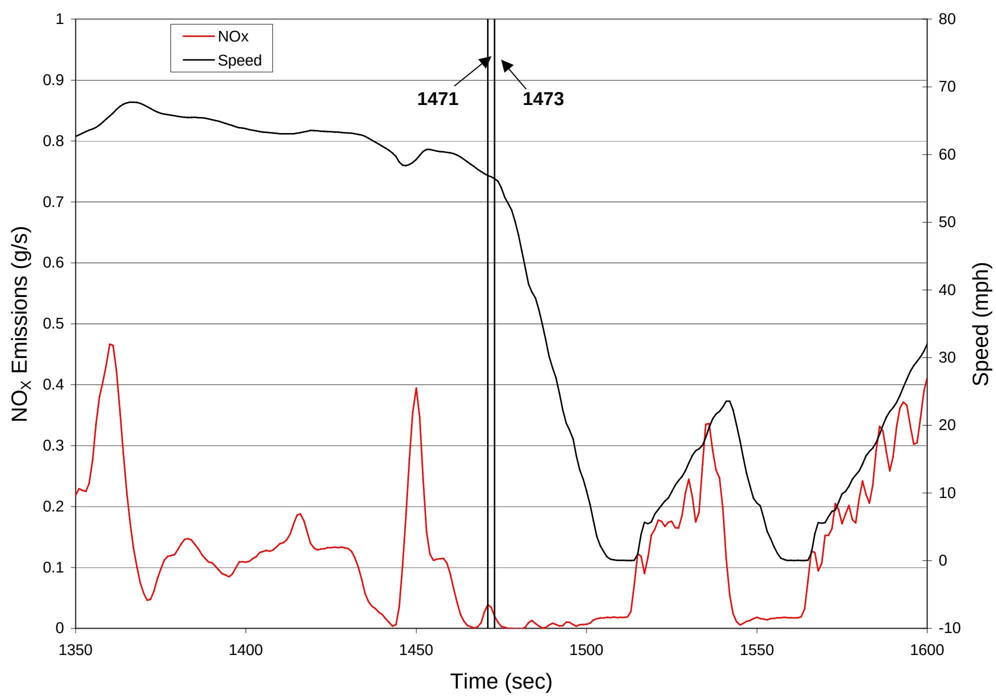
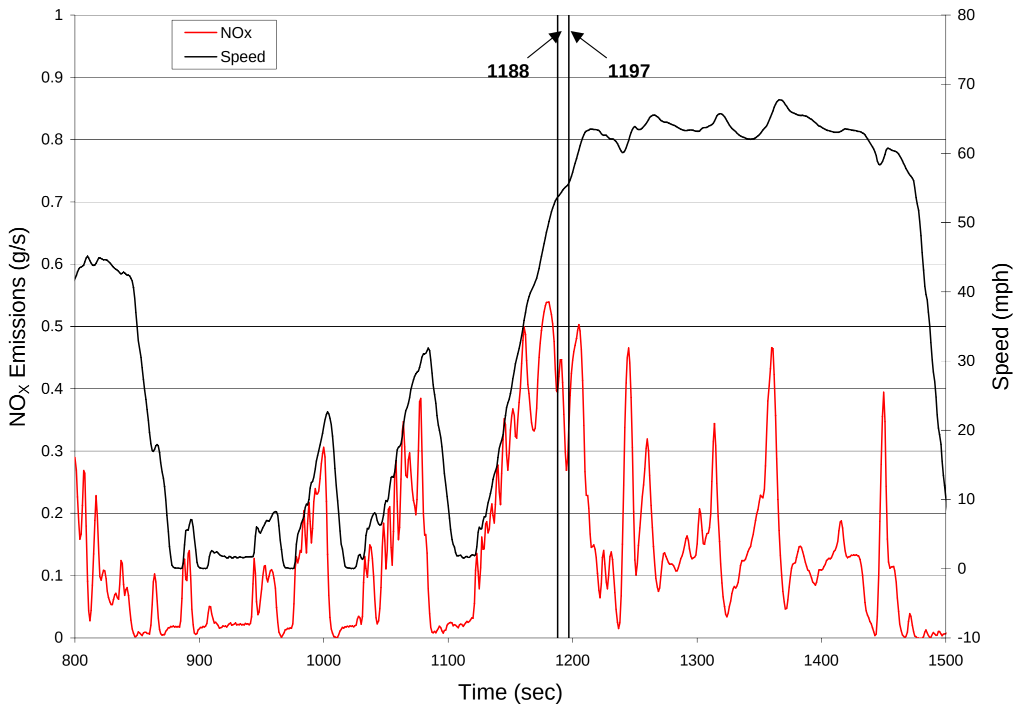


Figure 5.16 Exploded view showing points 1471-1473 for NO_X emissions and actual driving speed plotted against time for Test Vehicle 1 on single map tested at 56,000lb.



Techniques were developed for extrapolating and smoothing emissions data to fill in unpopulated (zero valued) cells and to quantify emissions as a function of speed for each mode of acceleration. Data smoothing (interpolation) was performed using fitted curves obtained for each of the acceleration bins; however, this smoothing should not be confused with "smoothing" of emissions by the dilution tunnel and analyzer. A best-fit polynomial or logarithmic curve of emissions versus speed, the form of which was chosen using a higher R^2 value and a good visual judgment, was obtained for each of the acceleration bins and the equation obtained was used to smooth and to fill in the zero valued cells. In all the cases, where a NO_X versus speed relationship was used, the NO_X values were plotted against the actual measured average speeds for each bin and not the bin median (mid point of the speed bin range). The actual average speed values varied significantly from the bin median values. Table 5.25 shows the actual average speed values for all the acceleration bins for the Test Vehicle 1 on the dual map. Figure 5.17

shows a 3-dimensional plot of the percentage difference between the bin median and the actual average speed as a function of speed and acceleration bin ranges. It is clearly seen that the actual average speed values vary significantly for most of the cells. As a further example, Figure 5.18 and Figure 5.19 show the plots of NO_X versus speed for both the average and bin median speed cases (light acceleration bin) and it can be seen that there is some difference in the curve fits. Hence, the actual average speed values were used to obtain the smoothing and extrapolation equations. While fitting the smoothing curves to the data, any of the values that were suspected to be an artifact or measurement error and had few points of operation, were excluded. This required careful judgment coupled with detailed review of the source data in some cases.

Table 5.25 Actual average speed values (mph) for the 1995 truck on dual map.

Bin Median Speed (mph)	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
1.25	1.21	1.22	1.27	0.35	1.33	1.91	ND
5	5.02	5.07	4.75	5.34	5.41	4.94	5.04
10	10.39	9.99	9.73	8.95	9.75	10.05	11.44
15	15.18	15.29	15.96	15.45	14.80	15.04	17.11
20	19.63	19.99	20.58	20.49	19.57	20.50	20.01
25	24.44	24.75	25.43	25.25	24.32	25.21	ND
30	29.82	29.69	30.34	30.57	30.20	29.37	ND
35	34.16	34.81	34.95	34.41	34.96	34.44	ND
40	38.86	39.46	40.22	40.45	39.97	40.46	ND
45	ND	44.70	44.06	44.49	44.71	ND	ND
50	ND	49.59	51.74	52.33	50.03	ND	ND
55	ND	54.80	55.44	53.15	55.04	ND	ND
60	ND	59.60	60.28	60.91	60.35	ND	ND
65	ND	ND	65.10	64.49	64.80	ND	ND

Figure 5.17 Variation of percentage difference between actual and bin median speed values as a function of speed and acceleration bins.

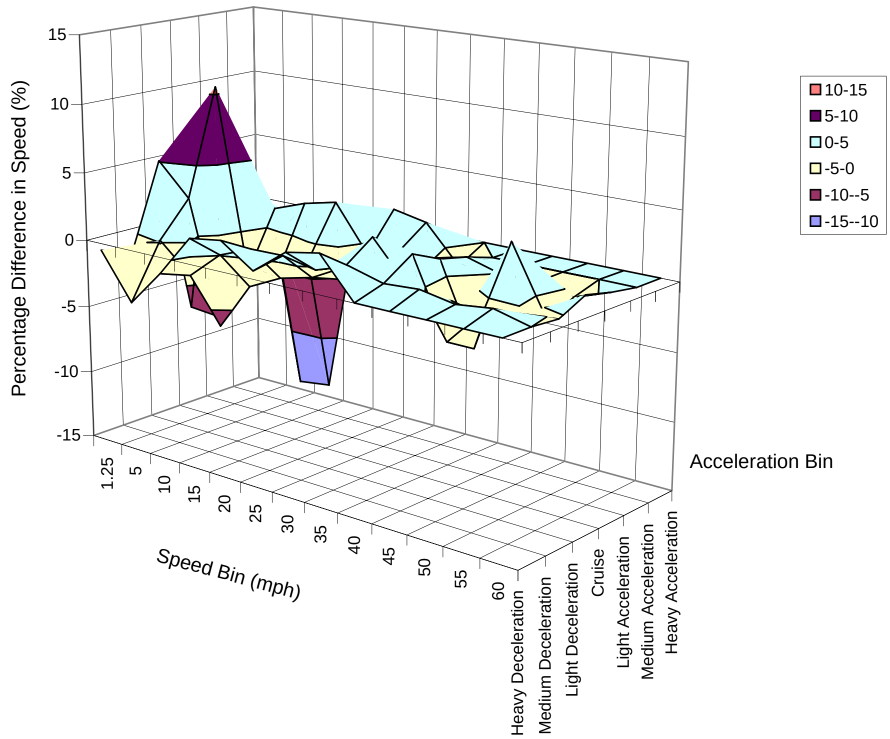


Figure 5.18 Variation of NO_X emissions in g/s with the bin median speed for the Test Vehicle 1 on dual map at 56,000 lb. – light acceleration bin.

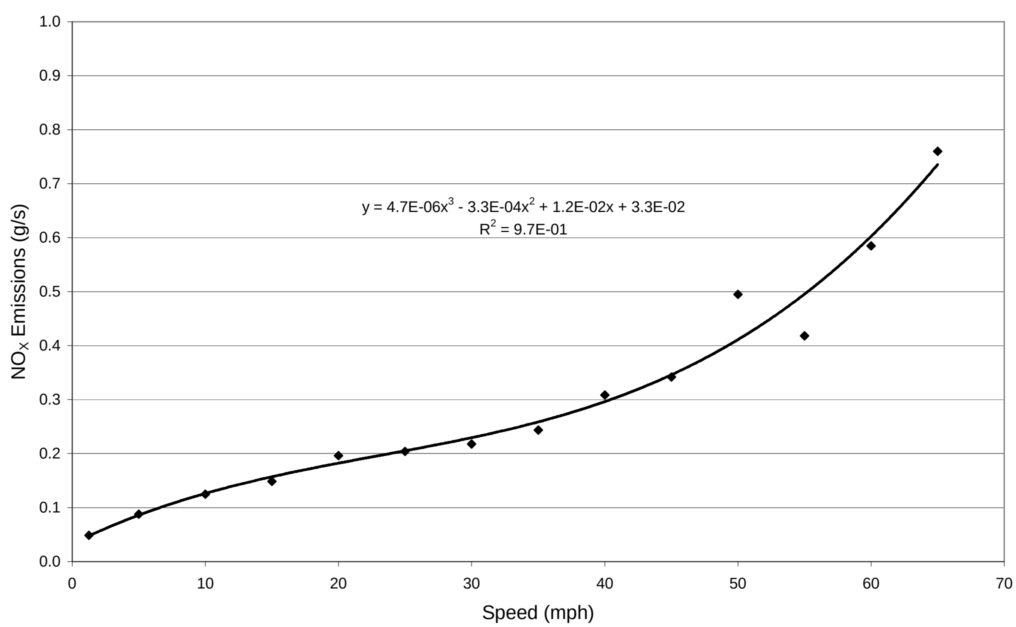
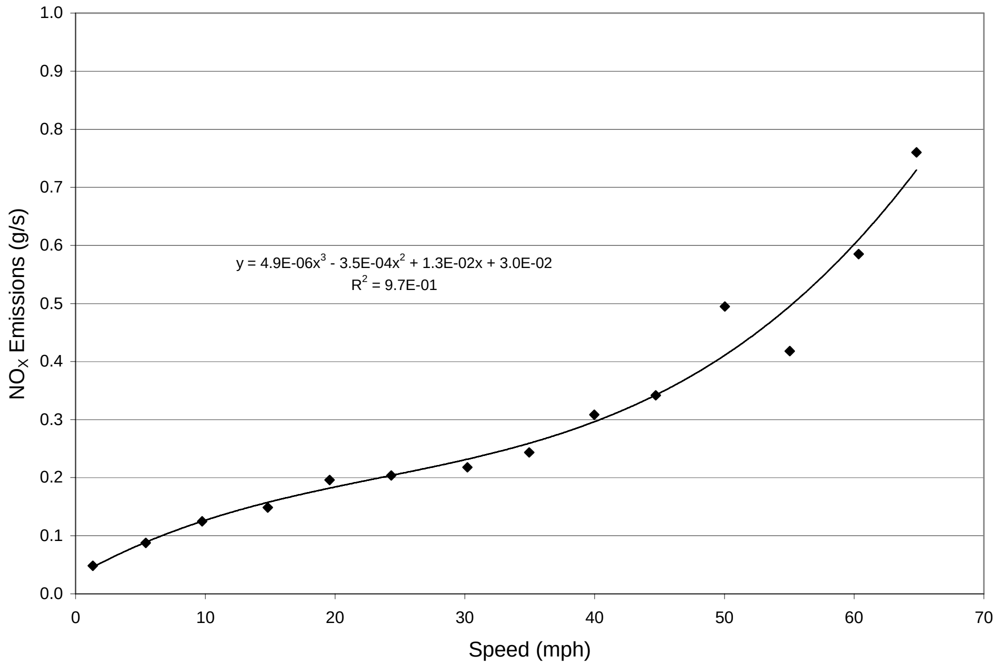


Figure 5.19 Variation of NO_X emissions in g/s with the actual average speed for the Test Vehicle 1 on the dual map at 56,000 lb. – light acceleration bin.



In Figure 5.18 and Figure 5.19 the NO_X emissions vary almost linearly with speed at low speeds. There is a quadratic relationship at medium and high speeds. This may be attributed to the nearly linear relationship of NO_X emissions with speed. At low speeds, the power required is dominated by the tire losses. At higher speeds aerodynamic drag force becomes predominant and the power is proportional to the cube of speed. Most of the data smoothing was conducted using the emissions versus speed domain; however, the heavy acceleration and medium acceleration bins were extrapolated using the vehicle power because there were too few existing cells to justify an accurate extrapolation using speed. Considering a flat terrain, the power demand of a vehicle is governed by the vehicle speed and acceleration for a particular vehicle weight. As the required power increases, the amount of fuel burnt also increases, and the rate of regulated emissions produced will generally increase. For heavy-duty vehicles, acceleration rates are low; hence power may be used as the independent variable without using the torque and speed. It has been shown that for a given engine meeting a given emissions standard, NO_X emissions may be related closely to CO_2 emissions. CO_2 directly relates to the amount of fuel burnt and hence the power demand. So, NO_X emissions can be correlated to the power. The relationships between power and NO_X emissions for medium and heavy acceleration bins for the Test Vehicle 1 on single map at 56,000 lb. are shown in Figures 5.20 and 5.21 respectively. These relationships were obtained by plotting the measured NO_X emissions value in the respective acceleration bins against the power required to maintain the corresponding speed and acceleration values. Power required was calculated using the road load equation (Equation 3.3) using the actual average speed and actual average acceleration values for each cell and not the bin median values. Terrain effects were neglected and the vehicle was assumed to be traveling on a level road.

The values of constants and variables used in Equation 3.3 to obtain the required power are given below. Same coefficients were used for all the four configurations except for the frontal area and mass.

Frontal area "A" – 8.32 m^2 (1995 truck), 5.95 m^2 (1982 truck)

Coefficient of friction "μ" – 0.00938

Acceleration due to gravity "g" – 9.807 m/s^2

Drag coefficient "C_D" – 0.76

Mass of the vehicle tested "M" – 19050.8 kg. (42,000 lbs.)

– 25401.2 kg. (56,000 lbs.)

– 27215.5 kg. (60,000 lbs.)

Figure 5.20 Variation of NO_X emissions (g/s) with power for the heavy acceleration bin (Test Vehicle 1, 56,000 lb., single map).

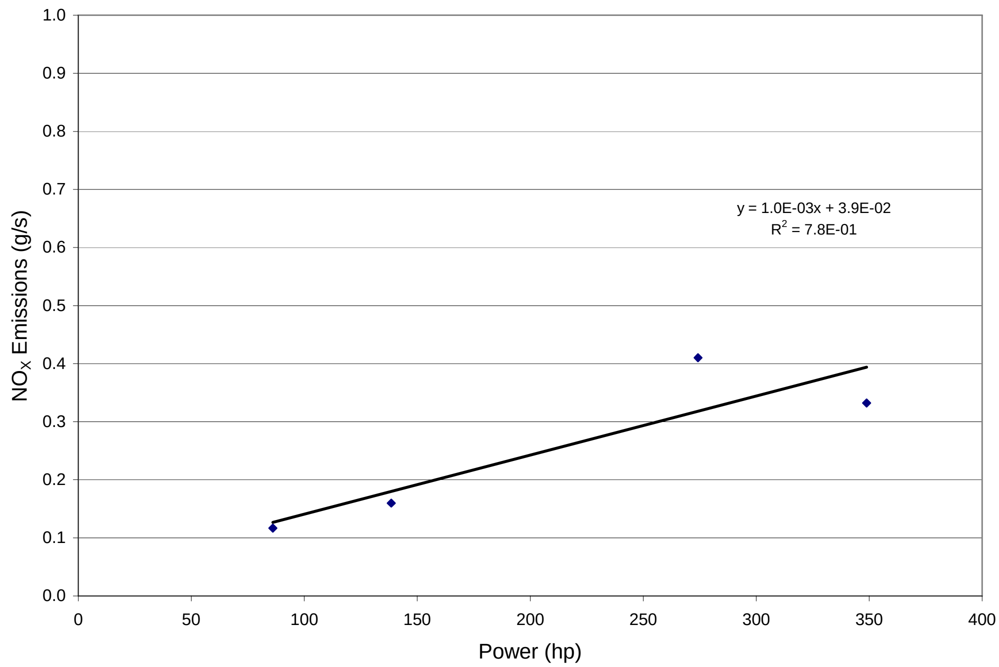
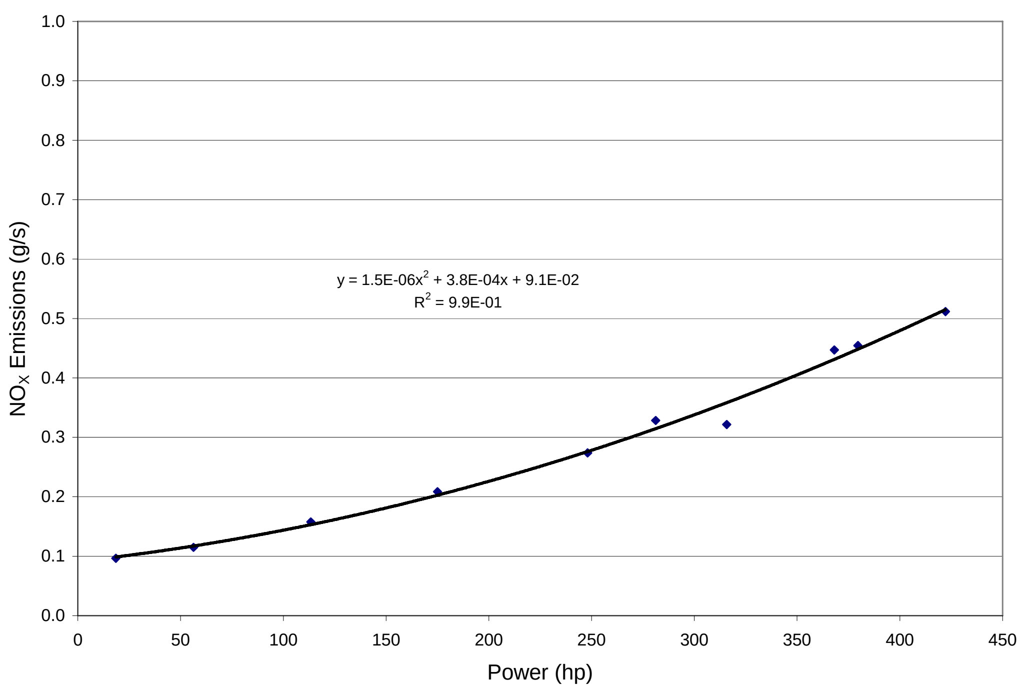


Figure 5.21 Variation of NO_X emissions (g/s) with power for the medium acceleration bin (Test Vehicle 1, 56,000 lb., single map).



The equation obtained from the road load relationship was used to extrapolate and smooth the NO_X emissions values for the first two acceleration bins. The power required was obtained by extrapolation. The relationship between the power required and the average speed (Figure 5.22 and Figure 5.23) was obtained and used for the extrapolation of the power values. It is recognized that the nature of the power versus speed relationship would depend on the ratio between vehicle wind drag and rolling resistance, but the values used in the road load equation are judged to be sufficiently representative.

Smoothing for the cruise bin was done using a logarithmic curve fit, and a linear fit was used for light deceleration bin. Remaining acceleration bins were smoothed using a polynomial curve fit between NO_X emissions and the actual average speed values for the corresponding speed bin. The curve fits used for all the five acceleration bins are shown below in Figures 5.24 through 5.28. All the axes are scaled similarly to permit visual comparison of emissions levels.

Figure 5.22 Variation of power (hp) with speed for the heavy acceleration bin (Test Vehicle 1, 56,000 lb., single map).

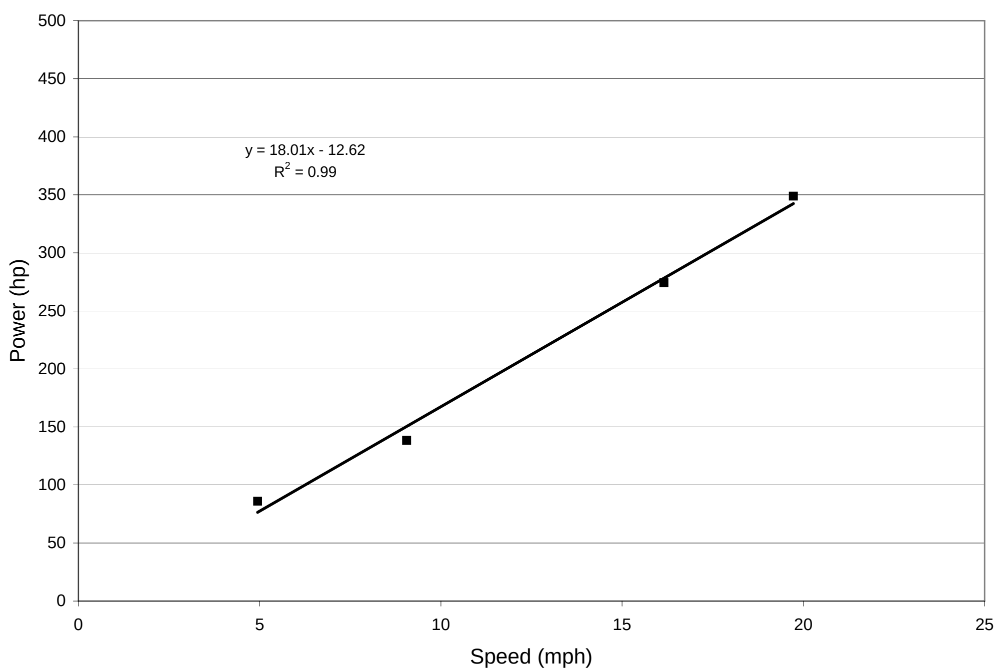


Figure 5.23 Variation of power (hp) with speed for the medium acceleration bin (Test Vehicle 1, 56,000 lb., single map).

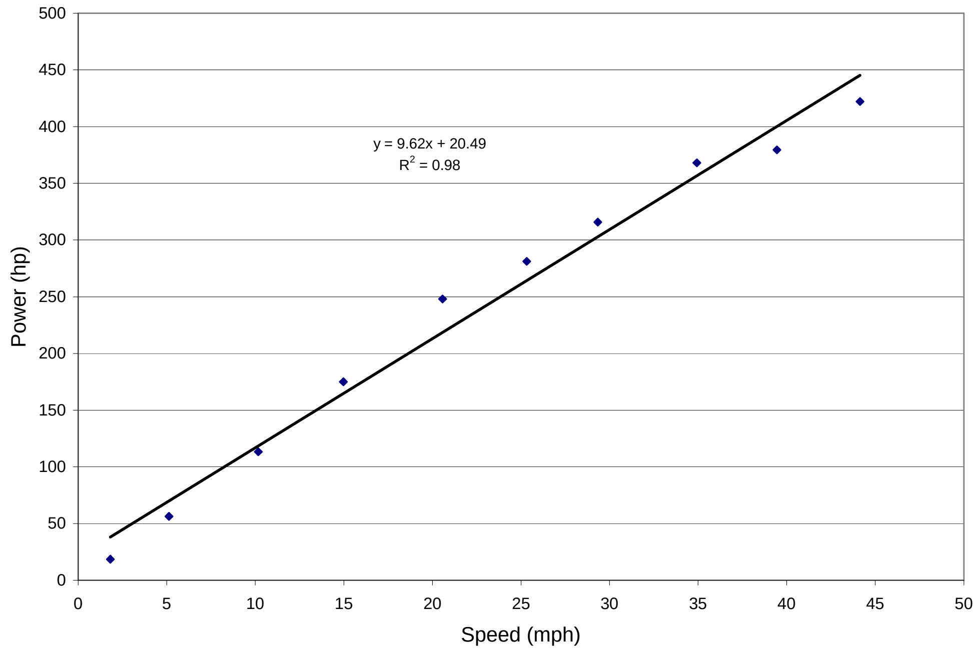


Figure 5.24 Variation of NO_X emissions (g/s) with speed for the light acceleration bin (Test Vehicle 1, 56,000 lb., single map).

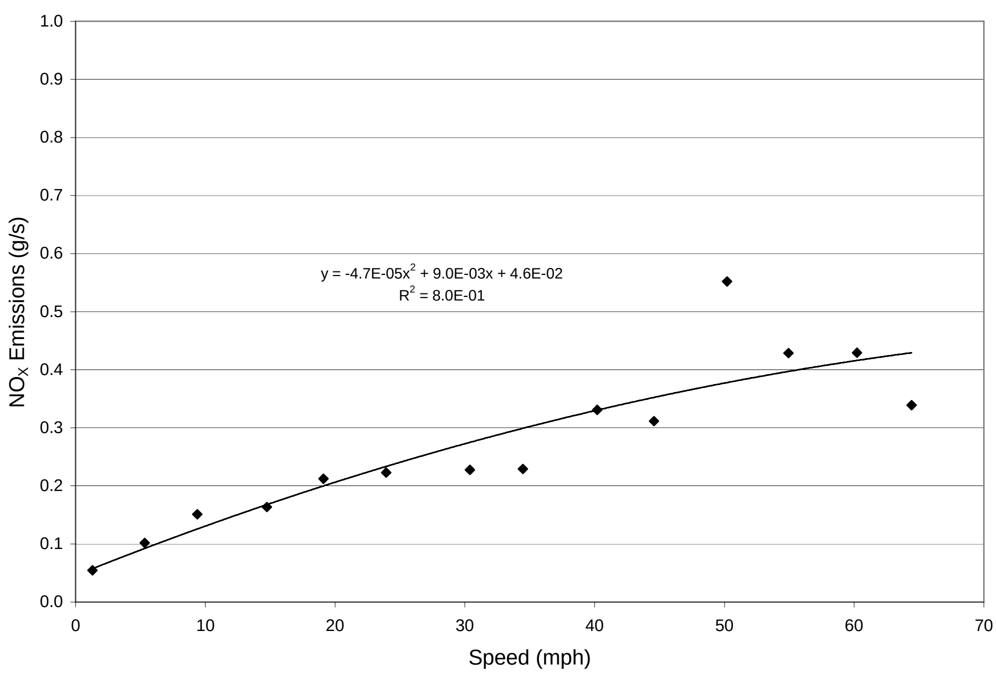


Figure 5.25 Variation of NO_X emissions (g/s) with speed for the cruise bin (Test Vehicle 1, 56,000 lb., single map).

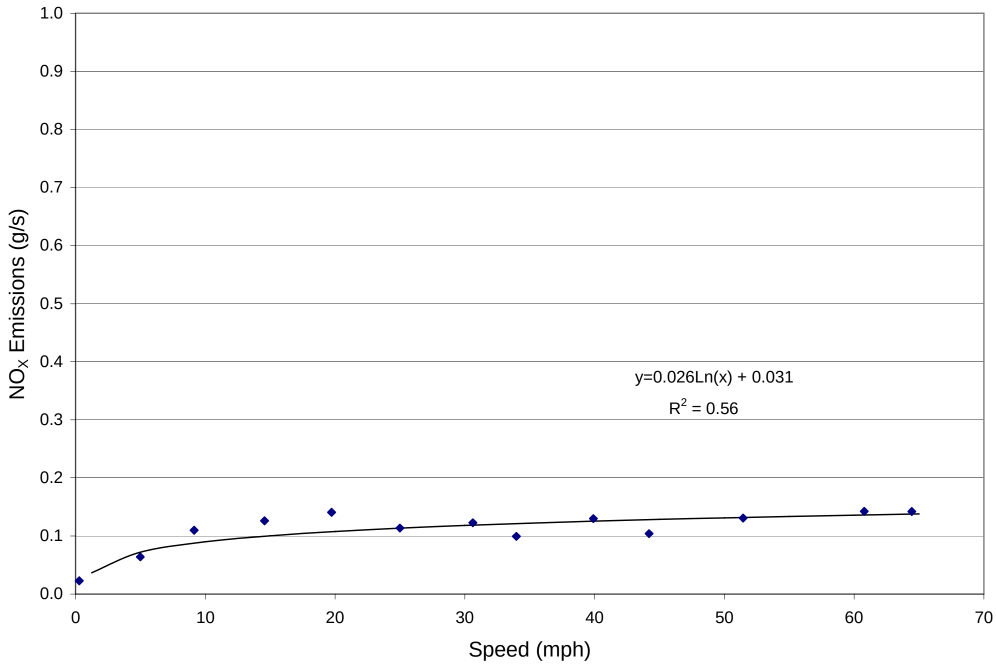


Figure 5.26 Variation of NO_X emissions (g/s) with speed for the light deceleration bin (Test Vehicle 1, 56,000 lb., single map).

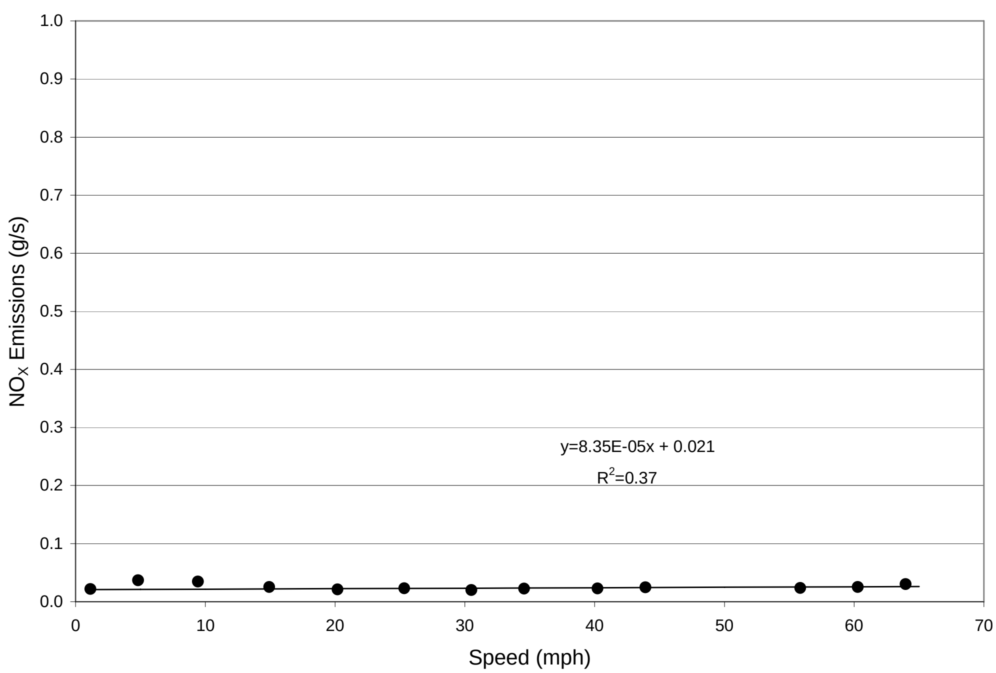


Figure 5.27 Variation of NO_X emissions (g/s) with speed for the medium deceleration bin (Test Vehicle 1, 56,000 lb., single map).

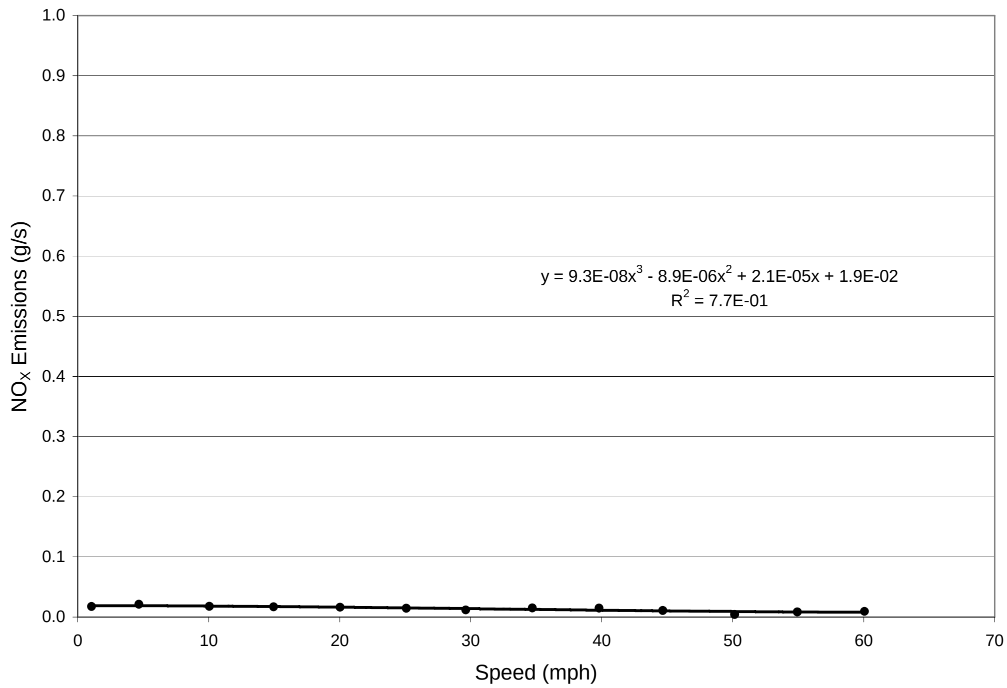
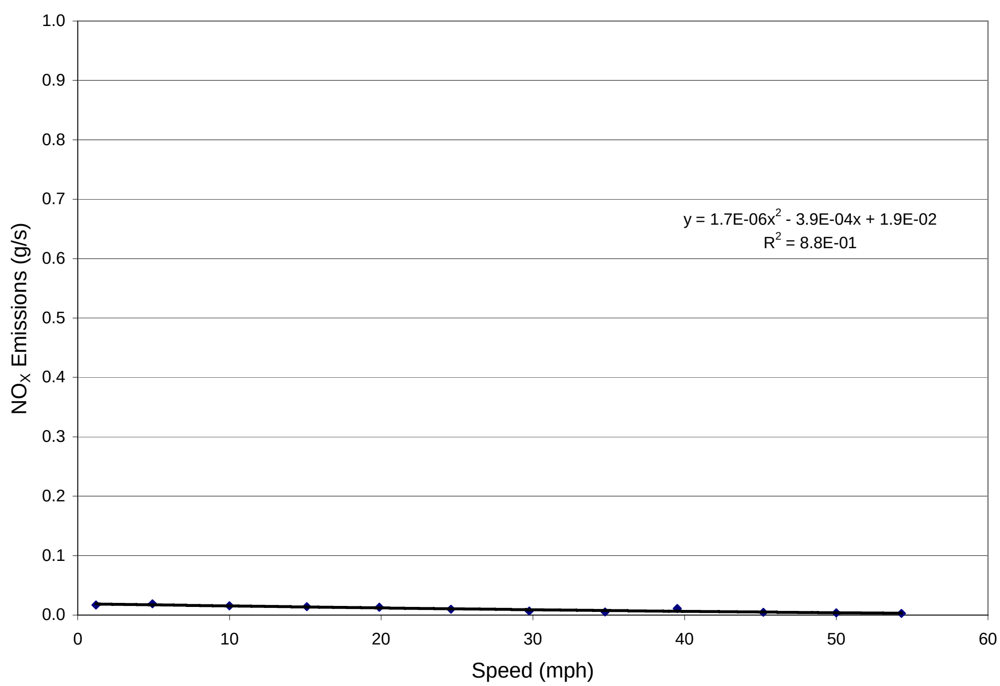


Figure 5.28 Variation of NO_X emissions (g/s) with speed for the heavy deceleration bin (Test Vehicle 1, 56,000 lb., single map).



The unsmoothed (raw) NO_X emissions data shown in Table 5.6 were smoothed using the curve fits obtained from Figures 5.20 through 5.28 and the resulting smoothed NO_X emissions data are presented in Table 5.26.

Table 5.26 Smoothed NO_X emissions data in g/s for the Test Vehicle 1 (56,000 lbs.) – Single map.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.01856	0.01878	0.02085	0.03656	0.05705	0.10505	0.04933
2.5 To 7.5	0.01714	0.01866	0.02116	0.07216	0.08953	0.12406	0.11799
7.5 To 12.5	0.01532	0.01818	0.02158	0.08996	0.13081	0.15542	0.20955
12.5 To 17.5	0.01359	0.01738	0.02200	0.10037	0.16975	0.19367	0.30111
17.5 To 22.5	0.01194	0.01635	0.02241	0.10775	0.20636	0.23879	0.39266
22.5 To 27.5	0.01037	0.01513	0.02283	0.11348	0.24064	0.29079	0.48422
27.5 To 32.5	0.00890	0.01381	0.02325	0.11817	0.27259	0.34967	0.57578
32.5 To 37.5	0.00751	0.01245	0.02366	0.12212	0.30221	0.41543	0.66734
37.5 To 42.5	0.00620	0.01111	0.02408	0.12555	0.32949	0.48807	0.75889
42.5 To 47.5	0.00499	0.00987	0.02450	0.12858	0.35445	0.56759	0.85045
47.5 To 52.5	0.00385	0.00879	0.02492	0.13128	0.37707	0.65399	0.94201
52.5 To 57.5	0.00281	0.00794	0.02533	0.13373	0.39736	0.74727	1.03356
57.5 To 62.5	0.00185	0.00739	0.02575	0.13596	0.41532	0.84743	1.12512
62.5 and above	0.00097	0.00720	0.02617	0.13802	0.43095	0.95446	1.21668

As discussed earlier in this section, Table 5.6, based on unsmoothed data, contains quirks and deviations from monotonic behavior that can be attributed to the original cycles used to acquire data. The smoothed data, shown in Table 5.26, eliminate anomalies arising from the original cycles and are therefore more suited to application to other vehicle activity patterns. If Table 5.6 were used, the unsmoothed values would impose their anomalies on other vehicle activity when used for emissions prediction. This discussion also applies to all the emissions species pertaining to the other vehicle and test weight data examined in this dissertation. Table 5.27 presents raw and smoothed NO_X emissions factors for Test Vehicle 1 on dual map at 42,000 lbs. as an example. It can be seen that smoothing of data does not have a significant effect on the final result after combining with the activity data giving NO_X emissions factor in grams/mile. Tables 5.28 through 5.30 present the NO_X emissions factors for the rest of the tests performed on the two Test Vehicles.

Table 5.27 Comparison of raw and smoothed NO_X emissions factors in g/mile for the Test Vehicle 1 (42,000 lbs. – Dual map) in rural and urban operation.

Urban Operation			
Average Speed (mph)	NO_X (g/mile)	Smoothed NO_X (g/mile)	Percentage Difference (%)
5.96	24.77	23.69	4.35
15.11	16.34	16.44	-0.63
24.21	12.51	12.46	0.39
34.29	10.11	9.82	2.93
45.88	8.54	8.19	4.13
56.06	**9.74**	**11.02**	**-13.22**
61.31	**14.61**	**14.46**	**1.04**
Rural Operation			
Average Speed (mph)	**NO_X (g/mile)**	**Smoothed NO_X (g/mile)**	**Percentage Difference (%)**
6.88	**17.87**	**16.22**	**9.25**
15.85	**17.70**	**18.18**	**-2.73**
25.27	13.41	13.38	0.18
35.38	10.36	10.17	1.85
45.93	8.97	9.17	-2.29
55.84	10.03	11.12	-10.92
62.33	16.10	15.32	4.81

Table 5.28 Smoothed NO_X emissions data in g/s for the Test Vehicle 1 (56,000 lbs.) – Dual map.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.01871	0.01938	0.02389	0.02719	0.04495	0.09939	0.05719
2.5 To 7.5	0.01909	0.01879	0.02713	0.05926	0.08501	0.11606	0.10396
7.5 To 12.5	0.01893	0.01799	0.02892	0.08635	0.12676	0.16181	0.17479
12.5 To 17.5	0.01804	0.01717	0.02854	0.09972	0.15855	0.22083	0.25530
17.5 To 22.5	0.01641	0.01634	0.02677	0.10396	0.18405	0.28250	0.34547
22.5 To 27.5	0.01403	0.01550	0.02441	0.10364	0.20692	0.33988	0.44532
27.5 To 32.5	0.01091	0.01464	0.02225	0.10334	0.23083	0.38897	0.55485
32.5 To 37.5	0.00705	0.01377	0.02108	0.10765	0.25945	0.42808	0.67404
37.5 To 42.5	0.00245	0.01288	0.02170	0.12113	0.29644	0.45711	0.80292
42.5 To 47.5	0.00245	0.01198	0.02489	0.14837	0.34547	0.47710	0.94146
47.5 To 52.5	0.00245	0.01107	0.03144	0.19395	0.41022	0.48973	1.08968
52.5 To 57.5	0.00245	0.01014	0.04215	0.26245	0.49434	0.49693	1.24757
57.5 To 62.5	0.00245	0.00919	0.05782	0.35844	0.60151	0.50052	1.41513
62.5 and above	0.00245	0.00823	0.07922	0.48650	0.73540	0.50200	1.59236

Table 5.29 Smoothed NO_X emissions data in g/s for the Test Vehicle 1 (42,000 lbs.) – Dual map.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.01711	0.02157	0.02024	0.01802	0.04217	0.06031	0.10380
2.5 To 7.5	0.01729	0.01924	0.02673	0.05602	0.08283	0.10291	0.11819
7.5 To 12.5	0.01740	0.01692	0.03144	0.08763	0.12042	0.13522	0.13737
12.5 To 17.5	0.01732	0.01546	0.03262	0.10220	0.14359	0.15388	0.15655
17.5 To 22.5	0.01703	0.01477	0.03138	0.10494	0.15736	0.17040	0.17573
22.5 To 27.5	0.01649	0.01478	0.02881	0.10102	0.16673	0.19255	0.19491
27.5 To 32.5	0.01568	0.01541	0.02599	0.09564	0.17671	0.22489	0.21409
32.5 To 37.5	0.01456	0.01659	0.02404	0.09400	0.19231	0.26942	0.23327
37.5 To 42.5	0.01311	0.01825	0.02403	0.10127	0.21855	0.32606	0.25245
42.5 To 47.5	0.01130	0.02030	0.02707	0.12265	0.26043	0.39312	0.27163
47.5 To 52.5	0.00909	0.02268	0.03424	0.16333	0.32296	0.46777	0.29081
52.5 To 57.5	0.00646	0.02530	0.04665	0.22850	0.41116	0.54645	0.30999
57.5 To 62.5	0.00337	0.02810	0.06538	0.32335	0.53003	0.62516	0.32917
62.5 and above	0.00337	0.03099	0.09153	0.45307	0.68458	0.69985	0.34835

Table 5.30 Smoothed NO_X emissions data in g/s for the Test Vehicle 2 (60,000 lbs.).

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.00551	0.00715	0.00406	0.02505	0.05432	0.08370	0.07304
2.5 To 7.5	0.00565	0.00744	0.01751	0.05818	0.06496	0.10396	0.10897
7.5 To 12.5	0.00590	0.00798	0.02965	0.09468	0.15493	0.15667	0.19338
12.5 To 17.5	0.00623	0.00869	0.03639	0.12374	0.23923	0.23875	0.32042
17.5 To 22.5	0.00663	0.00956	0.03903	0.14678	0.31786	0.35018	0.49164
22.5 To 27.5	0.00711	0.01061	0.03888	0.16524	0.39082	0.49098	0.70920
27.5 To 32.5	0.00765	0.01182	0.03725	0.18053	0.45812	0.66114	0.97587
32.5 To 37.5	0.00828	0.01319	0.03547	0.19410	0.51974	0.86066	1.29507
37.5 To 42.5	0.00898	0.01474	0.03483	0.20736	0.57569	1.08954	1.67091
42.5 To 47.5	0.00975	0.01645	0.03665	0.22175	0.62597	1.34779	2.10820
47.5 To 52.5	0.01060	0.01833	0.04224	0.23870	0.67059	1.63540	2.61250
52.5 To 57.5	0.01152	0.02038	0.05291	0.25964	0.70953	1.95237	3.19014
57.5 To 62.5	0.01251	0.02259	0.06998	0.28599	0.74280	2.29870	3.84831
62.5 and above	0.01358	0.02497	0.09476	0.31919	0.77040	2.67439	4.59510

Similar analyses were performed on the HC and CO emissions and the resulting smoothed emissions factors are presented in the following Tables. Tables 5.31 through 5.34 present the CO emissions factors and Tables 5.35 through 5.38 present the HC emissions factors for the two test vehicles (Test Vehicle 1 and Test Vehicle 2).

Table 5.31 Smoothed CO emissions data in g/s for the Test Vehicle 1 (56,000 lbs.) – Single map.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.00819	0.00840	0.01375	0.02214	0.01921	0.01224	0.01504
2.5 To 7.5	0.00856	0.00865	0.01356	0.03454	0.02925	0.02789	0.01504
7.5 To 12.5	0.00906	0.00899	0.01354	0.04074	0.03968	0.04353	0.06064
12.5 To 17.5	0.00956	0.00934	0.01381	0.04437	0.04727	0.05416	0.10624
17.5 To 22.5	0.01005	0.00972	0.01436	0.04694	0.05261	0.06078	0.15184
22.5 To 27.5	0.01052	0.01010	0.01519	0.04894	0.05629	0.06429	0.19744
27.5 To 32.5	0.01093	0.01051	0.01631	0.05057	0.05891	0.06549	0.24304
32.5 To 37.5	0.01129	0.01094	0.01770	0.05195	0.06105	0.06509	0.28864
37.5 To 42.5	0.01157	0.01138	0.01938	0.05315	0.06330	0.06371	0.33424
42.5 To 47.5	0.01175	0.01185	0.02135	0.05420	0.06625	0.06186	0.37985
47.5 To 52.5	0.01183	0.01234	0.02359	0.05514	0.07049	0.05997	0.42545
52.5 To 57.5	0.01178	0.01285	0.02612	0.05599	0.07662	0.05838	0.47105
57.5 To 62.5	0.01159	0.01338	0.02893	0.05677	0.08521	0.05731	0.51665
62.5 and above	0.01124	0.01394	0.03202	0.05749	0.09686	0.05693	0.56225

Table 5.32 Smoothed CO emissions data in g/s for the Test Vehicle 1 (56,000 lbs.) – Dual map.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.00459	0.00465	0.00516	0.01743	0.00552	0.00400	0.00400
2.5 To 7.5	0.00533	0.00548	0.00750	0.01748	0.01238	0.02292	0.00775
7.5 To 12.5	0.00596	0.00623	0.00976	0.01756	0.02097	0.04816	0.11533
12.5 To 17.5	0.00617	0.00661	0.01118	0.01764	0.02891	0.07339	0.22291
17.5 To 22.5	0.00596	0.00668	0.01185	0.01772	0.03622	0.09863	0.33049
22.5 To 27.5	0.00532	0.00647	0.01190	0.01780	0.04289	0.12386	0.43807
27.5 To 32.5	0.00424	0.00602	0.01144	0.01788	0.04892	0.14910	0.54565
32.5 To 37.5	0.00272	0.00537	0.01060	0.01795	0.05431	0.17433	0.65324
37.5 To 42.5	0.00075	0.00458	0.00948	0.01803	0.05906	0.19957	0.76082
42.5 To 47.5	0.00075	0.00367	0.00820	0.01811	0.06318	0.22480	0.86840
47.5 To 52.5	0.00075	0.00270	0.00689	0.01819	0.06666	0.25003	0.97598
52.5 To 57.5	0.00075	0.00171	0.00565	0.01827	0.06949	0.27527	1.08356
57.5 To 62.5	0.00075	0.00073	0.00460	0.01835	0.07169	0.30050	1.19114
62.5 and above	0.00075	0.00073	0.00387	0.01842	0.07325	0.32574	1.29872

Table 5.33 Smoothed CO emissions data in g/s for the Test Vehicle 1 (42,000 lbs.) – Dual map.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.00179	0.00226	0.00515	0.01870	0.00710	0.00486	0.01413
2.5 To 7.5	0.00176	0.00236	0.00545	0.01854	0.01152	0.01458	0.02204
7.5 To 12.5	0.00179	0.00253	0.00586	0.01832	0.01700	0.02336	0.03225
12.5 To 17.5	0.00190	0.00273	0.00627	0.01811	0.02201	0.02798	0.04207
17.5 To 22.5	0.00209	0.00297	0.00667	0.01789	0.02656	0.03038	0.05151
22.5 To 27.5	0.00236	0.00324	0.00708	0.01768	0.03064	0.03289	0.06057
27.5 To 32.5	0.00270	0.00355	0.00748	0.01746	0.03425	0.03713	0.06924
32.5 To 37.5	0.00312	0.00389	0.00789	0.01724	0.03741	0.04325	0.07753
37.5 To 42.5	0.00361	0.00427	0.00829	0.01703	0.04009	0.04978	0.08543
42.5 To 47.5	0.00419	0.00468	0.00870	0.01681	0.04231	0.05422	0.09295
47.5 To 52.5	0.00484	0.00513	0.00911	0.01660	0.04407	0.05423	0.10009
52.5 To 57.5	0.00556	0.00561	0.00951	0.01638	0.04536	0.04914	0.10684
57.5 To 62.5	0.00637	0.00612	0.00992	0.01617	0.04618	0.04094	0.11321
62.5 and above	0.00725	0.00668	0.01032	0.01595	0.04654	0.03366	0.11919

Table 5.34 Smoothed CO emissions data in g/s for the Test Vehicle 2 (60,000 lbs.).

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.01932	0.01466	0.02051	0.04108	0.03556	0.02595	0.01775
2.5 To 7.5	0.01951	0.01619	0.04099	0.05173	0.08435	0.15394	0.12898
7.5 To 12.5	0.01989	0.01822	0.05004	0.06487	0.12783	0.21632	0.21888
12.5 To 17.5	0.02024	0.02026	0.05455	0.07672	0.15492	0.22298	0.26387
17.5 To 22.5	0.02034	0.02229	0.05720	0.08718	0.17284	0.21927	0.28818
22.5 To 27.5	0.02000	0.02432	0.05882	0.09616	0.18678	0.22738	0.31735
27.5 To 32.5	0.01901	0.02636	0.05981	0.10355	0.19999	0.25325	0.37913
32.5 To 37.5	0.01718	0.02839	0.06034	0.10924	0.21374	0.29262	0.50452
37.5 To 42.5	0.01429	0.03043	0.06055	0.11316	0.22730	0.33602	0.72889
42.5 To 47.5	0.01014	0.03246	0.06052	0.11518	0.23797	0.37277	1.09319
47.5 To 52.5	0.00453	0.03449	0.06028	0.11522	0.24110	0.39401	1.64540
52.5 To 57.5	0.00453	0.03653	0.05989	0.11317	0.23004	0.39471	2.44207
57.5 To 62.5	0.00453	0.03856	0.05937	0.10894	0.19615	0.37472	3.55010
62.5 and above	0.00453	0.04060	0.05873	0.10242	0.12884	0.33875	5.04883

Table 5.35 Smoothed HC emissions data in g/s for the Test Vehicle 1 (56,000 lbs.) – Single map.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.00190	0.00149	0.00183	0.00202	0.00205	0.00243	0.00220
2.5 To 7.5	0.00183	0.00150	0.00184	0.00207	0.00212	0.00244	0.00216
7.5 To 12.5	0.00174	0.00151	0.00186	0.00214	0.00221	0.00246	0.00212
12.5 To 17.5	0.00164	0.00152	0.00188	0.00221	0.00230	0.00247	0.00208
17.5 To 22.5	0.00155	0.00152	0.00190	0.00228	0.00239	0.00248	0.00204
22.5 To 27.5	0.00146	0.00153	0.00192	0.00235	0.00248	0.00249	0.00200
27.5 To 32.5	0.00136	0.00154	0.00194	0.00242	0.00257	0.00249	0.00196
32.5 To 37.5	0.00127	0.00155	0.00196	0.00249	0.00266	0.00250	ND
37.5 To 42.5	0.00118	0.00156	0.00198	0.00256	0.00275	0.00251	ND
42.5 To 47.5	0.00108	0.00156	0.00200	0.00263	0.00284	0.00251	ND
47.5 To 52.5	0.00099	0.00157	0.00202	0.00270	0.00293	0.00251	ND
52.5 To 57.5	0.00090	0.00158	0.00204	0.00277	0.00302	0.00252	ND
57.5 To 62.5	0.00081	0.00159	0.00206	0.00284	0.00311	0.00252	ND
62.5 and above	0.00071	0.00160	0.00208	0.00291	0.00320	0.00252	ND

Table 5.36 Smoothed HC emissions data in g/s for the Test Vehicle 1 (56,000 lbs.) – Dual map.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.00164	0.00136	0.00161	0.00207	0.00221	0.00264	0.00387
2.5 To 7.5	0.00146	0.00137	0.00166	0.00210	0.00226	0.00259	0.00346
7.5 To 12.5	0.00133	0.00140	0.00172	0.00214	0.00232	0.00252	0.00292
12.5 To 17.5	0.00127	0.00142	0.00178	0.00218	0.00238	0.00245	0.00238
17.5 To 22.5	0.00123	0.00144	0.00184	0.00222	0.00244	0.00238	0.00184
22.5 To 27.5	0.00114	0.00146	0.00190	0.00226	0.00249	0.00232	0.00130
27.5 To 32.5	0.00095	0.00149	0.00196	0.00229	0.00255	0.00225	0.00076
32.5 To 37.5	0.00061	0.00151	0.00202	0.00233	0.00261	0.00218	ND
37.5 To 42.5	0.00005	0.00153	0.00208	0.00237	0.00267	0.00211	ND
42.5 To 47.5	0.00005	0.00156	0.00214	0.00241	0.00273	0.00204	ND
47.5 To 52.5	ND	0.00158	0.00220	0.00245	0.00279	0.00197	ND
52.5 To 57.5	ND	0.00160	0.00226	0.00249	0.00285	0.00191	ND
57.5 To 62.5	ND	0.00163	0.00232	0.00252	0.00291	0.00184	ND
62.5 and above	ND	0.00165	0.00239	0.00256	0.00296	0.00177	ND

Table 5.37 Smoothed HC emissions data in g/s for the Test Vehicle 1 (42,000 lbs.) – Dual map.

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.00124	0.00140	0.00185	0.00245	0.00268	0.00283	0.00364
2.5 To 7.5	0.00127	0.00144	0.00189	0.00249	0.00272	0.00285	0.00327
7.5 To 12.5	0.00131	0.00149	0.00196	0.00254	0.00277	0.00289	0.00279
12.5 To 17.5	0.00134	0.00155	0.00202	0.00260	0.00282	0.00293	0.00232
17.5 To 22.5	0.00138	0.00161	0.00209	0.00265	0.00287	0.00296	0.00188
22.5 To 27.5	0.00141	0.00166	0.00215	0.00270	0.00292	0.00300	0.00146
27.5 To 32.5	0.00145	0.00172	0.00221	0.00275	0.00297	0.00303	0.00105
32.5 To 37.5	0.00148	0.00177	0.00228	0.00280	0.00303	0.00306	0.00066
37.5 To 42.5	0.00152	0.00183	0.00234	0.00285	0.00308	0.00308	ND
42.5 To 47.5	0.00155	0.00189	0.00241	0.00291	0.00313	0.00309	ND
47.5 To 52.5	0.00159	0.00194	0.00247	0.00296	0.00318	0.00309	ND
52.5 To 57.5	0.00162	0.00200	0.00254	0.00301	0.00323	0.00308	ND
57.5 To 62.5	0.00166	0.00205	0.00260	0.00306	0.00328	0.00305	ND
62.5 and above	0.00170	0.00211	0.00266	0.00311	0.00334	0.00301	ND

Table 5.38 Smoothed HC emissions data in g/s for the Test Vehicle 2 (60,000 lbs.).

Speed Bin	Heavy Deceleration	Medium Deceleration	Light Deceleration	Cruise	Light Acceleration	Medium Acceleration	Heavy Acceleration
0 To 2.5	0.01527	0.01404	0.01739	0.02011	0.02480	0.02532	0.02341
2.5 To 7.5	0.01472	0.01414	0.01795	0.02047	0.02486	0.02580	0.01974
7.5 To 12.5	0.01398	0.01428	0.01869	0.02095	0.02494	0.02637	0.02689
12.5 To 17.5	0.01325	0.01441	0.01943	0.02143	0.02502	0.02689	0.02676
17.5 To 22.5	0.01251	0.01455	0.02017	0.02191	0.02510	0.02734	0.02751
22.5 To 27.5	0.01178	0.01468	0.02091	0.02239	0.02518	0.02772	0.03057
27.5 To 32.5	0.01104	0.01482	0.02165	0.02287	0.02526	0.02805	0.03007
32.5 To 37.5	0.01031	0.01495	0.02239	0.02335	0.02534	0.02830	0.03414
37.5 To 42.5	0.00958	0.01509	0.02314	0.02383	0.02542	0.02850	ND
42.5 To 47.5	0.00884	0.01522	0.02388	0.02431	0.02549	0.02863	ND
47.5 To 52.5	0.00811	0.01536	0.02462	0.02479	0.02557	0.02869	ND
52.5 To 57.5	0.00737	0.01549	0.02536	0.02527	0.02565	0.02870	ND
57.5 To 62.5	0.00664	0.01563	0.02610	0.02575	0.02573	0.02863	ND
62.5 and above	ND	0.01576	0.02684	0.02623	0.02581	0.02851	ND

5.6 Presentation of Emissions Factors in grams/mile as a function of Average Speed Class

The smoothed NO_X emissions values presented as a speed-acceleration based two-dimensional matrix for the vehicle configurations discussed above were combined with the Battelle activity data for each Battelle average speed class. The smoothed NO_X emissions table (Table 5.26) was multiplied with the activity data for a particular average speed class and the values were summed up to obtain a single value. This procedure was repeated for all of the average speed classes and the resulting NO_X emissions factors in grams/mile as a function of average speed class are presented below in Table 5.39. The emission values in grams/mile were obtained for both rural and urban mode of operation. It can be observed that the NO_X emissions factor values at low average speeds are higher for urban operation. This is due to the fact that urban mode involves considerable operation in typical stop and go city driving pattern. It should be noted that same NO_X emissions factor table was used to obtain both rural and urban factors. The difference in values exists due to the difference in percentage of time of operation in each cell present in the Battelle activity data.

Table 5.39 NO_X emissions factors in grams/mile for all the trucks as a function of average speed class in rural and urban mode of operation.

Test details	Average Speed Bin in mph						
	0-10	10-20	20-30	30-40	40-50	50-60	60-70
Rural							
Test Vehicle 1 (1995 truck) - 56000 lbs. Dual Map	34.55	22.24	17.20	15.40	15.18	18.30	23.79
Test Vehicle 1 (1995 truck) - 56000 lbs. Single Map	39.24	23.25	17.95	14.92	12.12	9.56	8.82
Test Vehicle 1 (1995 truck) - 42000 lbs. Dual Map	32.43	21.11	15.29	12.88	12.66	16.07	21.82
Test Vehicle 2 (1982 truck) - 60000 lbs.	36.46	30.35	27.52	25.40	22.27	18.98	19.39
Urban							
Test Vehicle 1 (1995 truck) - 56000 lbs. Dual Map	36.22	26.54	21.43	15.23	13.65	18.31	22.77
Test Vehicle 1 (1995 truck) - 56000 lbs. Single Map	41.79	28.74	23.29	16.53	11.66	9.14	8.61
Test Vehicle 1 (1995 truck) - 42000 lbs. Dual Map	32.49	24.01	18.33	12.31	11.24	16.10	20.75
Test Vehicle 2 (1982 truck) - 60000 lbs.	39.93	35.70	34.14	28.37	21.02	18.16	18.55

Tables 5.40 and 5.41 present the CO and HC emissions factors in grams/mile as a function of the average speed class, in rural and urban mode of operation, for all the tests conducted on Test Vehicle 1 and Test Vehicle 2.

Table 5.40 CO emissions factors in grams/mile for all the trucks as a function of average speed class in rural and urban mode of operation.

Test details	0-10	10-20	20-30	30-40	40-50	50-60	60-70
			Average Speed Bin in mph				
Rural							
Test Vehicle 1 (1995 truck) - 56000 lbs. Dual Map	9.54	5.21	4.03	3.37	2.48	1.55	1.46
Test Vehicle 1 (1995 truck) - 56000 lbs. Single Map	18.17	9.44	6.75	5.19	4.27	3.64	3.40
Test Vehicle 1 (1995 truck) - 42000 lbs. Dual Map	9.54	4.06	2.68	2.01	1.53	1.16	1.02
Test Vehicle 2 (1982 truck) - 60000 lbs.	29.76	19.18	15.24	12.63	10.23	7.81	6.82
Urban							
Test Vehicle 1 (1995 truck) - 56000 lbs. Dual Map	11.87	7.50	6.47	4.06	2.11	1.39	1.32
Test Vehicle 1 (1995 truck) - 56000 lbs. Single Map	19.01	10.64	7.91	5.49	4.27	3.62	3.39
Test Vehicle 1 (1995 truck) - 42000 lbs. Dual Map	10.76	4.76	3.35	2.19	1.48	1.11	1.01
Test Vehicle 2 (1982 truck) - 60000 lbs.	35.63	25.42	20.34	14.01	9.99	7.55	6.69

Table 5.41 HC emissions factors in grams/mile for all the trucks as a function of average speed class in rural and urban mode of operation.

Test details	0-10	10-20	20-30	30-40	40-50	50-60	60-70
			Average Speed Bin in mph				
Rural							
Test Vehicle 1 (1995 truck) - 56000 lbs. Dual Map	1.10	0.49	0.32	0.23	0.19	0.16	0.15
Test Vehicle 1 (1995 truck) - 56000 lbs. Single Map	1.09	0.50	0.33	0.25	0.20	0.18	0.16
Test Vehicle 1 (1995 truck) - 42000 lbs. Dual Map	1.30	0.58	0.37	0.28	0.22	0.19	0.18
Test Vehicle 2 (1982 truck) - 60000 lbs.	10.80	4.88	3.19	2.37	1.90	1.63	1.49
Urban							
Test Vehicle 1 (1995 truck) - 56000 lbs. Dual Map	1.26	0.61	0.38	0.24	0.19	0.16	0.15
Test Vehicle 1 (1995 truck) - 56000 lbs. Single Map	1.25	0.61	0.39	0.25	0.20	0.18	0.17
Test Vehicle 1 (1995 truck) - 42000 lbs. Dual Map	1.48	0.70	0.45	0.28	0.23	0.19	0.18
Test Vehicle 2 (1982 truck) - 60000 lbs.	12.45	6.16	3.95	2.43	1.90	1.63	1.52

5.7 Verification of Speed-Acceleration Approach

Verification of the speed-acceleration approach for NO_X emissions was done in the following manner. For this purpose, the Test Vehicle 1 operating on the single map was tested over the UDDS (UDDS) cycle at 56,000 lbs. The emission factors as a function of the average speed class (shown above) were obtained for the emissions results from UDDS for the Test Vehicle 1 and are presented in Table 5.42.

Table 5.42 NO_X emissions factors in grams/mile for the Test Vehicle 1 as a function of average speed class in rural and urban mode of operation.

Test details	Average Speed Bin in mph						
	0-10	10-20	20-30	30-40	40-50	50-60	60-70
Rural							
Test Vehicle 1 (1995 truck) - 56000 lbs. - Test_D	37.71	25.15	19.66	16.28	14.59	14.41	15.46
Urban							
Test Vehicle 1 (1995 truck) - 56000 lbs. - Test_D	39.74	27.78	22.03	16.83	14.44	14.55	15.34

A basic assumption used in constructing emissions factors from the UDDSata is that the continuous second-by-second emissions at a given speed-acceleration point are independent of the overall speed-time profile over which the vehicle is being driven. To assess the validation of this assumption and to verify the speed-acceleration method for emissions predictions, the UDDSata were divided into 0.5 mile segments as shown in Tables 5.43 – 5.45. Travel demand models available to transportation agencies provide speed estimates for links whose lengths are typically about half-mile long. The speed values and the emissions values were averaged for every 0.5-mile interval and placed in the respective bin. Then, a polynomial curve was fitted to the NO_X versus average speed class (as in Table 5.39) and the resulting equation was used to predict the NO_X emissions for each of the 0.5-mile segment (shown in tables below). For each bin, the NO_X emissions were predicted using the two emissions factor in grams/mile tables. One table corresponds to the CSHVR and IHC combined (Table 5.39) and the other one for UDDS (UDDS), obtained in a similar manner (Table 5.42). The predicted values were then averaged over all the bins and a single averaged value was obtained. The results are also summarized and presented in Table 5.46. It can be seen from Tables 5.43 through 5.45 that for some links, the NO_X emissions were poorly predicted. Consider segment numbers 5, 8, and 9 for the CSHVR table (Table 5.43). The percentage difference between predicted and actual NO_X emissions were over 30% for segments 8 and 9. Segment 9 had an average speed of 5.88 mph, but examination of continuous data revealed that most of the operation in this segment was spent in deceleration and idle. As seen in Figure 5.29, of the total duration of 306 seconds, the vehicle decelerated from 42.5 mph to 1.25 mph during the first 60 seconds and almost 120 seconds were spent in idling. The NO_X emissions were over predicted for this case because, for this average speed class (0 – 10 mph) in the Battelle activity data, most of the operation occurs in the first two speed bins in cruise. Segments 5 and 8 have the same average speed (approx 24.3 mph). Examination of the continuous data showed that segment 5 exhibited considerable operation in cruise and a little operation in acceleration and deceleration similar to the Battelle activity data. Segment 8 has the same average speed as segment 5, but most of the operation occurs in acceleration. The vehicle accelerates from a speed of 1.14 mph at 7 seconds to a speed of 43 mph at 64 seconds during the total of 74 seconds of operation. Hence the emissions are under predicted for this segment. Examination of the continuous data for IHC revealed the similar results for cells with high percentage error.

It can be seen from Table 5.45 that NO_X predictions were poor for UDDS for segments 7 and 10. Figures 5.30 and 5.31 show the 3-dimensional plots of activity for Battelle data, corresponding to an average speed class of 10 – 20 mph, and UDDS activity. It can be seen that activity data for UDDS (with an average speed of 18.25 mph) is not representative of the Battelle activity data. One third of the activity in UDDS occurs in cruise and in 0 – 2.5 mph speed bin. Nearly 50% of activity in Battelle data for average speed class of 10 – 20 mph occurs in the first five speed bins in cruise. This can be attributed to the consistent over prediction of NO_X emissions for some segments, which do not represent Battelle activity data.

Table 5.43 Predicted and actual NO_X for Test Vehicle 1 over CSHVR at 56,000 lb.

CSHVR - 1995 Truck (56000 lbs.) - Single Map

Segment	Length	Avg. speed	Actual NOx	NOx predicted - Test_D - Rural	NOx predicted - Test_D - Urban	NOx predicted - CSHVR & IHC - Rural	NOx predicted - CSHVR & IHC - Urban	Percentage diff. - Test_D - Rural	Percentage diff. - Test_D - Urban	Percentage diff. - CSHVR & IHC - rural	Percentage diff. - CSHVR & IHC - Urban
	(mile)	(mph)	(g/mile)	(g/mile)	(g/mile)	(g/mile)	(g/mile)	(%)	(%)	(%)	(%)
1	0.5	10.97	30.49	29.37	30.84	28.18	31.54	-3.66	1.14	-7.58	3.46
2	0.5	31.74	19.4	17.12	18.29	15.76	18.71	-11.75	-5.74	-18.78	-3.56
3	0.5	10.59	24.21	29.81	31.20	28.72	31.91	23.12	28.88	18.62	31.80
4	0.5	28.15	21.78	18.16	20.22	16.65	21.19	-16.61	-7.17	-23.56	-2.69
5	0.5	24.35	19.85	19.59	22.39	17.83	23.71	-1.29	12.81	-10.16	19.44
6	0.5	8.55	28.85	32.34	33.52	31.96	34.38	12.11	16.18	10.78	19.15
7	0.5	18.25	28.14	22.92	25.85	20.89	27.09	-18.56	-8.13	-25.75	-3.73
8	0.5	24.26	32.32	19.63	22.44	17.87	23.77	-39.25	-30.56	-44.72	-26.47
9	0.5	5.88	28.41	36.22	37.86	37.18	39.46	27.49	33.27	30.87	38.90
10	0.5	21.74	30.16	20.84	23.88	18.91	25.26	-30.92	-20.81	-37.29	-16.25
11	0.5	18.92	21.09	22.48	25.47	20.45	26.75	6.57	20.79	-3.01	26.86
12	0.5	15.47	32.16	25.00	27.49	23.07	28.49	-22.27	-14.53	-28.26	-11.41
13	0.5	28.73	23.3	17.98	19.90	16.49	20.79	-22.85	-14.61	-29.21	-10.75
Averaged	**6.50**	**14.86**	**26.17**	**23.96**	**26.10**	**22.61**	**27.16**	**-8.44**	**-0.24**	**-13.58**	**3.79**

Figure 5.29 Variation of speed and NO_X emissions (g/s) with time for segment # 9 for the CSHVR prediction table (Table 5.43).

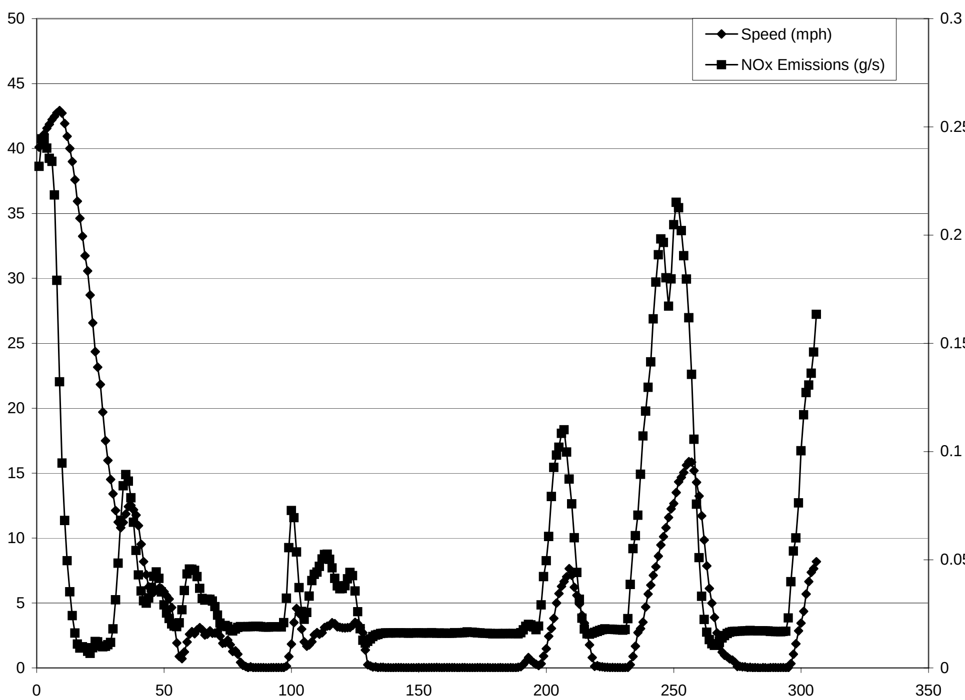


Figure 5.30 3-Dimensional plot of activity for Battelle database corresponding to average speed class of 10 – 20 mph.

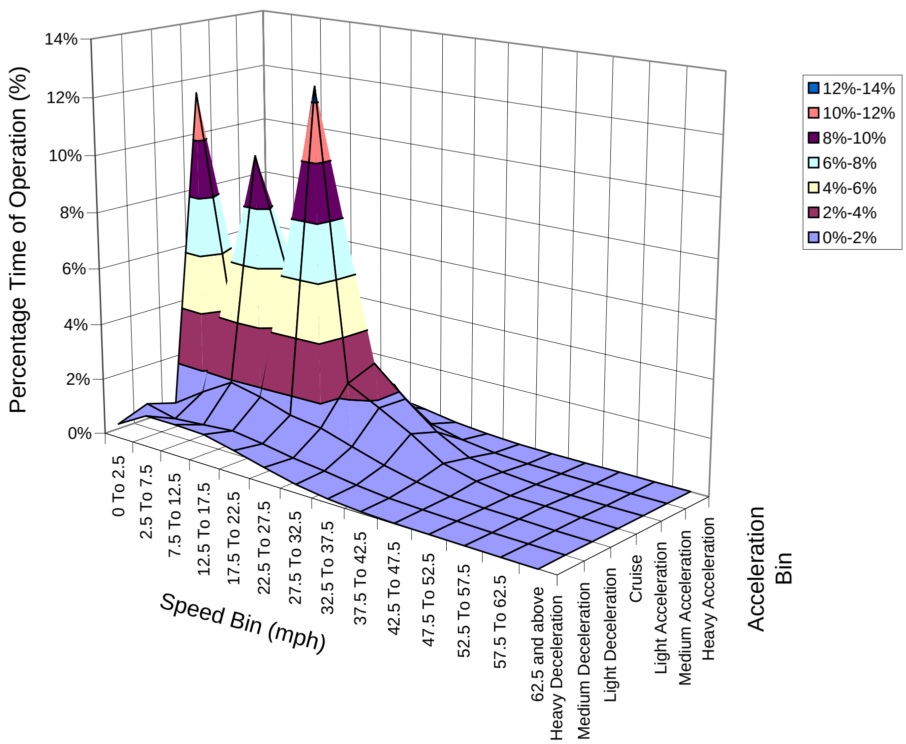


Figure 5.31 3-Dimensional plot of activity for UDDS cycle corresponding to average speed of 18.25 mph.

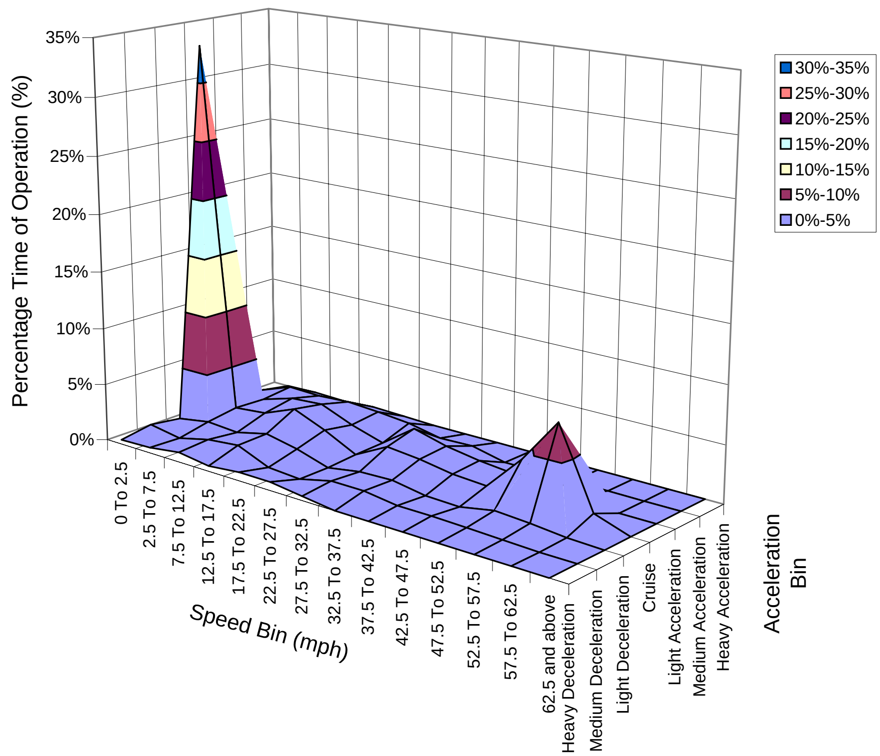


Table 5.44 Predicted and actual NO_X for the Test Vehicle 1 over IHC at 56,000 lb.

Segment	Length (mile)	Avg. speed (mph)	Actual NOx (g/mile)	NOx predicted - Test_D - Rural (g/mile)	NOx predicted - Test_D - Urban (g/mile)	NOx predicted - CSHVR & IHC - Rural (g/mile)	NOx predicted - CSHVR & IHC - Urban (g/mile)	Percentage diff. - Test_D - Rural (%)	Percentage diff. - Test_D - Urban (%)	Percentage diff. - CSHVR & IHC - rural (%)	Percentage diff. - CSHVR & IHC - Urban (%)
1	0.5	13.41	32.19	26.83	28.85	25.13	29.67	-16.64	-10.37	-21.92	-7.82
2	0.5	21.61	18.53	20.90	23.96	18.98	25.33	12.81	29.29	2.40	36.71
3	0.5	21.84	42.93	20.78	23.83	18.87	25.20	-51.59	-44.50	-56.05	-41.29
4	0.5	57.93	20.1	14.32	13.34	8.75	9.09	-28.74	-33.65	-56.48	-54.77
5	0.5	60.87	11.66	14.63	13.02	8.46	8.89	25.49	11.63	-27.47	-23.72
6	0.5	65.1	9.28	15.54	12.66	8.89	9.68	67.43	36.44	-4.16	4.31
7	0.5	65.13	8.25	15.55	12.66	8.90	9.69	88.44	53.46	7.90	17.50
8	0.5	64.65	7.41	15.41	12.67	8.79	9.50	107.97	71.04	18.58	28.15
9	0.5	63.73	7.07	15.18	12.73	8.62	9.21	114.65	80.01	21.88	30.27
10	0.5	63.89	10.65	15.21	12.72	8.64	9.25	42.86	19.39	-18.85	-13.13
11	0.5	64.67	8.29	15.42	12.67	8.79	9.50	85.96	52.87	6.05	14.64
12	0.5	64.61	7.69	15.40	12.68	8.78	9.48	100.26	64.83	14.15	23.29
13	0.5	64.42	8.12	15.35	12.68	8.74	9.41	89.03	56.21	7.62	15.93
14	0.5	58.91	11.08	14.40	13.24	8.61	8.99	29.98	19.46	-22.30	-18.86
15	0.5	63.94	13	15.23	12.71	8.65	9.27	17.13	-2.22	-33.46	-28.73
16	0.5	64.31	9.58	15.32	12.69	8.72	9.38	59.92	32.46	-9.01	-2.12
17	0.5	65.13	7.79	15.55	12.66	8.90	9.69	99.57	62.53	14.27	24.44
18	0.5	59.93	4.78	14.51	13.12	8.51	8.92	203.54	174.56	77.97	86.58
19	0.5	30.24	16.77	17.52	19.07	16.11	19.75	4.50	13.71	-3.91	17.74
20	0.5	42.13	18.35	15.16	14.57	13.19	12.81	-17.38	-20.58	-28.14	-30.18
21	0.5	10.87	17.95	29.49	30.93	28.32	31.64	64.27	72.32	57.76	76.26
22	0.5	12.28	33.76	27.96	29.70	26.46	30.45	-17.19	-12.01	-21.63	-9.80
23	0.5	37.95	38.92	15.81	15.65	14.30	14.81	-59.39	-59.78	-63.27	-61.95
24	0.5	59.58	10.05	14.47	13.16	8.54	8.94	43.97	30.98	-15.06	-11.06
25	0.5	61.96	4.93	14.81	12.89	8.46	8.93	200.37	161.53	71.57	81.20
26	0.5	64.51	4.61	15.37	12.68	8.76	9.45	233.47	175.05	89.96	104.88
27	0.5	63.62	8.01	15.15	12.73	8.60	9.18	89.13	58.99	7.38	14.65
28	0.5	64.39	7.86	15.34	12.69	8.73	9.40	95.18	61.39	11.10	19.64
29	0.5	62.95	11.78	15.00	12.79	8.52	9.05	27.34	8.59	-27.66	-23.18
30	0.5	66.38	8.61	15.94	12.69	9.29	10.40	85.18	47.39	7.93	20.75
31	0.5	63.8	6.86	15.19	12.72	8.63	9.23	121.46	85.45	25.77	34.52
32	0.5	62.47	5.27	14.90	12.84	8.48	8.98	182.79	143.63	60.97	70.44
33	0.5	58.7	6.27	14.38	13.26	8.64	9.01	129.40	111.46	37.73	43.69
34	0.5	14.77	27.3	25.59	27.93	23.73	28.87	-6.26	2.30	-13.09	5.74
35	0.5	22.49	33.56	20.45	23.46	18.57	24.83	-39.05	-30.10	-44.65	-26.01
36	0.5	43.98	14.31	14.92	14.27	12.65	12.11	4.28	-0.28	-11.60	-15.37
37	0.5	33.87	3.33	16.61	17.26	15.26	17.28	398.85	418.32	358.40	418.86
Averaged	**18.5**	**37.57**	**13.97**	**17.02**	**15.95**	**12.13**	**13.66**	**21.80**	**14.18**	**-13.15**	**-2.25**

Table 5.45 Predicted and actual NO_X for the Test Vehicle 1 over Test-D at 56,000 lb.

Test-D - 1995 Truck (56000 lbs.) - Single Map											
Segment	Length (mile)	Avg. speed (mph)	Actual NOx (g/mile)	NOx predicted - Test_D - Rural (g/mile)	NOx predicted - Test_D - Urban (g/mile)	NOx predicted - CSHVR & IHC - Rural (g/mile)	NOx predicted - CSHVR & IHC - Urban (g/mile)	Percentage diff. - Test_D - Rural (%)	Percentage diff. - Test_D - Urban (%)	Percentage diff. - CSHVR & IHC - Rural (%)	Percentage diff. - CSHVR & IHC - Urban (%)
1	0.5	13.8	23.2	26.46	28.58	24.71	29.43	14.07	23.17	6.51	26.85
2	0.5	5.96	34.3	36.09	37.70	37.01	39.27	5.23	9.92	7.89	14.48
3	0.5	34.7	16.05	16.43	16.89	15.07	16.74	2.38	5.25	-6.09	4.31
4	0.5	16.01	23.94	24.56	27.16	22.60	28.21	2.60	13.44	-5.60	17.83
5	0.5	48.01	13.18	14.51	13.89	11.41	10.92	10.08	5.41	-13.43	-17.17
6	0.5	50.53	12.9	14.33	13.77	10.62	10.34	11.09	6.77	-17.66	-19.82
7	0.5	53.5	20.7	14.22	13.65	9.75	9.77	-31.30	-34.06	-52.91	-52.80
8	0.5	55.57	11.88	14.22	13.53	9.22	9.42	19.72	13.90	-22.40	-20.70
9	0.5	55.85	15.03	14.23	13.51	9.15	9.38	-5.33	-10.10	-39.09	-37.61
10	0.5	17.1	14.51	23.73	26.51	21.72	27.66	63.53	82.72	49.69	90.63
11	0.39	7.41	27.5	33.92	35.15	34.04	36.23	23.34	27.83	23.80	31.76
Averaged	**5.39**	**18.25**	**19.38**	**21.16**	**21.85**	**18.66**	**20.67**	**9.15**	**12.74**	**-3.70**	**6.65**

Table 5.46 Summary of predicted results for NO_X emissions.

					Using Test_D Data		Using CSHVR & IHC Data		Using Test_D Data		Using CSHVR & IHC Data	
	Tital Miles	Cycle	Average Speed	Measured NO_X	NO_X - Predicted - Rural	NO_X - Predicted - Urban	NO_X - Predicted - Rural	NO_X - Predicted - Urban	Percentage Difference - Rural	Percentage Difference - Urban	Percentage Difference - Rural	Percentage Difference - Urban
Averaged from 0.5 mph segments	6.5	CSHVR	14.86	26.17	23.96	26.10	22.61	27.16	-8.44	-0.24	-13.58	3.79
Averaged from 0.5 mph segments	18.5	IHC	37.57	13.97	17.02	15.95	12.13	13.66	21.80	14.18	-13.15	-2.25
Averaged from 0.5 mph segments	5.4	Test_D	18.25	19.38	21.16	21.85	18.66	20.67	9.15	12.74	-3.70	6.65
Averaged from 0.5 mph segments for the first 5 miles	5	Test_D	20.61	18.57	19.88	20.52	17.13	19.11	7.05	10.51	-7.77	2.93

The results of the NO_X analysis show very strong agreement between measured and predicted values. The values in the last two columns represent the percentage difference between the predicted and actual NO_X emission values using the IHC and CSHVR data. It can be seen that this method predicts the NO_X emissions reasonably accurately. The differences between measured and predicted values for the rural mode are greater than that predicted for the urban mode. The NO_X emissions are under predicted by about 14% for the IHC and CSHVR cycle. The percentage error for UDDS was about 4% for the whole cycle and about 8% if only the first 5 miles of the cycle were used. Both CSHVR and UDDS are driving schedules developed to represent urban operation, hence the poor agreement between the actual and predicted NO_X emissions for rural mode are to be expected. IHC reflects highway operation in both urban and rural areas. The results confirm the validity of this methodology as the error was within 15%. Also, the fact that NO_X emissions for UDDS were predicted within 8% of the actual value further validates the present approach. One should, however, be aware that this verification was undertaken using the emissions results from a single vehicle. The accuracy of the prediction may improve if a large number of test results were used, thus minimizing any bias that may exist. The validity of this method was verified with additional test results covering a wide range of test cycles and test vehicles, and the results are presented in the following section.

5.8 Additional Analysis to Validate Speed-Acceleration Method

The analyses and results presented in Section 5.7 pertain to the two over the road test vehicles discussed in Chapter 4. In order to validate the speed-acceleration method, additional data that were available at WVU from different research efforts were used. Two different data sets were used for this purpose, which are explained in detail in Chapter 4. The first data set was available from Phase I of the Coordinating Research Council (CRC) E55 research project conducted on one of the Translabs operated by WVU. This project involved the testing of 25 different Class 8 trucks covering the following model year groups: 1974-77, 1978-81, 1982-85, 1986-89, 1990-93, 1994-97 and 1998 and newer. Chapter 4 presents the details of the test vehicles and tests conducted on these vehicles. Analysis of this data set resulted in the generation of the emissions factors in grams/mile for the range of model year groups.

The second data set was from a single 1995 model year Box Truck that was tested on 16 different driving schedules. This data set enabled to study the effect of driving test schedule on the heavy-duty diesel emissions.

The speed-acceleration based emissions factors were developed for both data sets using the same approach that was discussed in detail earlier in this chapter. The results of the analyses follow.

Table 5.47 presents the NO_X emissions factors in grams/mile as a function of average speed class for all the model year groups for a test weight of 56,000 lbs. Table 5.48 presents the NO_X emissions factors for a test weight of 30,000 lbs. The procedures used to generate these emissions factors were discussed in detail in the beginning of this chapter. For each model year group, the emissions data in grams per second were averaged for all the test runs. The resulting emissions factors tables in grams per second were combined with the vehicle activity data (presented in section 5.4) to generate the grams/mile emissions factor tables. Tables 5.49 through 5.52 present the grams/mile emissions factor tables for CO and HC emissions respectively.

Table 5.47 NO_X Emissions factors in g/mile as a function of average speed class for the CRC data – 56,000 lbs.

NO_X Emissions in grams/mile for the CRC PHASE I Data

			Average Speed Bin in mph				
Test details	0-10	10-20	20-30	30-40	40-50	50-60	60-70
Rural							
1974-77 Trucks - 56000 lbs.	28.09	26.80	26.03	25.80	25.07	25.66	27.87
1978-81 Trucks - 56000 lbs.	26.21	17.83	13.90	11.38	9.95	9.64	10.50
1982-85 Trucks - 56000 lbs.	30.09	18.41	14.01	11.15	8.93	7.63	7.60
1986-89 Trucks - 56000 lbs.	8.18	9.84	11.92	12.89	12.54	11.35	9.89
1990-93 Trucks - 56000 lbs.	28.56	18.99	19.10	19.56	18.66	17.17	15.74
1994-97 Trucks - 56000 lbs.	30.15	24.11	24.04	25.42	27.17	31.50	36.28
1998 and later Trucks - 56000 lbs.	21.19	12.90	15.22	18.77	21.84	26.52	30.38
Urban							
1974-77 Trucks - 56000 lbs.	30.51	32.07	31.30	27.04	24.30	25.64	27.51
1978-81 Trucks - 56000 lbs.	28.57	20.82	16.98	12.22	9.73	9.85	10.48
1982-85 Trucks - 56000 lbs.	31.56	19.89	16.53	12.58	8.85	7.65	7.67
1986-89 Trucks - 56000 lbs.	11.04	13.07	14.04	13.87	12.77	11.41	10.27
1990-93 Trucks - 56000 lbs.	35.01	25.15	22.83	20.80	18.67	17.07	16.04
1994-97 Trucks - 56000 lbs.	33.24	29.37	27.38	24.84	26.33	32.02	35.83
1998 and later Trucks - 56000 lbs.	26.96	19.16	17.79	17.46	21.09	27.10	30.14
All Vehicles Averaged Rural	21.15	13.07	15.35	18.86	21.86	26.54	30.53
All Vehicles Averaged Urban	26.68	19.25	17.96	17.67	21.07	27.12	30.28

Table 5.48 NO_X Emissions factors in g/mile as a function of average speed class for the CRC data – 30,000 lbs.

NO_X Emissions in grams/mile for the CRC PHASE I Data

			Average Speed Bin in mph				
Test details	0-10	10-20	20-30	30-40	40-50	50-60	60-70
Rural							
1974-77 Trucks - 30000 lbs.	16.45	18.55	18.34	17.34	16.20	15.08	14.40
1978-81 Trucks - 30000 lbs.	15.63	10.41	8.85	7.90	7.06	6.46	6.34
1982-85 Trucks - 30000 lbs.	11.60	10.39	9.10	7.88	6.99	6.19	5.95
1986-89 Trucks - 30000 lbs.	5.98	6.09	6.94	7.23	6.87	6.04	5.13
1990-93 Trucks - 30000 lbs.	31.50	20.73	17.77	15.99	14.81	14.28	14.10
1994-97 Trucks - 30000 lbs.	24.35	17.77	17.93	19.40	21.45	25.41	29.34
1998 and later Trucks - 30000 lbs.	18.04	9.60	9.42	11.38	13.96	18.72	23.77
Urban							
1974-77 Trucks - 30000 lbs.	18.76	19.64	19.18	18.06	16.35	14.91	14.36
1978-81 Trucks - 30000 lbs.	18.33	13.50	11.05	8.46	7.01	6.50	6.38
1982-85 Trucks - 30000 lbs.	12.10	11.43	9.99	8.33	7.03	6.14	5.93
1986-89 Trucks - 30000 lbs.	7.53	7.52	7.84	7.86	7.02	6.05	5.33
1990-93 Trucks - 30000 lbs.	35.79	25.03	20.69	16.47	14.88	14.36	14.19
1994-97 Trucks - 30000 lbs.	27.32	22.09	19.19	17.89	20.69	25.61	28.72
1998 and later Trucks - 30000 lbs.	19.52	12.06	10.10	9.86	12.81	19.01	23.10
All Vehicles Averaged Rural	18.04	9.60	9.41	11.36	13.93	18.72	23.77
All Vehicles Averaged Urban	19.52	12.05	10.08	9.83	12.78	19.00	23.10

Table 5.49 CO Emissions factors in g/mile as a function of average speed class for the CRC data – 56,000 lbs.

CO Emissions in grams/mile for the CRC PHASE I Data

			Average Speed Bin in mph				
Test details	0-10	10-20	20-30	30-40	40-50	50-60	60-70
Rural							
1974-77 Trucks - 56000 lbs.	18.94	14.09	9.47	5.94	3.73	2.46	2.41
1978-81 Trucks - 56000 lbs.	28.10	18.87	12.63	8.98	7.24	5.99	4.50
1982-85 Trucks - 56000 lbs.	17.09	10.05	5.99	3.33	1.82	1.40	2.06
1986-89 Trucks - 56000 lbs.	16.24	13.23	10.48	7.87	5.98	4.28	2.90
1990-93 Trucks - 56000 lbs.	4.70	4.54	4.95	4.76	4.17	2.82	1.11
1994-97 Trucks - 56000 lbs.	8.67	6.15	4.79	3.73	2.96	2.35	1.92
1998 and later Trucks - 56000 lbs.	8.75	7.15	6.05	5.06	4.34	3.78	3.33
Urban							
1974-77 Trucks - 56000 lbs.	19.12	15.17	11.34	6.63	3.74	2.38	2.34
1978-81 Trucks - 56000 lbs.	26.86	19.60	14.48	9.29	7.49	5.98	4.76
1982-85 Trucks - 56000 lbs.	17.18	10.53	7.55	3.83	1.65	1.38	1.91
1986-89 Trucks - 56000 lbs.	17.94	14.92	12.21	8.51	6.40	4.27	3.09
1990-93 Trucks - 56000 lbs.	6.70	6.06	5.63	5.14	4.55	2.78	1.38
1994-97 Trucks - 56000 lbs.	10.04	7.72	5.89	3.95	3.06	2.34	1.98
1998 and later Trucks - 56000 lbs.	9.83	8.49	7.09	5.37	4.50	3.83	3.44
All Vehicles Averaged Rural	8.77	7.18	6.11	5.14	4.39	3.80	3.35
All Vehicles Averaged Urban	9.86	8.53	7.18	5.48	4.54	3.84	3.45

Table 5.50 CO Emissions factors in g/mile as a function of average speed class for the CRC data – 30,000 lbs.

CO Emissions in grams/mile for the CRC PHASE I Data

			Average Speed Bin in mph				
Test details	0-10	10-20	20-30	30-40	40-50	50-60	60-70
Rural							
1974-77 Trucks - 30000 lbs.	6.75	6.07	5.49	4.58	3.55	1.94	0.23
1978-81 Trucks - 30000 lbs.	15.10	12.14	9.03	6.80	5.54	5.30	5.88
1982-85 Trucks - 30000 lbs.	3.10	3.33	2.85	2.25	1.70	1.05	0.58
1986-89 Trucks - 30000 lbs.	12.93	10.01	9.02	7.18	5.38	3.35	1.99
1990-93 Trucks - 30000 lbs.	5.85	4.93	4.45	3.82	3.08	2.04	1.05
1994-97 Trucks - 30000 lbs.	4.82	3.40	2.78	2.34	1.99	1.67	1.49
1998 and later Trucks - 30000 lbs.	8.05	5.84	4.84	4.05	3.42	2.80	2.40
Urban							
1974-77 Trucks - 30000 lbs.	8.22	7.13	6.21	5.16	3.95	1.91	0.51
1978-81 Trucks - 30000 lbs.	15.31	13.23	10.59	7.11	5.46	5.30	5.75
1982-85 Trucks - 30000 lbs.	3.05	3.33	3.07	2.56	1.81	1.03	0.64
1986-89 Trucks - 30000 lbs.	16.20	11.43	9.51	7.89	5.92	3.29	2.13
1990-93 Trucks - 30000 lbs.	6.71	5.58	5.12	4.31	3.29	2.01	1.22
1994-97 Trucks - 30000 lbs.	5.38	3.94	3.15	2.40	1.99	1.60	1.47
1998 and later Trucks - 30000 lbs.	8.81	6.54	5.50	4.35	3.48	2.77	2.44
All Vehicles Averaged Rural	8.05	5.83	4.83	4.04	3.41	2.80	2.40
All Vehicles Averaged Urban	8.78	6.53	5.48	4.33	3.47	2.76	2.44

Table 5.51 HC Emissions factors in g/mile as a function of average speed class for the CRC data – 56,000 lbs.

HC Emissions in grams/mile for the CRC PHASE I Data

			Average Speed Bin in mph				
Test details	0-10	10-20	20-30	30-40	40-50	50-60	60-70
Rural							
1974-77 Trucks - 56000 lbs.	5.46	2.98	1.92	1.31	0.95	0.80	0.84
1978-81 Trucks - 56000 lbs.	3.39	3.91	4.36	4.02	3.38	1.76	0.48
1982-85 Trucks - 56000 lbs.	11.14	4.23	2.57	1.88	1.58	1.52	1.56
1986-89 Trucks - 56000 lbs.	7.35	5.47	4.38	3.51	2.88	2.30	1.86
1990-93 Trucks - 56000 lbs.	0.61	0.36	0.26	0.20	0.16	0.13	0.11
1994-97 Trucks - 56000 lbs.	2.89	1.54	1.07	0.77	0.57	0.43	0.36
1998 and later Trucks - 56000 lbs.	2.33	1.42	0.98	0.68	0.48	0.33	0.28
Urban							
1974-77 Trucks - 56000 lbs.	6.28	3.90	2.55	1.39	0.91	0.79	0.82
1978-81 Trucks - 56000 lbs.	4.49	4.13	3.98	4.38	4.00	1.76	0.47
1982-85 Trucks - 56000 lbs.	12.83	5.34	3.16	1.87	1.56	1.54	1.56
1986-89 Trucks - 56000 lbs.	8.08	6.23	5.03	3.78	3.00	2.30	1.94
1990-93 Trucks - 56000 lbs.	0.74	0.52	0.36	0.21	0.16	0.13	0.11
1994-97 Trucks - 56000 lbs.	3.49	2.17	1.45	0.81	0.57	0.43	0.37
1998 and later Trucks - 56000 lbs.	2.56	1.65	1.20	0.75	0.49	0.33	0.28
All Vehicles Averaged Rural	2.32	1.42	0.98	0.68	0.47	0.33	0.28
All Vehicles Averaged Urban	2.56	1.65	1.20	0.75	0.48	0.33	0.28

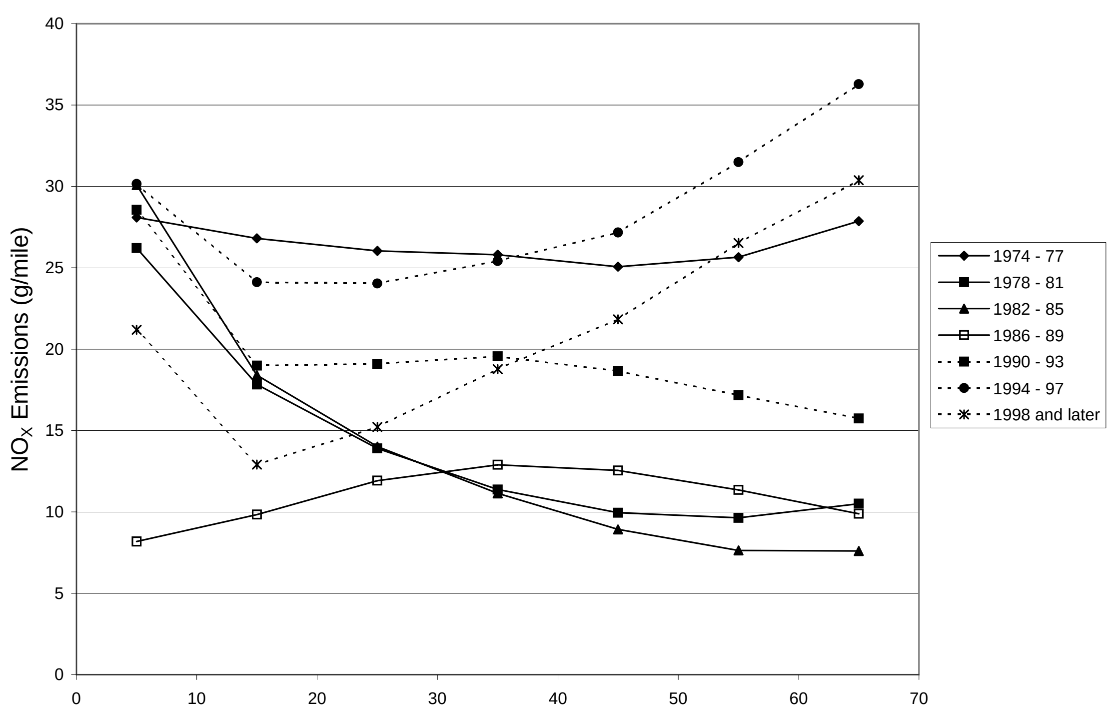
Table 5.52 HC Emissions factors in g/mile as a function of average speed class for the CRC data – 30,000 lbs.

HC Emissions in grams/mile for the CRC PHASE I Data

			Average Speed Bin in mph				
Test details	0-10	10-20	20-30	30-40	40-50	50-60	60-70
Rural							
1974-77 Trucks - 30000 lbs.	5.07	2.74	1.85	1.31	0.93	0.60	0.40
1978-81 Trucks - 30000 lbs.	4.58	2.88	2.32	2.02	1.80	1.69	1.64
1982-85 Trucks - 30000 lbs.	6.45	3.64	2.69	2.11	1.77	1.54	1.37
1986-89 Trucks - 30000 lbs.	11.93	6.84	4.92	3.82	3.16	2.73	2.49
1990-93 Trucks - 30000 lbs.	0.86	0.56	0.39	0.28	0.20	0.15	0.14
1994-97 Trucks - 30000 lbs.	2.42	1.38	1.00	0.76	0.60	0.46	0.38
1998 and later Trucks - 30000 lbs.	2.42	1.56	1.13	0.84	0.65	0.52	0.45
Urban							
1974-77 Trucks - 30000 lbs.	5.89	3.52	2.41	1.42	0.94	0.58	0.42
1978-81 Trucks - 30000 lbs.	5.37	3.69	2.89	2.08	1.79	1.69	1.65
1982-85 Trucks - 30000 lbs.	7.27	4.29	3.09	2.18	1.82	1.56	1.41
1986-89 Trucks - 30000 lbs.	12.18	7.79	5.83	4.02	3.20	2.75	2.54
1990-93 Trucks - 30000 lbs.	1.04	0.81	0.55	0.31	0.20	0.14	0.13
1994-97 Trucks - 30000 lbs.	2.77	1.68	1.22	0.81	0.61	0.45	0.39
1998 and later Trucks - 30000 lbs.	2.63	1.75	1.32	0.90	0.66	0.52	0.46
All Vehicles Averaged Rural	2.42	1.56	1.13	0.84	0.65	0.52	0.45
All Vehicles Averaged Urban	2.63	1.76	1.33	0.90	0.66	0.52	0.46

It can be observed from Table 5.47 that the NO_X emissions factors in grams/mile decrease as the average speed value increases. NO_X emissions factors reach a minimum point after which it starts increasing. Figure 5.32 shows the variation of NO_X emissions (g/mile) with average speed class for the rural operation for a test weight of 56,000 lb.

Figure 5.32 Variation of NO_X emissions (g/mile) with average speed class for the CRC data for a test weight of 56,000 lb. – rural operation.

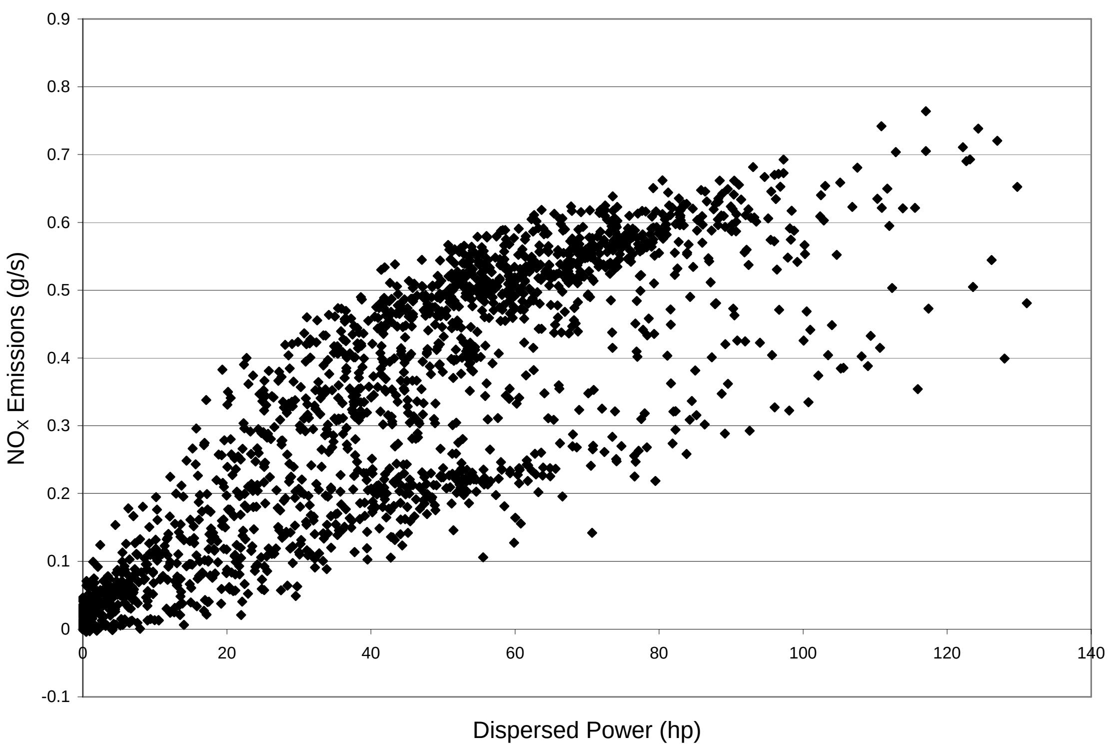


It can be seen from Figure 5.32 that for the 1994-97 and 1998 and newer model year vehicles, NO_X emissions increase drastically at high average speeds. This could be attributed to the off-cycle operation. Figure 5.33 shows the plot of NO_X emissions in g/s versus dispersed axle power for one of the test runs from the data corresponding to the 1994-97 model year group. The bifurcation in NO_X emissions values is clearly evident. When compared to the NO_X emissions factors for the Test Vehicle 1 (1995 model year) from Table 5.39, the NO_X emissions factor reaches a minimum at 25 mph however the general trends are similar. NO_X emissions factor for the Test Vehicle 1 from Table 5.39 showed a minimum at 45 mph.

If we consider the 1982-85 model year group, the trends are similar. In Table 5.39, the NO_X emissions factor for Test Vehicle 2 (1982 model year) is 39.93 g/mile at 5 mph bin and drops to a minimum of 18.98 g/mile at 55 mph. It can be observed from Table 5.47 that the NO_X emissions factor for the 1982-85 model year group has a value of 30.09 g/mile at 5 mph bin and drops to a minimum of 7.6 g/mile at 65 mph. However, it should be noted that the Test Vehicle 2 discussed in Table 5.39 was tested at 60,000 lbs. as compared to the 1982-85 model year group in Table 5.47, which were tested at 56,000 lb.

CO emissions factors presented in Table 5.49 and Table 5.50 at 56,000 lb and 30,000 lb respectively correlate well with the data presented in Table 5.40. For the entire model year group the CO emissions factor steadily decreases with increase in average speed as expected. Let us consider the CO emissions factor value for 1994-97 model year group from Table 5.49 and the values for Test Vehicle 1 in Table 5.39 for rural operation. CO emissions value from Table 5.49 drops from 8.67 g/mile at 5 mph to a value of 1.92 at 65 mph. In Table 5.39, for the same change in speed the CO values were 9.54 and 1.46 g/mile respectively.

Figure 5.33 Variation of NO_X emissions (g/s) with dispersed power for one of the test runs corresponding to 1994-97 model year group.



HC emissions factors also exhibit similar trends. However, it can be seen that for lower average speeds, HC emissions factors values are higher in Table 5.51 as compared to the corresponding value in Table 5.41.

With these emissions factors tables one can predict the emissions in grams/mile for any average speed value. There are two ways by which emissions can be predicted from these emissions factors tables. The emissions factors can be plotted against the average bin median speed and a relationship can be obtained using a curve fit. Either a best-fit polynomial fit can be used to interpolate between the data values or the interpolation can be done using a linear fit between the neighboring points. As an example, if one would like to find the emissions for the model year group 1994-97 with a test weight of 56,000 lbs. on the rural operation for an average speed of 23.8 mph. The data values corresponding to that model year group from Table 5.47 at average speed values of 15 mph (bin median of 10-20 mph class) and 25 mph (bin median for the class 20-30) will be used to obtain a linear interpolation. In this example, corresponding to an average speed of 23.8 mph, the NO_X emissions value would be 24.048 g/mile. However, as can be seen from the emissions factor tables, the emissions factor value rises sharply at low average speeds. In which case a best-fit polynomial would yield more accurate results. As the slope of the curve changes drastically, a linear fit between adjacent points would not be representative of the actual variation in emissions factor values. For example, the lowest average speed value for which there is a non-zero value is 5 mph (bin median for the 0-10 mph class). If one wants to predict emissions for an average speed of 3.3 mph, which is typical of a Yard Cycle, there is no value to the left hand side of the 3.3 mph average speed to obtain a linear interpolation. A polynomial curve would better represent the trend of the emissions factor and will allow fairly accurate prediction of the emissions in this case. Figure 5.34 shows this point clearly as we can see the sharp increase in the emissions factor value near low average speeds. Applying this equation to an average speed would result in grams/mile of emissions for that particular species.

Table 5.53 presents the actual and predicted NO_X emissions in g/mile for the two Test Vehicles (Test Vehicle 1 and Test Vehicle 2) using the relationship obtained from Table 5.39.

Figure 5.34 Plot of NO_X emissions factor vs. average speed class for the Test Vehicle 1 in rural operation. Dotted line represents linear interpolation between points.

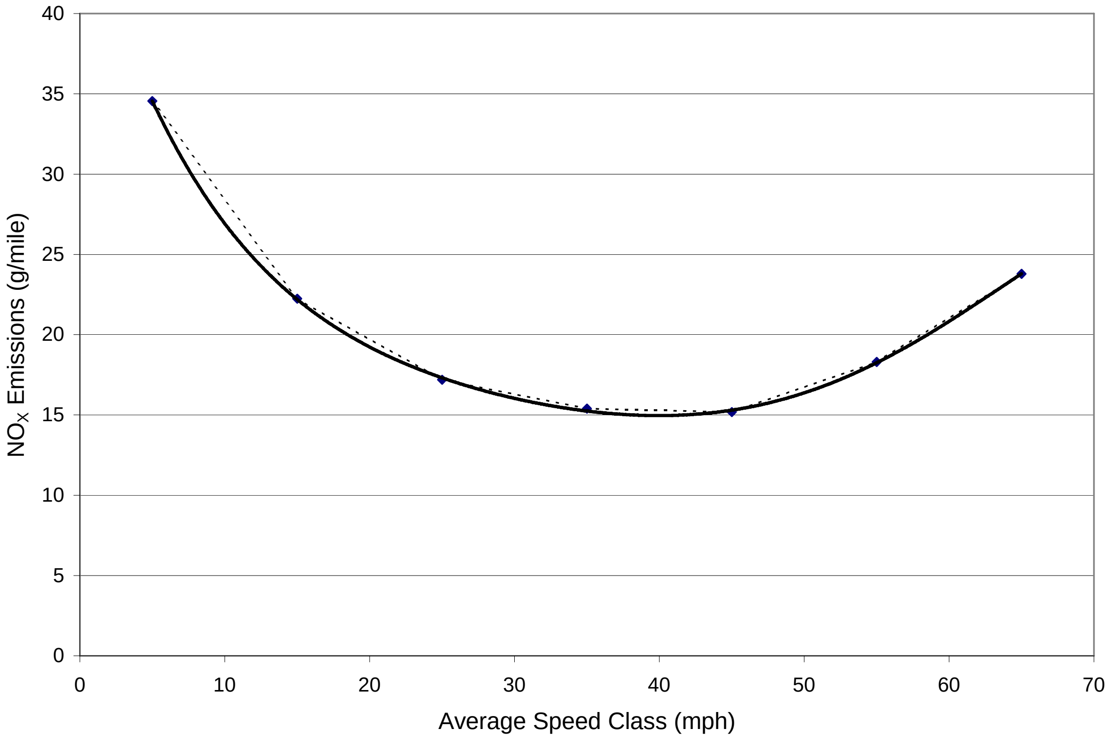


Table 5.53 Actual and predicted NO_X Emissions for the two Test Vehicles ("Test Vehicle 1" and "Test Vehicle 2").

	CSHVR				IHC				CSHVR		IHC	
Test Information	Average Speed (mph)	Actual NO_X Emissions (g/mile)	Predicted NO_X Emissions (g/mile)		Average Speed (mph)	Actual NO_X Emissions (g/mile)	Predicted NO_X Emissions (g/mile)		Percentage Difference		Percentage Difference	
			Rural	Urban			Rural	Urban	Rural	Urban	Rural	Urban
Test Vehicle 1 at 56,000 lbs. on Single Map	15.50	25.91	22.85	28.50	36.94	14.61	14.45	15.68	-11.80	10.00	-1.10	7.29
Test Vehicle 1 at 56,000 lbs. on Dual Map	15.50	21.81	21.83	27.13	36.94	24.75	15.07	15.01	0.11	24.37	-39.12	-39.37
Test Vehicle 1 at 42,000 lbs. on Dual Map	15.50	19.04	20.83	24.41	36.94	21.20	12.58	12.08	9.39	28.21	-40.66	-43.01
Test Vehicle 2 at 60,000 lbs.	15.50	29.46	30.06	36.33	36.94	24.30	24.82	27.12	2.05	23.33	2.15	11.59

Relationships obtained between the NO_X emissions and the average speed values from Table 5.39 were used to predict the average emissions for the two test vehicles on the two test schedules (CSHVR and IHC). For each test schedule, the average speed value from the speed-time trace was used and the predicted results are compared to the actual average emissions in g/mile obtained from the actual test runs. In other words, the model predicts the emissions that would result from the two vehicles if they were driven over the CSHVR and IHC cycle. The actual average emissions were obtained from the actual test runs the two vehicles were driven on the chassis dynamometer. The last four columns show the percentage difference between the predicted and actual emissions. It can be seen that the model predicts the NO_X emissions with reasonable accuracy for the CSHVR cycle on the rural operation. The model also predicts the NO_X emissions values fairly well for both the cycles for the single map and the 1982 model year vehicle, which does not have the capability to be configured to operate on the dual map (off-cycle mode). It is clear that the off-cycle operation has profound effect on the emissions, especially for a high average speed typical of freeway operation. This is clear from the prediction of NO_X emissions for IHC using the above method. The NO_X values were consistently under predicted for the dual map, as the off-cycle effect was not profound at the average spped corresponding to 37 mph.

To test the validity of the model, the relationship obtained from Table 5.47 corresponding to the 1994-97 model year group was used to predict the emissions for the Test Vehicle 1 (1995 model year) on the dual map. The relationship could not be used to predict the single map because the test vehicles used to generate the emissions factor in Table 5.47 could not be configured to operate on the single map, hence some off-cycle operation could be present in the emissions data. Table 5.54 shows the actual and predicted emissions for the Test Vehicle 1 using the relationship obtained for emissions factors from the Table 5.47, corresponding to the 1994-97 model year group, as a function of average speed. It should be noted that the relationship used was obtained from the data pertaining to a group of vehicles corresponding to 1994-97 model year group from a different study (CRC E55).

Table 5.54 Actual and predicted NO_X emissions in g/mile for the Test Vehicle 1 using the emissions factors from Table 5.44 (CRC E55 – Phase I Data), corresponding to 1994-97 model year group.

	CSHVR				IHC				CSHVR		IHC	
Test Information	Average Speed (mph)	Actual NO_X Emissions (g/mile)	Predicted NO_X Emissions (g/mile)		Average Speed (mph)	Actual NO_X Emissions (g/mile)	Predicted NO_X Emissions (g/mile)					
			Rural	Urban			Rural	Urban	Rural	Urban	Rural	Urban
Teast Vehicle 1 at 56,000 lbs. on Dual Map	15.50	21.81	23.99	29.87	36.94	24.75	25.53	25.15	10.00	36.94	3.16	1.63

It can be seen from Table 5.54 that the NO_X emissions are predicted accurately except for CSHVR on urban mode. The percentage error was within about 3% when the model was used to predict the IHC emissions in both rural and urban operation. For the CSHVR, the rural mode prediction was within 10%, however, the urban mode value was over predicted. This could be attributed to the presence of some off-cycle operation in the data used to generate the emissions factors table. Table 5.55 shows the actual and predicted NO_X emissions for the 1974-77 model year group as an example. This is a self-prediction unlike Table 5.54 because the emissions factors generated using the test runs are used to predict the average emissions for the respective test schedules over which the vehicles were tested.

Table 5.55 Actual and predicted NO_X emissions for the 1974-77 model year trucks tested at 56,000 lbs.

Test Schedule	Average Speed (mph)	Actual NO_X Emissions (g/mile)	Predicted NO_X Emissions (g/mile)		Percentage Difference (%)	
			Rural	Urban	Rural	Urban
Test_D	18.58	26.98	26.51	32.22	-1.74	19.42
CARB Cruise	39.94	18.80	25.39	25.82	35.06	37.34
CARB Trans3	14.00	29.20	26.86	32.72	-8.02	12.06
CARB Creep3	1.75	27.30	28.86	27.91	5.70	2.24

It can be observed that the model predicts the NO_X emissions fairly well for all the cycles except for the CARB Cruise3 cycle, which has an average speed of about 40 mph. Emissions data from all the cycles mentioned in Table 5.55, were used to generate the emissions factor table. It can also be seen that for lower average speeds, the urban prediction is better than the rural as would be expected because the low average speeds typically represent urban stop and go driving pattern.

5.9 Comparison of Speed-Acceleration Model with Other Models

5.9.1 Comparison with EMFAC 2002 Model

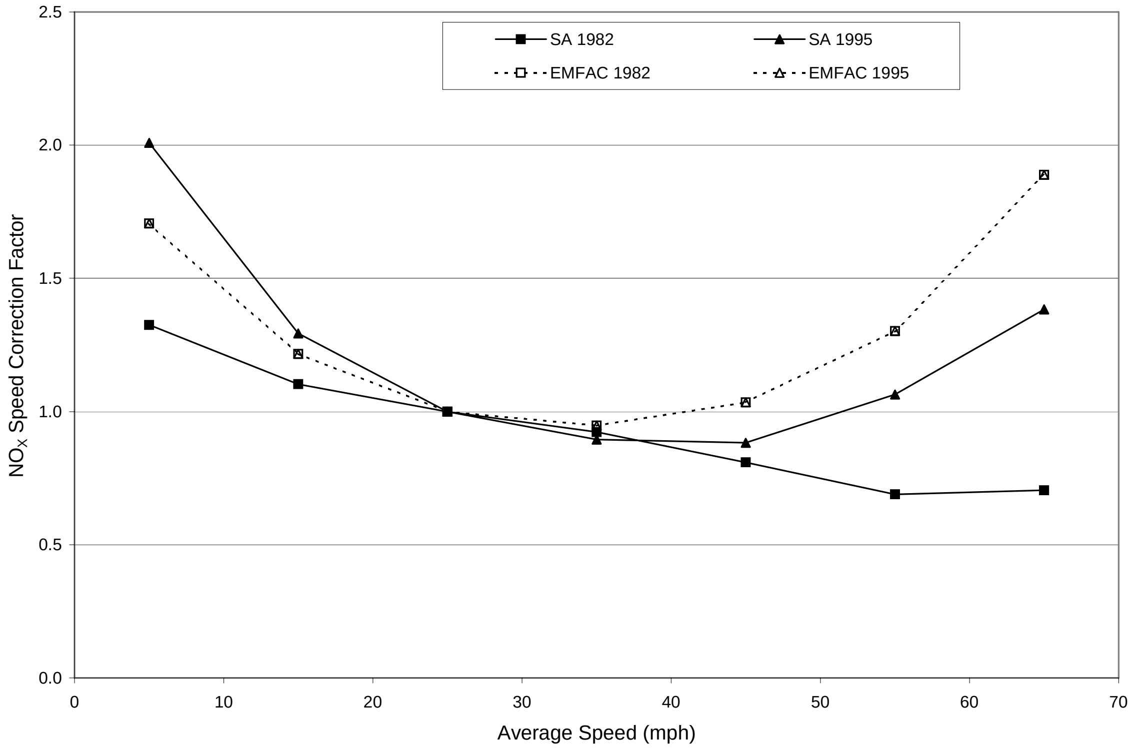
In order to compare the speed-acceleration based model with the EMFAC 2002 model, NO_X emissions were predicted using the EMFAC 2002 model software as a function of average speed corresponding to the bin median of the average speed class presented in the g/mile emissions factor tables presented in this chapter. The EMFAC 2002 software allowed the user to obtain the emissions factors in g/mile for any vehicle class. The model was run to give emissions factors for heavy-duty diesel vehicles (Class 8), and the results were tabulated. Emission factors were obtained for the same range of model year groups as presented in Table 5.47; however, EMFAC did not allow the user to choose a specific test weight. In order to compare the NO_X emissions factors generated by the speed-acceleration model (Table 5.47) and EMFAC 2002 (Table 5.56), the emissions factors were divided by the value corresponding to a speed of 25 mph. The resulting speed correction factors for the EMFAC and Speed-Acceleration (SA) model are plotted in Figure 5.30 for two different model year groups; 1982-85 and 1994-97.

Table 5.56 NO_X Emissions (g/mile) predicted for Class 8 diesel trucks using EMFAC 2002 model.

			Average Speed in mph				
Test details	5	15	25	35	45	55	65
1974-77 Trucks	46.84	33.41	27.46	26.02	28.41	35.76	51.87
1978-81 Trucks	46.19	32.94	27.08	25.65	28.01	35.26	51.15
1982-85 Trucks	37.17	26.51	21.79	20.65	22.55	28.38	41.17
1986-89 Trucks	28.60	20.40	16.77	15.89	17.35	21.83	31.67
1990-93 Trucks	27.30	19.47	16.01	15.16	16.56	20.84	30.23
1994-97 Trucks	32.53	23.20	19.07	18.07	19.73	24.83	36.02
1998 and later Trucks	23.85	17.01	13.98	13.25	14.47	18.21	26.42

As seen in Figure 5.35, the speed correction factors for both 1982 and 1995 model year groups predicted by EMFAC are the same. The low point in emissions is achieved at 35 mph. The shape of the speed correction factor obtained using the speed-acceleration method for the 1982 model year vehicle flattens out at high average speeds. The speed-acceleration model exhibits different trends. The EMFAC model showed a minimum value corresponding to a speed of 35 mph. However, the speed-acceleration model showed a minimum for the Test Vehicle 1 (corresponding to 1994-97 model year group) at 15 mph and for the 1982-85 model year group (Test Vehicle 2), the minimum occurred at a speed of 55 mph. EMFAC employs the same speed correction factors for the whole range of model year groups presented in Table 5.56. NO_X emissions are shown to increase at both lower and higher speeds relative to the 35 mph with a value of 1.71 at 5 mph and 1.89 at 65 mph. The shape of the speed correction factors employed by EMFAC is not supported by the results of this analysis. Data presented in Table 5.37 indicate that the low point for the Test Vehicle 1 occurs at a speed of 45 mph and for the Test Vehicle 2, the low point occurs at a speed of 55 mph.

Figure 5.35 Variation of NO_X speed correction factor with speed for two model year groups predicted using speed-acceleration and EMFAC models.



5.9.2 Comparison with Artificial Neural Network (ANN) Model

Artificial Neural Network (ANN) is most appropriate when there are imprecise or fuzzy correlations exist between one or more variables. ANN can identify highly non-linear relations between multiple input and output data, making them well suited for the task of emissions prediction. The user is not required to hypothesize the relationship between input and output variables, rather is required only to choose the relevant input variables. ANN serves as a pattern recognizer and maps them into responses. These responses are then used to predict future events or trends in a time series. Trained with adequate amount of relevant data, a suitably configured ANN will mimic the function. During the training process, the network learns to ignore any inputs that do not contribute to a reliable solution. To compare the speed-acceleration method with ANN for emissions predictions, ANN data from a prior study at WVU was used. NO_X

emissions were predicted using ANN for a 1995 box truck, which was tested on 16 different test schedules. The ANN was trained using the axle speed and torque as inputs along with their first and second derivatives at different time ranges. The ANN software used for this purpose was NeuroShell 2. The results from the ANN are tabulated and compared with speed-acceleration method in Table 5.58

The continuous data from a 1995 GMC Box Truck over 16 different cycles were used to obtain the speed-acceleration based emissions factors using the method described earlier in this chapter. The emissions factors in g/s were combined with activity data to obtain emissions factors in g/mile as a function of average speed and the values for NO_X emissions in rural operation is presented in Table 5.57.

Table 5.57 NO_X emissions factors in g/mile for the 1995 GMC Box Truck exercised through 16 different driving schedules.

			Average Speed Bin in mph				
Emissions Species	0-10	10-20	20-30	30-40	40-50	50-60	60-70
Rural							
NO_X	24.98	15.56	11.97	9.87	8.65	8.30	8.33

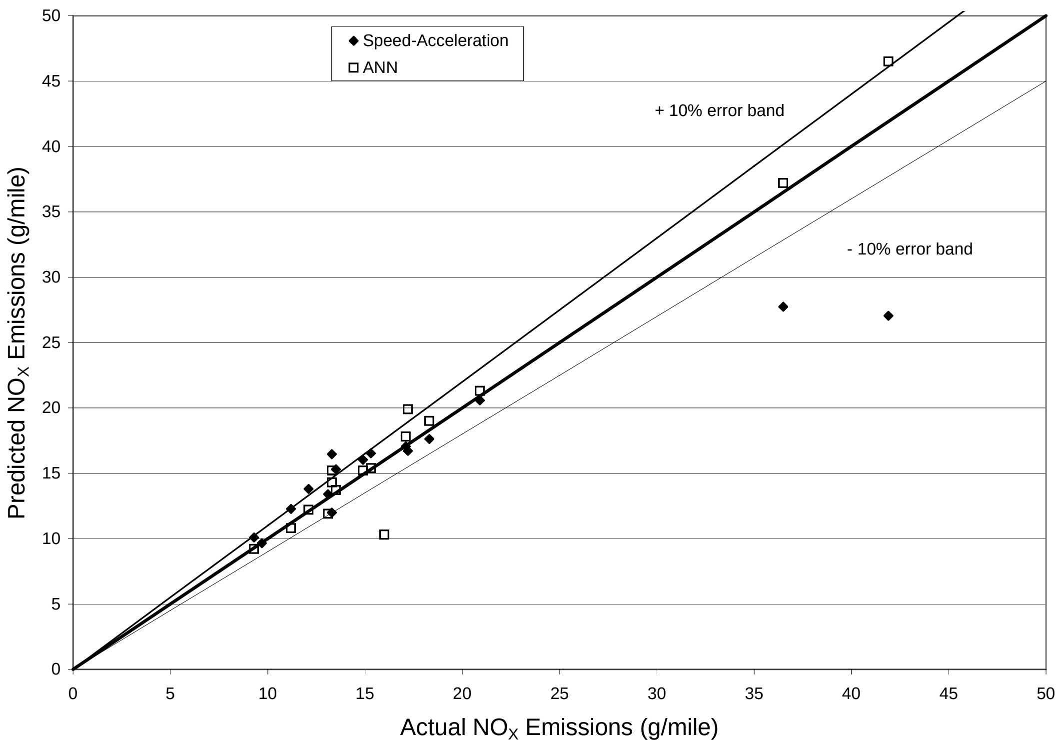
The values in Table 5.58 represent the average value for all the tests conducted on the truck over the 16 different driving schedules. Using these emissions factor values and the average speed values for the 16 driving schedules from their target speed-time trace, NO_X emissions were predicted and are compared with the ANN results in Table 5.58. The column in Table 5.58 labeled ANN (Self-Predicted) corresponds to the self predicted NO_X emissions values using ANN. These values were obtained for each driving schedule by training the ANN with the corresponding schedule. In addition to self-predicted NO_X values, results from three other driving schedules are also presented for comparison. These include the results from ANN trained on CBD cycle, FIGE cycle and the Yard cycle. The Yard cycle has an average speed of 3.3 mph and represents stop-and-go operation, FIGE has an average speed of 36.6 mph representing typical freeway operation. The CBD cycle with an average speed of 12.6 is an in between operation.

Table 5.58 Comparison of Speed-Acceleration based predicted NO_X emissions with actual and ANN predicted NO_X emissions for the 1995 GMC box truck.

Using the Proposed Speed-Acceleration based Model					Using Artificial Neural Network Model							
Test Schedule	Average Speed (mph)	Actual NO_X Emissions (g/mile)	Predicted NO_X Emissions (g/mile)	Percentage Error (%)	ANN (Self-Predicted)	% Error	ANN Trained on CBD	% Error	ANN Trained on FIGE	% Error	ANN Trained on Yard	% Error
CBD	12.6	17.1	17.0	-0.3	17.8	4.1	17.8	4.1	20.7	20.6	16.1	-6.6
CBD ROUTE	13.1	17.2	16.7	-2.8	19.9	15.7	17.3	-10.7	21.3	9.9	15.9	-18.1
14-C	11.8	18.3	17.6	-3.7	19.0	3.8	18.2	-1.5	21.8	17.6	16.5	-11.0
NYBUS	3.7	41.9	27.0	-35.5	46.5	11.0	36.8	-12.3	48.0	14.5	37.2	-11.3
ARTERIAL	24.8	13.3	12.0	-9.9	15.2	14.3	13.7	3.2	17.1	28.8	9.1	-31.9
5-PEAK CYC	20.0	13.1	13.4	2.2	11.9	-9.2	15.3	17.0	12.8	-2.2	9.9	-24.4
ROUTE	23.7	11.2	12.3	9.6	10.8	-3.6	12.6	13.4	11.6	4.2	8.6	-22.6
CSR	15.5	13.5	15.3	13.4	13.7	1.5	15.1	11.8	15.8	17.2	11.8	-12.4
CSC	13.5	13.3	16.5	23.7	14.3	7.5	16.3	22.6	17.2	29.5	13.1	-1.2
ALT 1	13.4	15.3	16.5	8.0	15.4	0.7	15.0	-2.2	16.1	5.0	12.5	-18.5
ALT 2	14.2	14.9	16.0	7.6	15.2	2.0	14.9	-0.2	15.4	3.4	12.2	-18.2
TEST_D	18.9	12.1	13.8	14.0	12.2	0.8	12.4	3.0	13.9	16.2	9.0	-25.3
YARD	3.3	36.5	27.7	-24.0	37.2	1.9	31.4	-13.7	45.9	26.1	37.2	2.1
HIGHWAY	34.0	9.3	10.1	8.4	9.2	-1.1	9.7	4.5	10.0	7.8	5.4	-42.4
CITY	8.5	20.9	20.6	-1.6	21.3	1.9	18.8	-10.1	22.4	7.2	18.1	-13.6
FIGE	36.6	9.7	9.7	-0.5	10.3	6.2	10.5	8.3	10.3	7.0	5.7	-41.5

It can be seen from Table 5.58 that the speed-acceleration based model predicts the NO_X emissions reasonably well. Eleven out of the 16 of the predicted values are within 10% of the actual values. ANN does very well with self-prediction, but under predicts when trained on Yard cycle and consistently over predicts when trained on the FIGE and CBD cycles respectively. As can be seen in Figure 5.36, except for the NYBUS cycle and the YARD cycle, the speed-acceleration model predicts the NO_X emissions reasonably well. These two cycles have average speeds of 3.7 and 3.3 mph respectively and represent typical urban stop-and-go operation. It can also be seen from Figure 5.32 that self predicted ANN NO_X emissions value lie well within the 10% error band. It can be concluded based on the results presented in Table 5.58 and Figure 5.36 that speed acceleration method can predict emissions comparable to ANN. It should also be noted that in the ANN model, the data are trained on a particular architecture, and hence the results obtained could vary significantly between two different architectures. For the same data used to train the ANN, a number of different outputs (predicted results) can be obtained depending on the type of architecture and type of ANN software employed. Speed-acceleration approach eliminates this problem, as the relationships obtained from the data set used to generate the emissions factors remain the same for a particular operation.

Figure 5.36 Actual vs. predicted NO_X emissions for the 1995 GMC box truck using speed-acceleration model.



6 Effect of various Parameters on Heavy-Duty Diesel Vehicle Emissions

6.1 Influence of Vehicle Weight (Load) on Emissions

Vehicle weight (load) is one of the many factors that affect the exhaust emissions. For a given speed and acceleration, the exhaust emissions from a vehicle operating with a heavier weight will tend to be higher. Vehicle weight thus becomes an important factor in any emissions predictive model. The weight effect is more pronounced in the case of urban buses and garbage trucks where the vehicle weight is not constant over the entire trip for a particular vehicle. For vehicles like tractor trailers the vehicle weight is generally constant over the entire trip for long hauls, but varies in city delivery. This section deals with the effect of test weight/load on vehicle emissions in detail.

6.1.1 Theoretical Approach

The effect of test weight on vehicle emissions can be best understood from an analytical point of view.

Ramamurthy and Clark (1999) examined the relationship between NO_X production (in units of g/sec.) and rear axle power of vehicles undergoing chassis dynamometer testing. Data were recorded on a second-by-second basis. The processing of these data required techniques to account for analyzer measurement delay and diffusion [Ganesan and Clark, 2001]. The analysis yielded relationships for several vehicles. A relationship between NO_X (in units of grams per second) and rear axle power (in units of hp) was obtained for a 1996 model year TT and it was found that

$$NO_X\,(g/s) = 0.0012199 * P + 0.029374 \qquad \text{Equation 6.1}$$

where, P is the rear axle power in hp. The equation had an R^2 value of 0.93.

This truck, from now on referred to as “Truck A,” was powered with a 6-cylinder, 365 hp, DDC engine, and had a gross combination vehicle weight of 80,000 lb. with a test weight of 48,000 lb. For a 1995 model year truck, from here on referred to as “Truck B,” powered with a 350 hp Mack E-7-350 engine, with a gross vehicle weight of 80,000 lb. and tested at 56,000 lb., the relationship between NO_X (in units of grams per second) and rear axle power (in units of hp) was found to be

$$NO_X\,(g/s) = 0.0012701 * P + 0.0669 \qquad \text{Equation 6.2}$$

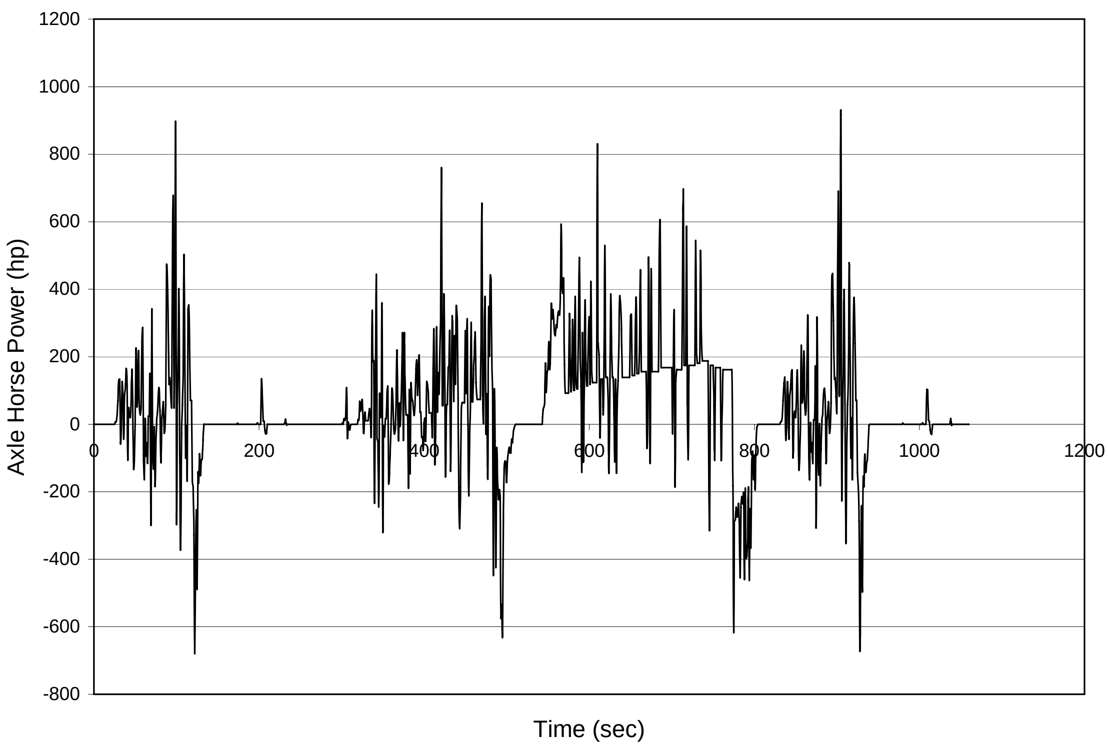
This relationship had an R^2 value of 0.77.

Now, let us consider the NO_X vs. axle power relationships for two different trucks (Truck A and Truck B) presented in equations 6.1 and 6.2. If these two equations remain reliable for a wide variety of truck applications, it is possible to apply these relationships to the rear axle power known for a test schedule or for real truck operation, and therefore to predict the total NO_X mass arising from the schedule or operation.

This approach was followed and was applied to the UDDS. The axle power (P) estimated by the road load equation (Equation 3.3) is the theoretical power demand at the rear axle for the given speed and acceleration conditions to be met In real world operation, the vehicle may not reach the theoretical power requirement due to the power limitations. The axle power “P” used in equations 6.1 and 6.2 is the actual measured rear axle power during the chassis dynamometer testing.

Using Equation 3.3 and the speed values for the UDDS cycle, an instantaneous power demand can be calculated, as shown in Figure 5.22, which is a plot of theoretical axle power demand versus time. A vehicle mass of 60,000 lb. (27216 kg) was used to obtain the axle power shown in Figure 6.1. “Spikes” in Figure 6.1 occur due to the high acceleration rates and deceleration rates demanded by the driving schedule and can also be attributed to dynamometer harmonics. Equation 6.1 (or Equation 6.2) may now be used to predict NO_X as a function of time, as shown in Figure 5.23. Equation 6.1 was used to obtain the instantaneous NO_X emissions shown in Figure 6.2.

Figure 6.1 Instantaneous power demand at the rear axle for the Heavy-Duty Urban Dynamometer Driving Schedule (UDDS). (C_D = 0.76, μ=0.00938, A=8.32 m^2, m=60,000 lb. (27216 kg)).



The modeled data shown in Figure 6.2 may next be integrated, to yield a modeled emissions level for the truck, in units of g/mile. In cases where the power demand is negative (that is, during braking), one may ascribe either zero or idle NO_X emissions to the vehicle, according to the fueling strategy, but this does not affect the NO_X emissions values substantially. In real world operation, fueling will be cut and no NO_X would be produced when the engine experiences high motoring (negative) torques.

In this research, NO_X emissions were set to zero for negative rear axle power and to at least idle value for zero or slight positive torques. Using this process, it is possible to calculate the g/mile NO_X values for “Truck A” operating at several different weights. Figure 6.3 shows the variation of the NO_X emissions with test weight for both “Truck A” and “Truck B.” It is clear that for a doubling of truck weight from 40,000 lb. to 80,000 lb., NO_X emissions rise by 54.6% and 41.8% respectively for “Truck A” and “Truck B”. Doubling the weight from 30,000 lb. to 60,000 lb. resulted in an increase in NO_X emissions by 47.2% and 34.7% respectively for “Truck A” and “Truck B.”

A similar analysis was repeated for the City Suburban Heavy Vehicle Route (CSHVR) [Clark et al, 1999], and the final results are shown in Figure 6.4. It can be seen from Figure 6.3 that for doubling the weight from 40,000 lb. to 80,000 lb., NO_X emissions rise by 60.5% and 43.3% respectively for “Truck A” and “Truck B”.

The percentage increase in NO_X emissions for three different changes in vehicle weights is presented in Table 6.1. It can be observed that for both the cases discussed, the percentage increase in NO_X emissions decreases with a lower starting vehicle weight. In other words, NO_X emissions increase more when the weight is doubled from 40,000 lb. to 80,000 lb., as opposed to doubling the weight from 30,000 lb. to 60,000 lb. or 20,000 lb. to 40,000 lb. This shows that there is a linear variation of NO_X emissions with vehicle weight. Figures 6.5 and 6.6 show the graphical representation of Table 6.1. In Figure 6.3 and Figure 6.4, the trend lines appear straight because inertial and tire loss effects dominate wind losses, which are unaffected by weight. For heavy trucks, wind losses become a substantial contribution only at sustained speeds of over 50 mph.

Table 6.1 Percentage increase in NO_X emissions for different change in vehicle weights.

Sl. No	Percentage Increase in NO_X Emissions (%)	CSHVR		Test D	
		Truck A	Truck B	Truck A	Truck B
1	40 - 80	60.5	43.3	54.6	41.8
2	30 - 60	53.0	35.9	47.2	34.7
3	20 - 40	42.1	26.6	36.5	25.3
1 - 2	Percentage Difference (%)	7.5	7.4	7.4	7.1
2 - 3	Percentage Difference (%)	9.9	9.3	10.7	9.4

Figure 6.2 Predicted NO_X emissions (g/s) for the 1996 model year truck using the NO_X vs. power relationship (equation 1.) over the UDDS at 60,000 lb.

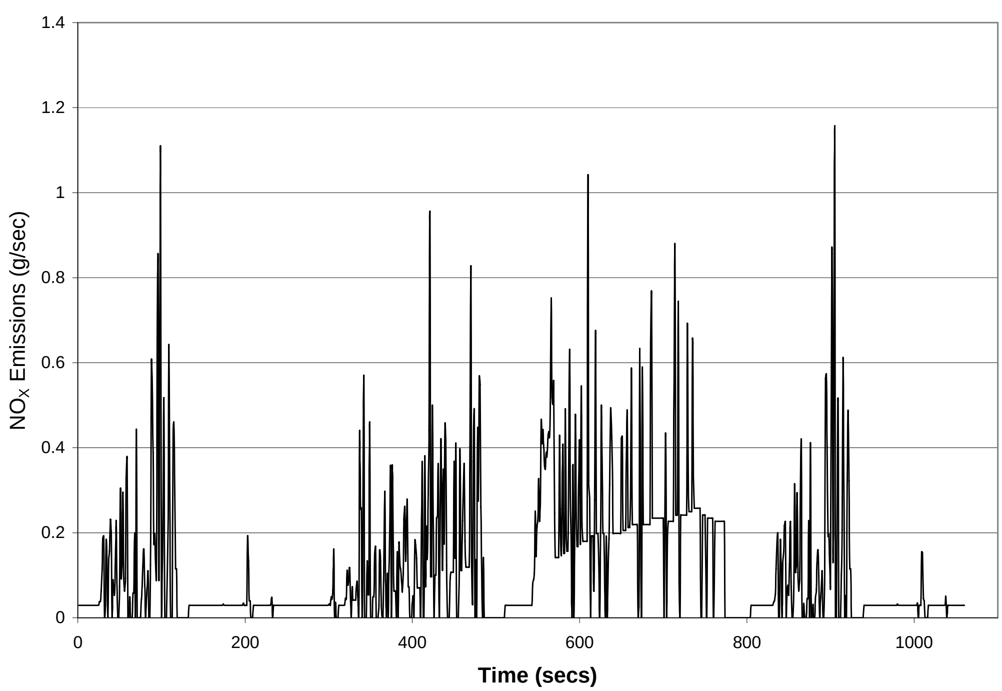


Figure 6.3 Variation of predicted NO_X emissions (g/s) with weight for the two trucks driven over the Heavy-Duty Urban Dynamometer Driving Schedule (UDDS).

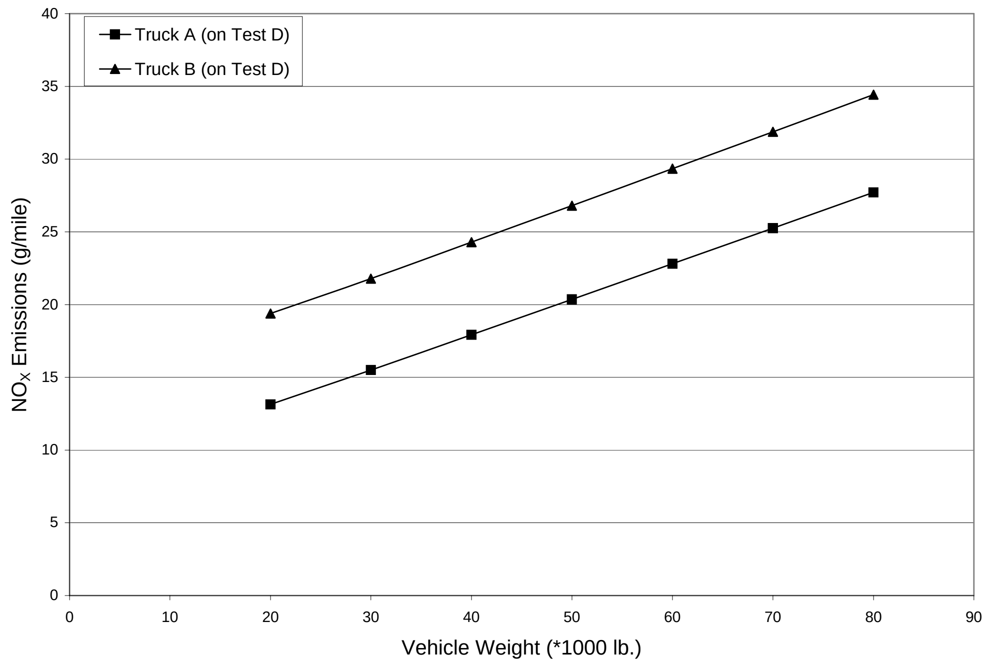


Figure 6.4 Variation of predicted NO_X emissions (g/s) with weight for the two trucks driven over the City-Suburban Heavy Vehicle Route (CSHVR).

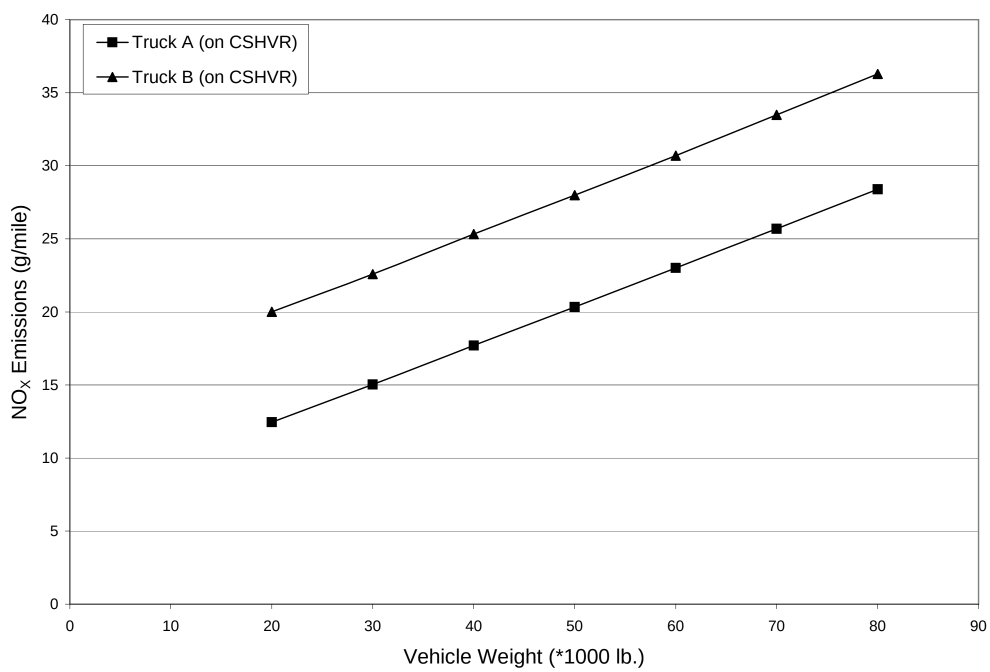


Figure 6.5 Variation of percentage increase in NO_X emissions with increase in vehicle weight for CSHVR.

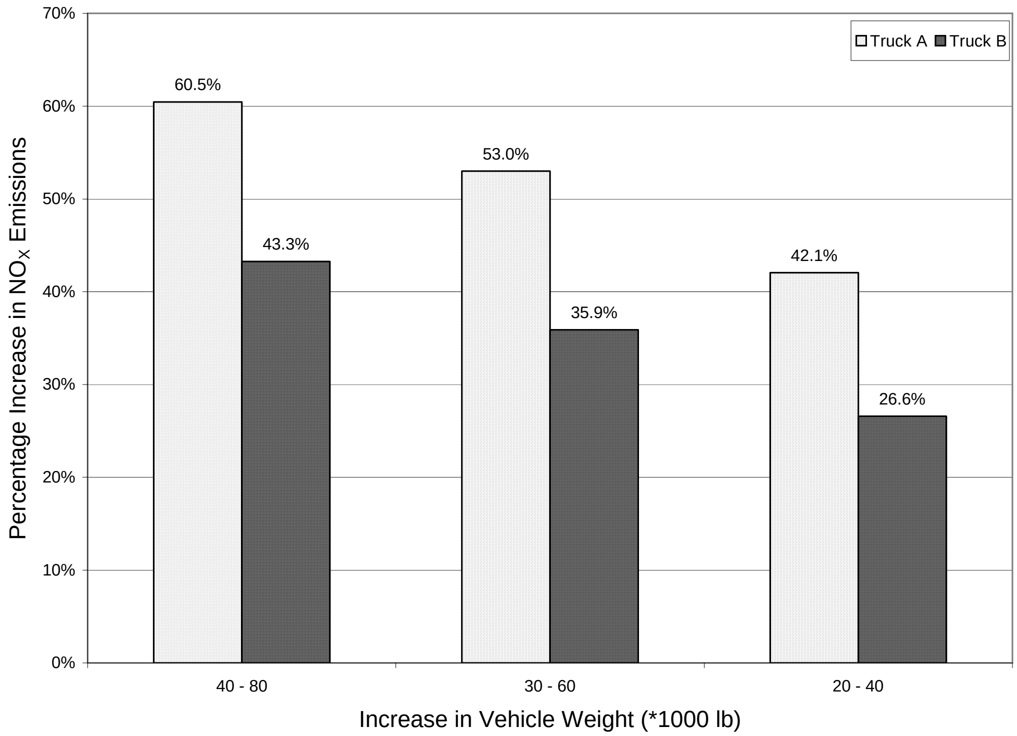


Figure 6.6 Variation of percentage increase in NO_X emissions with increase in vehicle weight for UDDS.

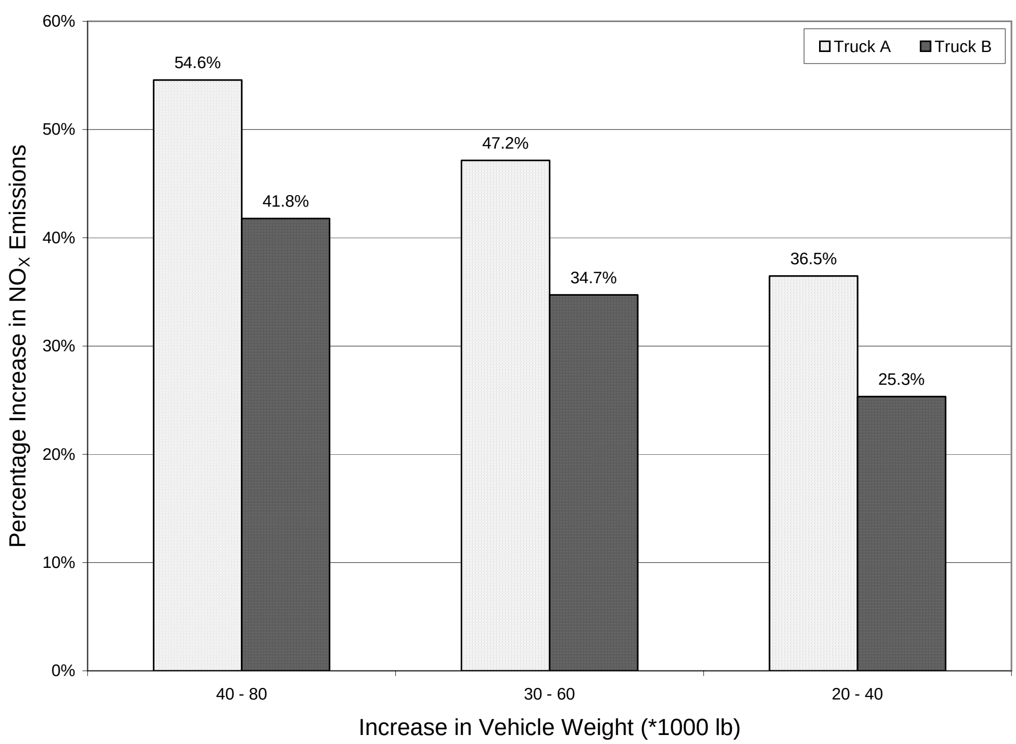


Figure 6.7 shows the ratio of the emissions for “Truck A” and “Truck B” at 80,000 lb. (common maximum load) to the emissions at 30,000 lb. (lightly loaded or empty) as a function of a steady state speed. It can be seen from Figure 6.7 that the NO_X production increases with speed until about 30 mph after which it falls. The NO_X production ratio for “Truck A” increases from 1.22 at a low speed of 5 mph to 1.33 at a speed of 70 mph and peaks at 30 mph with a value of 1.61. This is due to the fact that at lower speeds, tire losses dominate the wind drag and hence, the power required increases drastically with increase in vehicle weight, which results in higher NO_X emissions. At higher speeds the wind drag dominates and the effect of weight is less profound. Figure 6.8 shows the plot of tire loss and wind drag as a function of steady state speed. It can be seen that until a speed of approximately 35 mph the tire loss dominates wind drag, after which, the wind drag force increases drastically. Figure 6.9 shows the plot of percentage increase in power required when the vehicle weight is increased from 30,000 lb. to 80,000 lb. as a function of speed. It can be seen that at lower speeds, the power required increases significantly (evident from the slope of the curve) with increase in vehicle weight. At higher speeds, the increase in power required falls as can be seen in Figure 6.9.

Figure 6.7. Variation of NO_X emissions production ratio with steady state speed for "Truck A" and "Truck B".

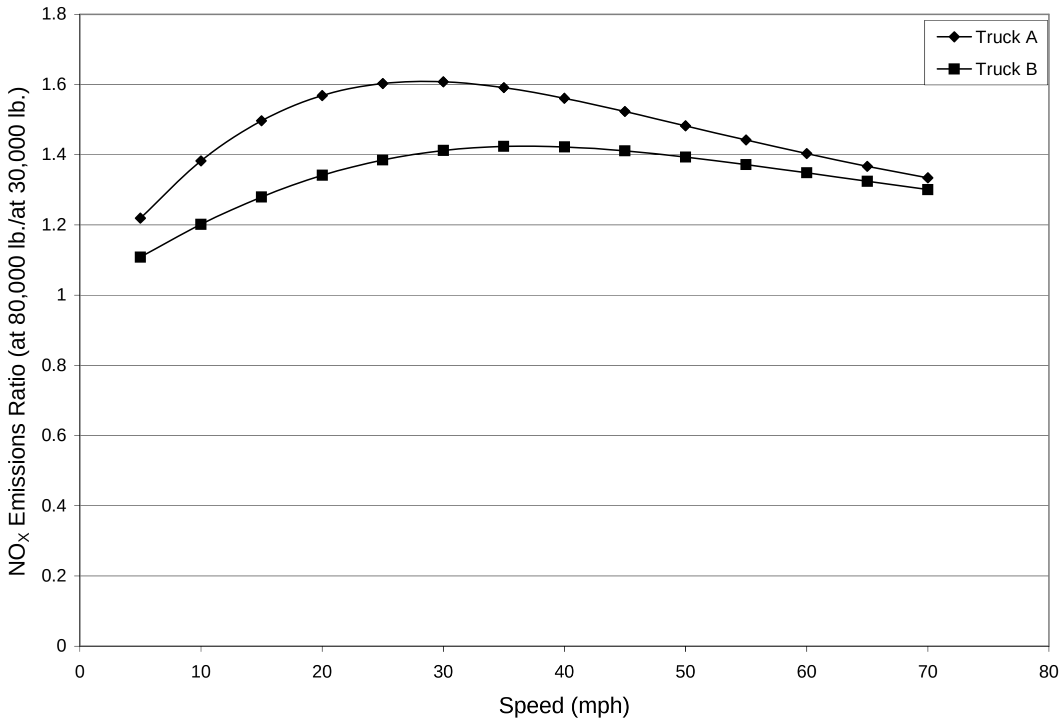


Figure 6.8. Variation of tire loss and wind drag force with steady state speed.

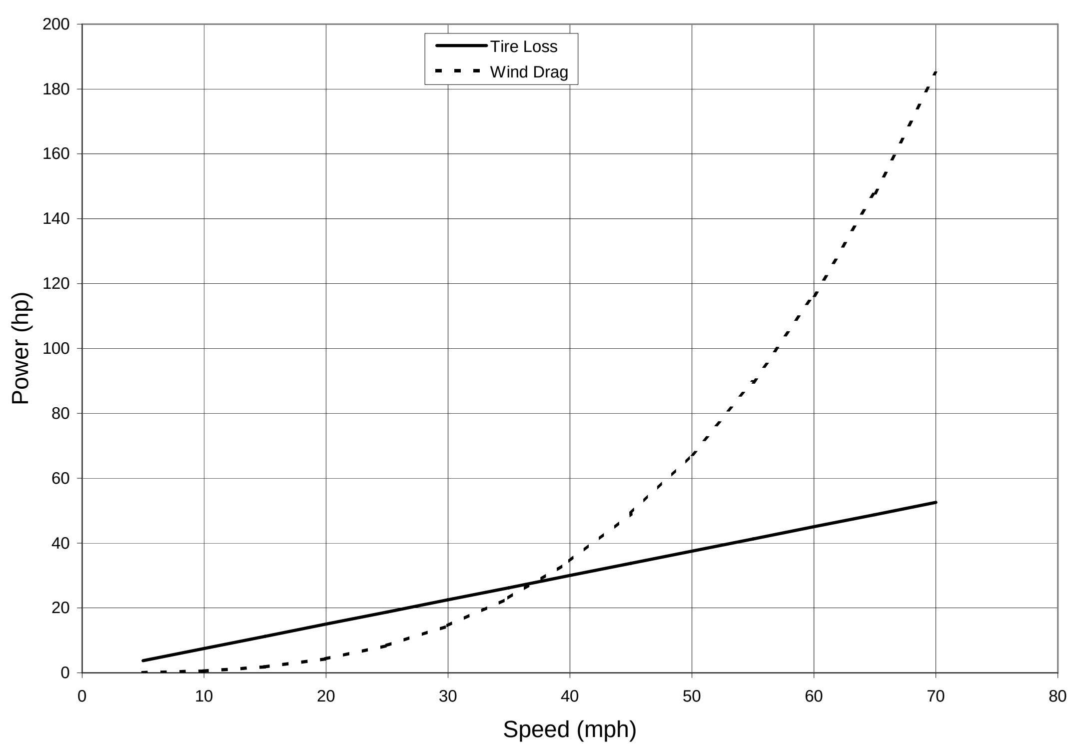
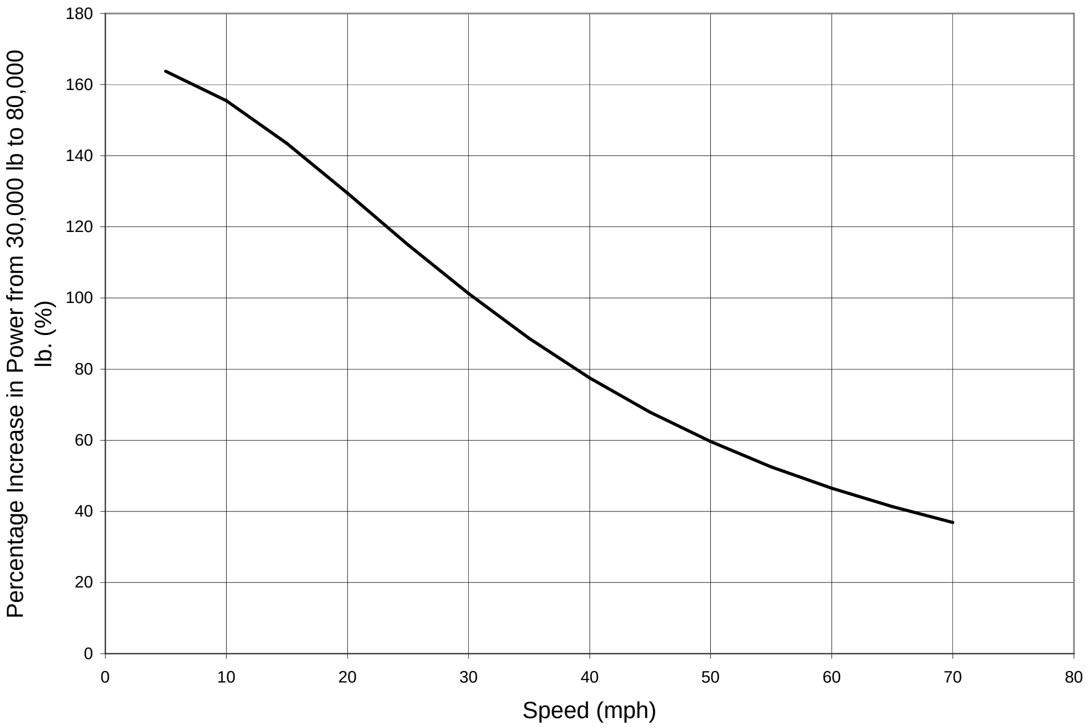


Figure 6.9. Variation of percentage increase in power required with steady state speed from a vehicle weight of 30,000 lb. to a vehicle weight of 80,000 lb.



In transient tests, a high proportion of the energy may be required for accelerations, and this energy is lost during braking. Since the acceleration energy is proportional to the vehicle mass, the effect here is similar to that of tire losses. In other words, a highly transient cycle is likely to emphasize the effect of weight on NO_X production in comparison to a steady state operation with the same average speed. Conversely, if a test schedule contains long periods of idle, the idle contribution may become significant and will be weight insensitive. The average speed of the UDDS (UDDS) is 18.9 mph. The difference in emissions at 30,000 lb. and 80,000 lb. for "Truck A" as a ratio (NO_X emissions at 80000 lb./NO_X emissions at 30000 lb.) on the UDDS is 1.79. If the same truck were operated at a steady state speed of 18.9 mph, the ratio would be 1.56, approximately a 15% increase.

The difference in NO_X emissions at 30,000 lb. and 80,000 lb. for the same truck (Truck A) on the CSHVR, a highly transient cycle, (with an average speed of 14.45 mph) is 1.89. If the truck were operated at a steady speed of 14.45 mph, the ratio would be 1.49, which represents a 33% increase. It is clear that transients can emphasize the weight effects on NO_X emissions significantly.

6.1.2 Experimental Data

Figures 6.10 through 6.13 show measured values of different emissions species as a function of vehicle weight for all of the test vehicles discussed in Chapter 4. Table 2 presents some details of vehicles considered in this analysis. In these figures, the emissions are plotted against the vehicle weight expressed as percentage of Gross Vehicle Weight Rating (GVWR). The GVWR is the maximum weight a vehicle is allowed to achieve, including the vehicle, driver, payload, and fuel.

The vehicles used in the plots are listed here in the same order as they appear in the plots.

Table 6.2 Details of vehicles considered for the analysis.

Vehicle Number	Model Year	Type	Cycle
1	1989	Transit Bus	CBD
2	1989	Transit Bus	NY Bus
3	1996	Transit Bus	CBD
4	1998	Tractor Truck	CSHVR
5	1994	Tractor Truck	CSHVR
6	1995	Tractor Truck	CSHVR
7	1995	Tractor Truck	Highway

Figure 6.10 Comparison of NO_X emissions in grams/mile from different vehicles as a function of percentage GVWR.

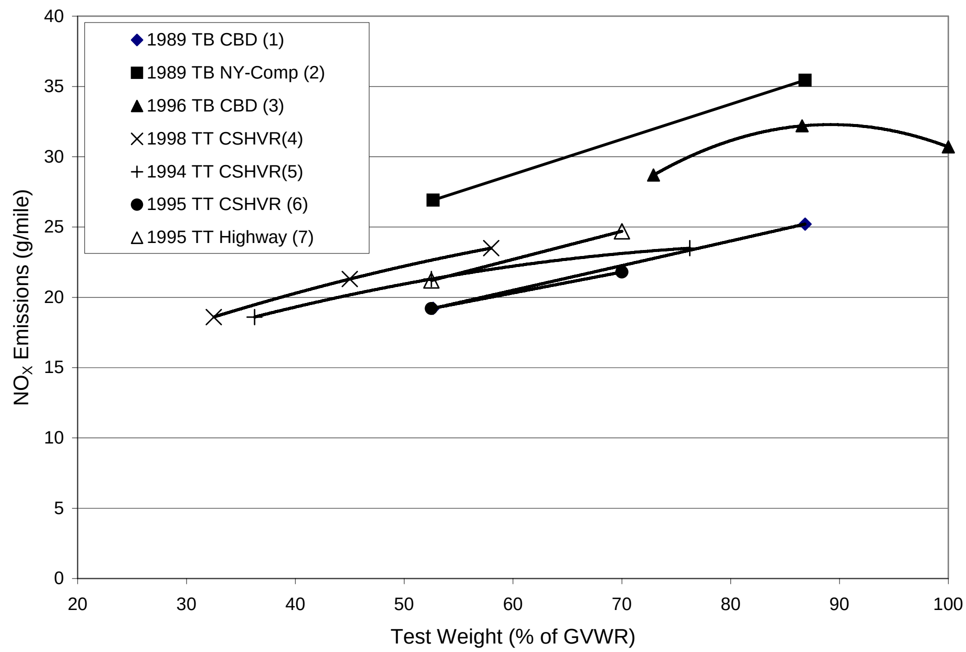


Figure 6.11 Comparison of HC emissions in grams/mile from different vehicles as a function of percentage GVWR.

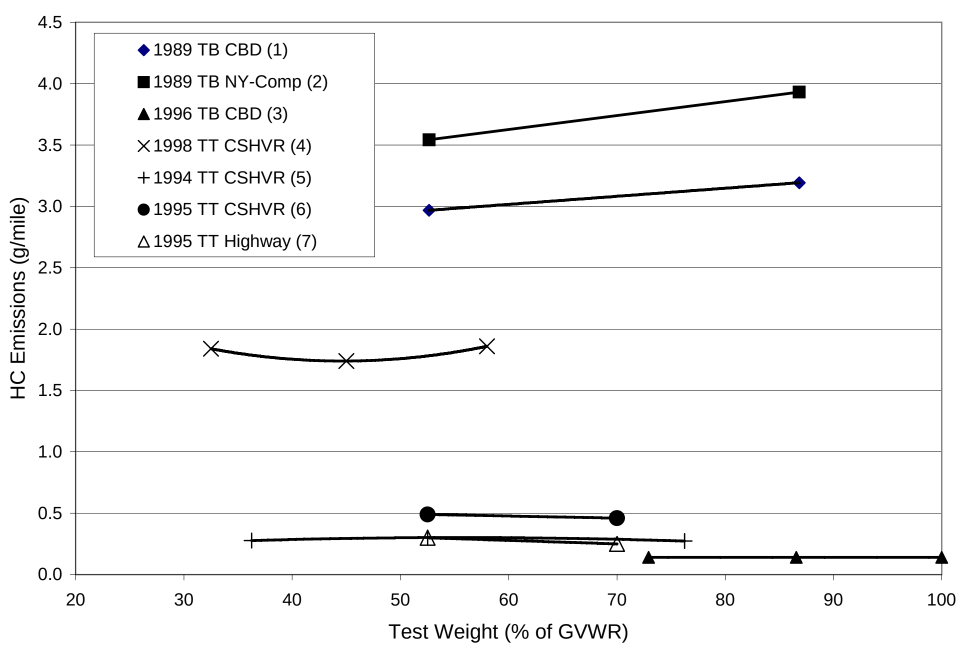


Figure 6.12 Comparison of CO emissions in grams/mile from different vehicles as a function of percentage GVWR.

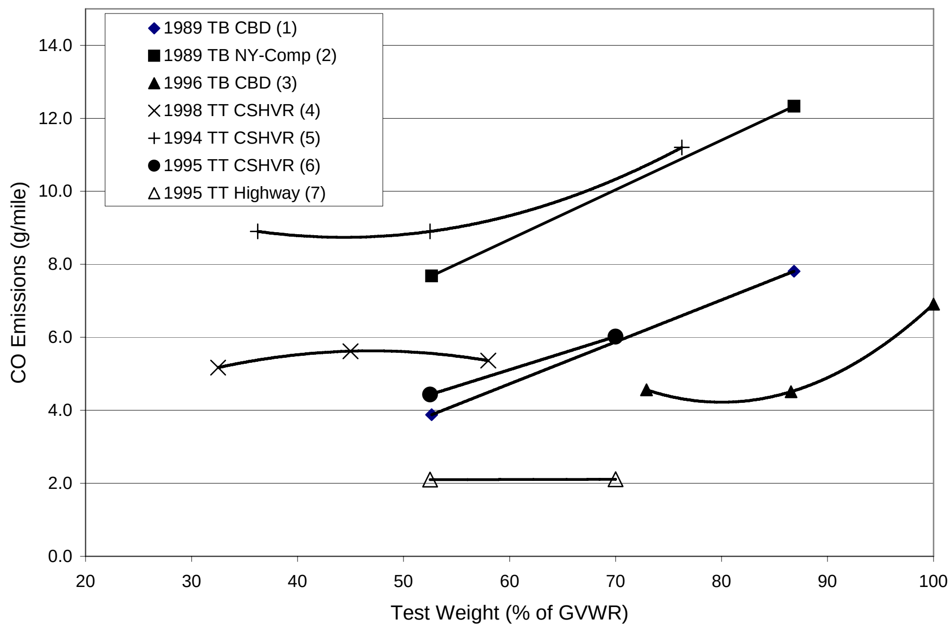
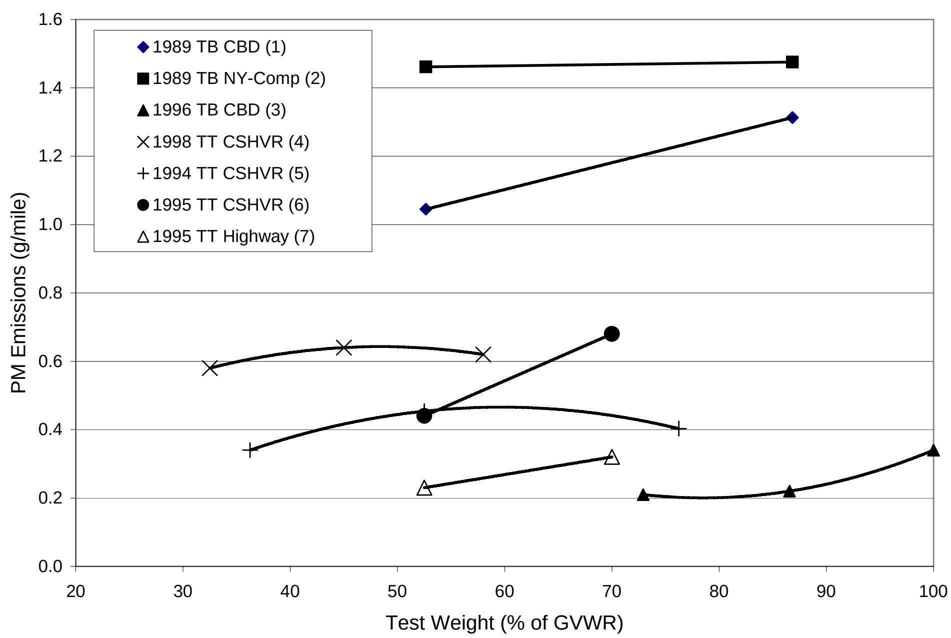


Figure 6.13 Comparison of PM emissions in grams/mile from different vehicles as a function of percentage GVWR.



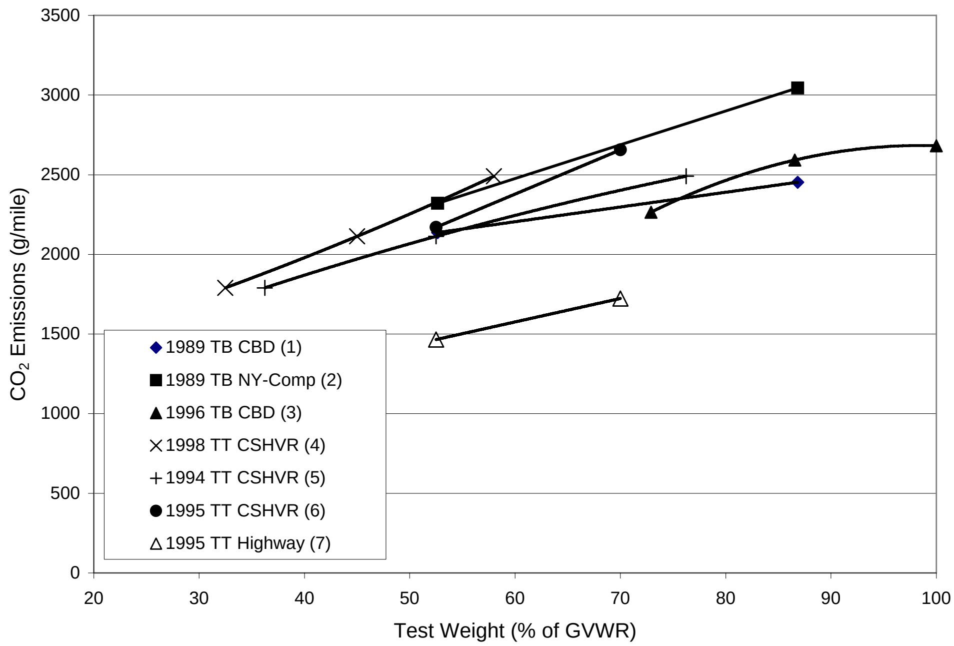
In the following discussions, the 1995 TT tested on two different cycles, are listed as vehicle (6) and (7). These correspond to the Test Vehicle 1 that was tested on dual map over CSHVR and IHC respectively. As can be seen from Figure 6.10, there is an increase in the NO_X emissions with an increase in the vehicle weight in general. However, the 1996 TB (TB) and the 1994 tractor truck (TT) show different trends. The slope of the curves for all the vehicles, except for the 1996 TB and the 1994 TT are close in value, which means that the NO_X emissions vary with the vehicle weight in a similar fashion irrespective of the vehicle type or the test cycle used. There is a sudden drop in the NO_X emissions from the 1996 TB at a test weight close to the rated GVW. This vehicle was powered with a 275 hp engine, and operation at a test weight close to the GVWR causes operation close to full power. In this way, the vehicle may not follow the cycle as closely and comparison may be compromised. Also, NO_X formation is strongly controlled by the temperature and the availability of oxygen, which may start to be impaired at full load in older engines. The trend observed for the 1994 truck can be attributed to the same cause. This vehicle was powered by a 365 hp engine and was rated with a GVW of 80,000 lb.

As seen in Figure 6.11, the HC emissions are almost constant for all of the vehicles except for the 1989 TB. HC emissions in a modern diesel engine are very low and are insensitive to the vehicle weight. As can be seen in Figure 6.11, the HC emissions are higher for the 1989 TB. The older model year vehicles yield higher emissions due to earlier engine technology and aging. Specifically, the older bus employs two-stroke engine technology.

As expected, there is scatter in the CO and PM emissions as seen in Figures 6.12 and 6.13. Both CO and PM emissions are strongly affected by the transients and are also usually less repeatable than NO_X in test measurements. This can be seen from the CO and PM emissions from the 1995 truck (Figures 6.12 and 6.13), which was tested on two different cycles. The truck was tested on the CSHVR, a highly transient route, and the Highway Cycle, which is a high-speed cycle typical of freeway operation with fewer transients. The CO emissions are almost constant with vehicle weight for the Highway cycle, whereas there is a higher relative increase in the CO emissions on the CSHVR. Similar trends are observed in the PM emissions too. There is an increasing trend in the CO and PM emissions with the vehicle weight for most of the cases.

Figure 6.14 shows the variation of the CO_2 emissions with weight for all the vehicles considered. It can be seen that there is a linear increase in the CO_2 emissions with increasing weight. The CO_2 emissions are a measure of the energy expended as they directly correspond to the fuel consumption of the vehicle. Transient operation involves extra energy spent during accelerations, which is lost during decelerations (braking). This means that a transient cycle (one like the CSHVR) will require the vehicle to expend higher energy with increasing weight. This can be seen from Figure 6.14, where the slope of the CO_2 emission curve is steeper for the CSHVR (transient operation). Figure 6.15 shows the plot of NO_X over CO_2 ratios against GVW for different vehicles. The ratio is fairly insensitive to the vehicle weight. This shows that NO_X emissions increase due to increase in fuel usage, and implies that NO_X emissions data in units of g/gal. of fuel consumed remain fairly constant despite a weight change.

Figure 6.14 Comparison of CO_2 emissions in grams/mile from different vehicles as a function of percentage GVWR. Fuel consumption is in direct proportion to CO_2



production.

Figure 6.15 Comparison of NO_X to CO_2 ratios for different vehicles as a function of percentage GVWR.

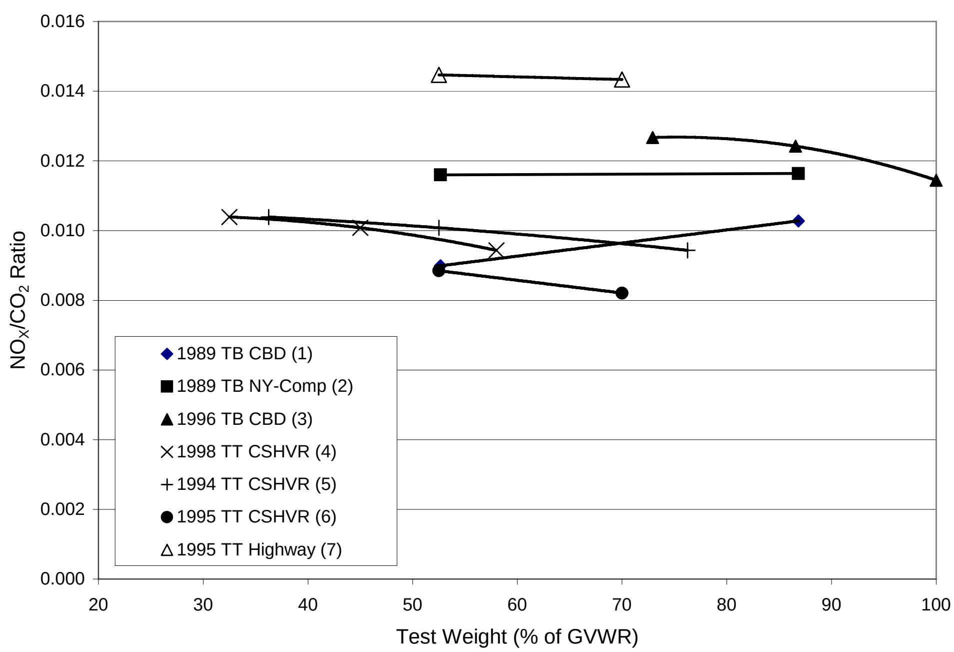


Table 6.3 Summary of the UDDSata gathered and the average emissions values for the vehicles listed in Table 6.1.

Vehicle Type	Cycle	Test Weight (lbs.)	GVWR	% GVWR	PM (g/mile)	NO_X (g/mile)	HC (g/mile)	CO (g/mile)
1989 Transit Bus	CBD	19429	36900	52.7	1.04	19.21	2.97	3.88
	CBD	32042	36900	86.8	1.31	25.21	3.19	7.81
	NY-Composite	19429	36900	52.7	1.46	26.91	3.54	7.68
	NY-Composite	32042	36900	86.8	1.48	35.45	3.93	12.33
1996 Transit Bus	CBD	27650	37920	72.9	0.21	28.7	0.14	4.56
	CBD	32825	37920	86.6	0.22	32.2	0.14	4.51
	CBD	38000	37920	100.2	0.34	30.7	0.14	6.91
1998 tractor Truck	CSHVR	26000	80000	32.5	0.58	18.6	1.84	5.17
	CSHVR	36000	80000	45	0.64	21.3	1.74	5.62
	CSHVR	46400	80000	58	0.62	23.5	1.86	5.36
1994 Tractor Truck	CSHVR	29000	80000	36.3	0.34	27.20	0.28	8.90
	CSHVR	42000	80000	52.5	0.45	33.00	0.30	8.90
	CSHVR	61000	80000	76.3	0.40	42.00	0.27	11.20
1995 tractor Truck	CSHVR	42000	80000	52.5	0.44	19.2	0.49	4.43
	CSHVR	56000	80000	70	0.68	21.8	0.46	6.02
	IHC	42000	80000	52.5	0.23	21.20	0.30	2.10
	IHC	56000	80000	70	0.32	24.70	0.25	2.11

It can be seen that vehicle weight has a significant effect on the emissions but that the emissions do not vary in direct proportion to test weight. The NO_X emissions showed a consistent trend with increasing vehicle weight for most of the cases, except for the 1996 TB and the 1994 TT. The relationship between NO_X and vehicle weight was found to be linear for all the cases except for the two vehicles mentioned above. This is in good agreement with the theory presented at the beginning of this chapter. The NO_X values predicted using the relationship obtained between NO_X and axle power exhibited a linear trend with weight. The theoretical approach showed that the NO_X emissions increased by about 54% for a doubling of test weight. It can be seen from Table 6.3 that for the 1994 TT, which was tested at three different weights, doubling of the vehicle weight increased the NO_X emissions by about 54%. The observed trends correlate well with the theory presented. Also, it can be seen from Figure 6.7 that the trends for the NO_X emissions are similar for the two test vehicles considered. Similar trends can be observed between the different vehicles considered in Figure 6.10. As discussed earlier, NO_X emissions are insensitive to the transients.

The HC emissions appear to be insensitive to the weight. The HC emissions values are low for the diesel engines and do not vary significantly with vehicle weight or the test cycle used.

The CO emissions values exhibit an erratic behavior. There is no clear trend in the CO emissions with weight although there is an increasing trend for some cases. CO emissions are severely affected by transients, as are PM emissions. It was found that the CO emissions were insensitive to vehicle weight during steady state operation (less transients). However, there is a considerable increase in the CO emissions with vehicle weight during transient operation. For example, consider the Test Vehicle 1 that was tested at 42,000 lb. and 56,000 lb. over the CSHVR (transient operation) and IHC (steady state operation). The CO emissions value did not vary significantly between 42,000 lb. and 56,000 lb. weights over the IHC; however, the CO emissions increased by 36% for the same vehicle when tested on the highly transient route, CSHVR. Similar trends were observed with PM emissions. The PM emissions were more scattered than the NO_X and CO_2 emissions.

To further study the effect of test weight on the heavy-duty diesel vehicles, data available from CRC E55 Phase I study, which involved testing of 25 different trucks at two different weights were analyzed in detail and are presented here. Details of tests conducted including vehicle information are discussed in Chapter 4. Figures 6.16 through 6.22 show the ratio of NO_X emissions at 56,000 lbs. to NO_X emissions at 30,000 lbs. for a range of vehicle model years. Figures 6.16 through 6.22 were obtained by taking the ratio of NO_X emissions factors in grams/mile presented in Tables 5.47 through 5.52 in section 5.8 and plotting them against the average speed class.

Figure 6.16 Ratio of NO_X emissions at 56,000 lbs. to NO_X emissions at 30,000 lbs. for the 1974-77 model year group.

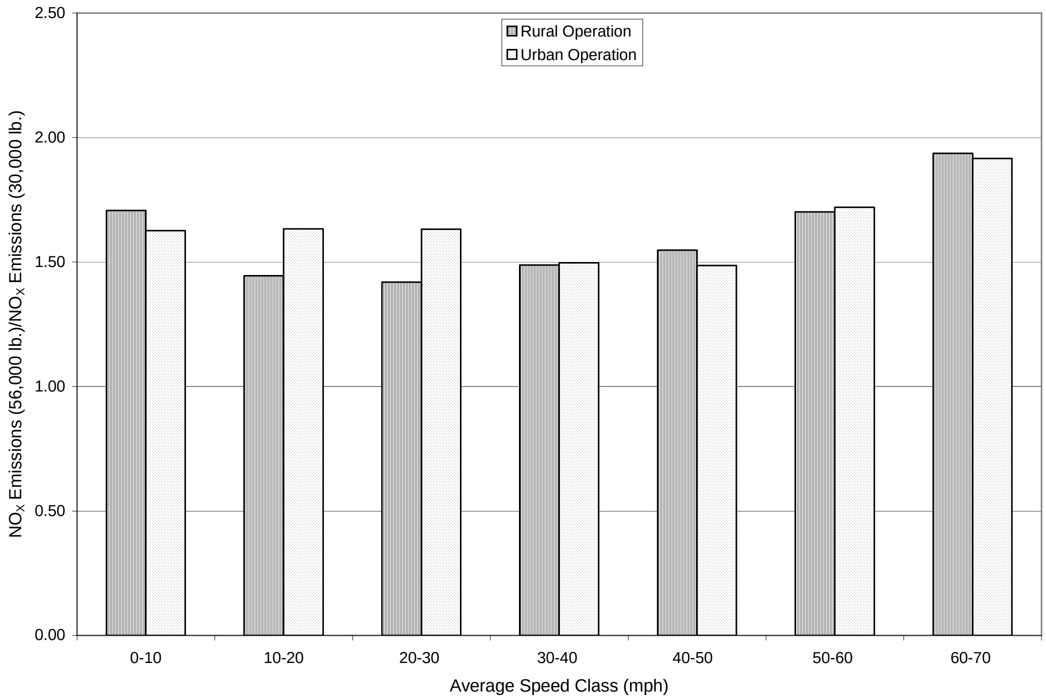


Figure 6.17 Ratio of NO_X emissions at 56,000 lbs. to NO_X emissions at 30,000 lbs. for the 1978-81 model year group.

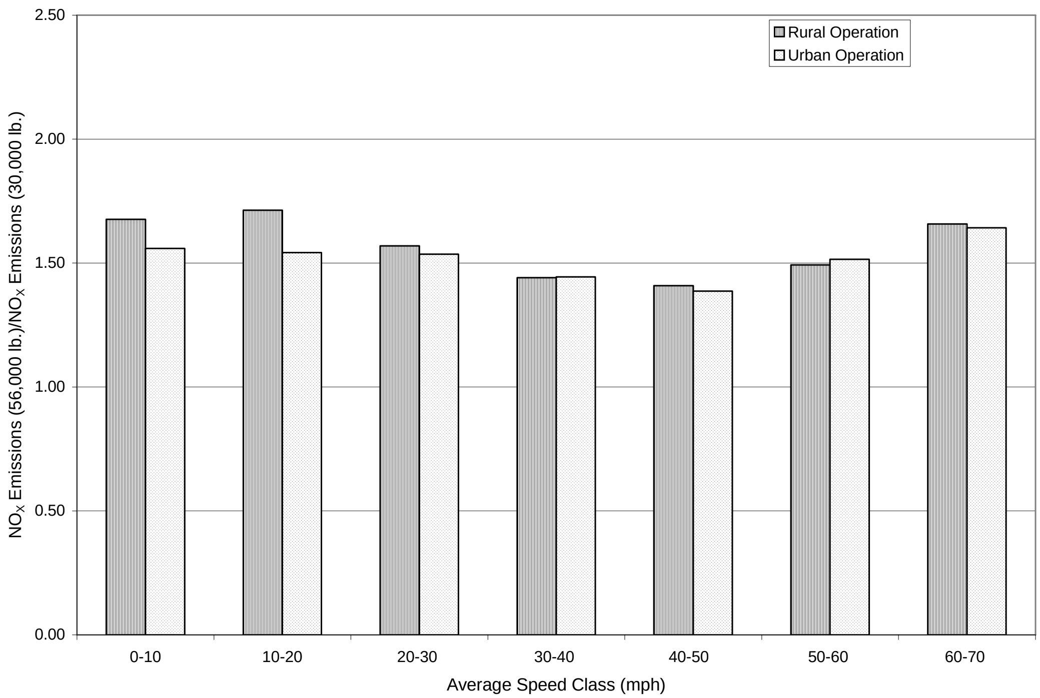


Figure 6.18 Ratio of NO_X emissions at 56,000 lbs. to NO_X emissions at 30,000 lbs. for the 1982-85 model year group.

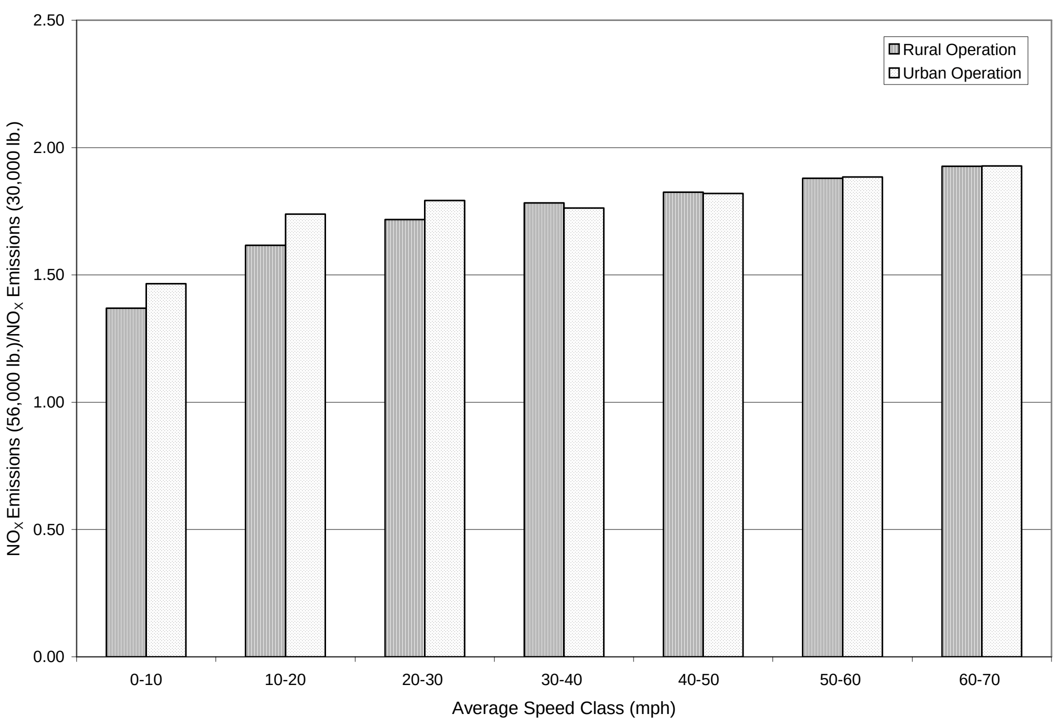


Figure 6.19 Ratio of NO_X emissions at 56,000 lbs. to NO_X emissions at 30,000 lbs. for the 1986-89 model year group.

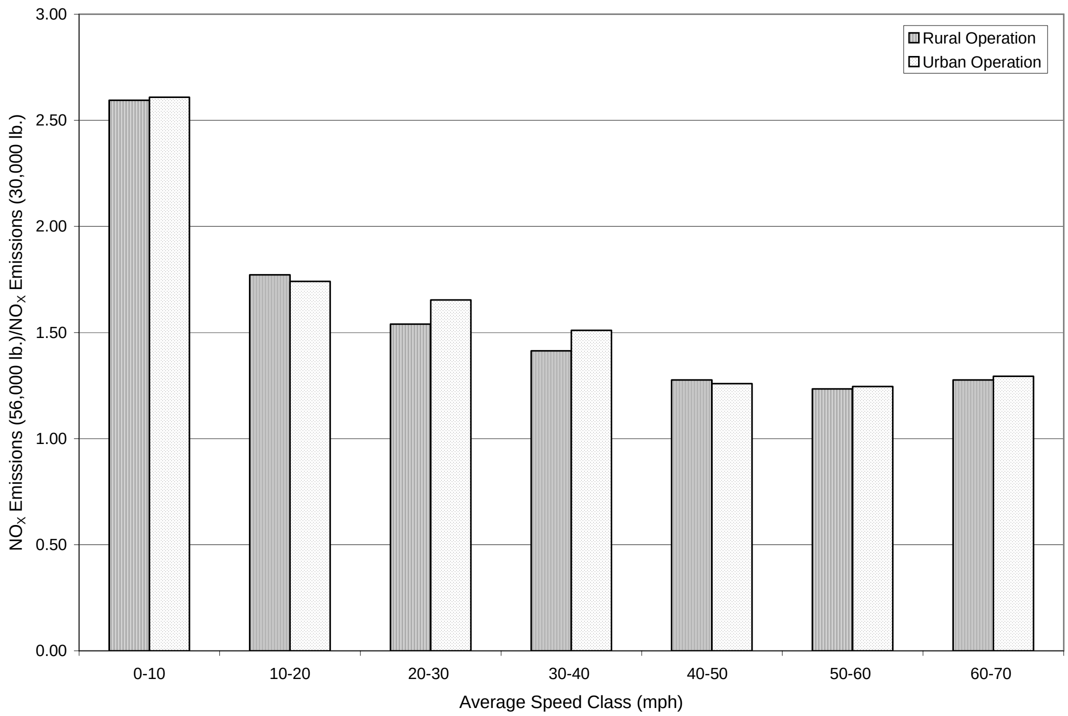


Figure 6.20 Ratio of NO_X emissions at 56,000 lbs. to NO_X emissions at 30,000 lbs. for the 1990-93 model year group.

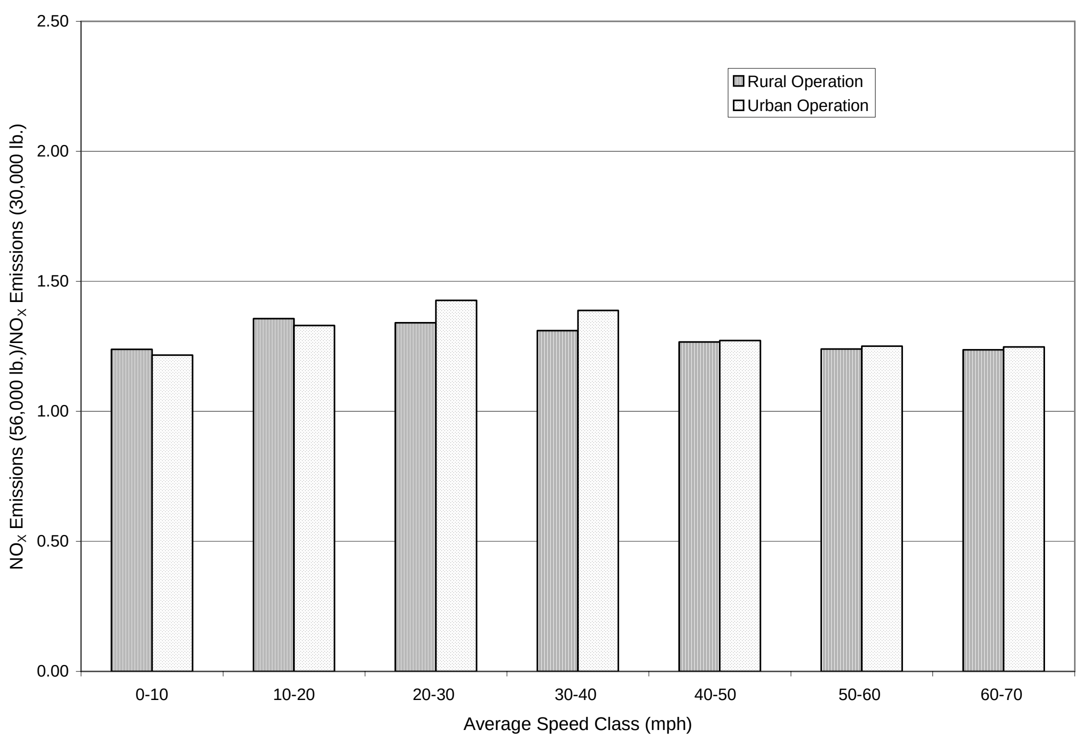


Figure 6.21 Ratio of NO_X emissions at 56,000 lbs. to NO_X emissions at 30,000 lbs. for the 1994-97 model year group.

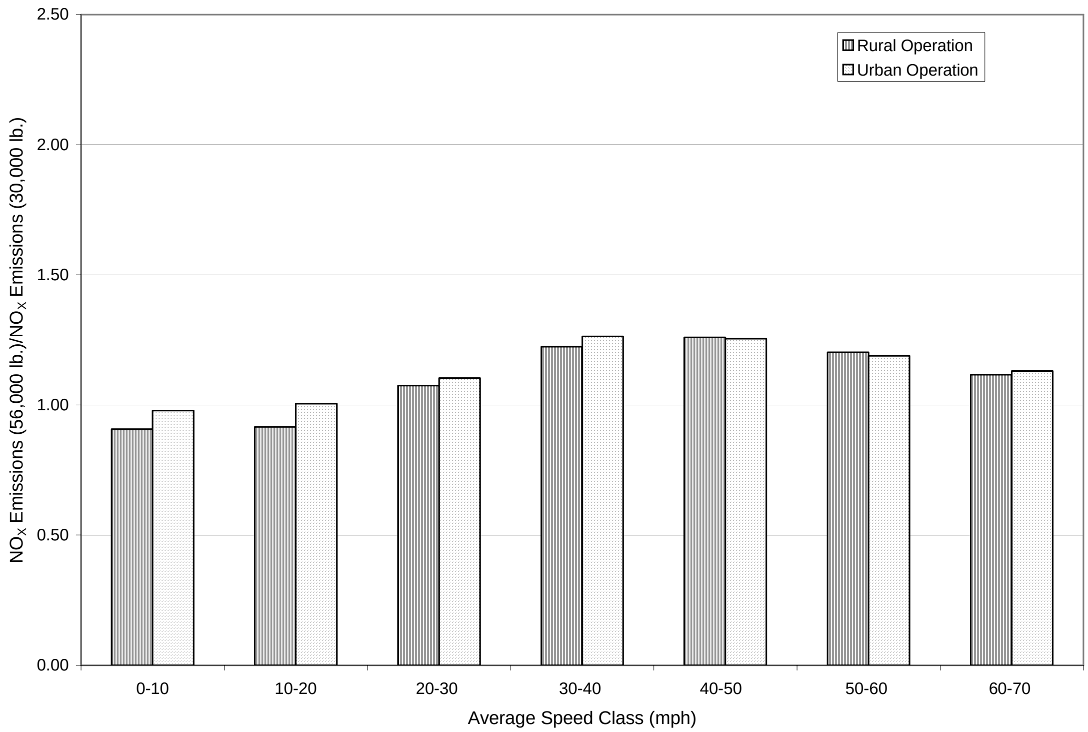
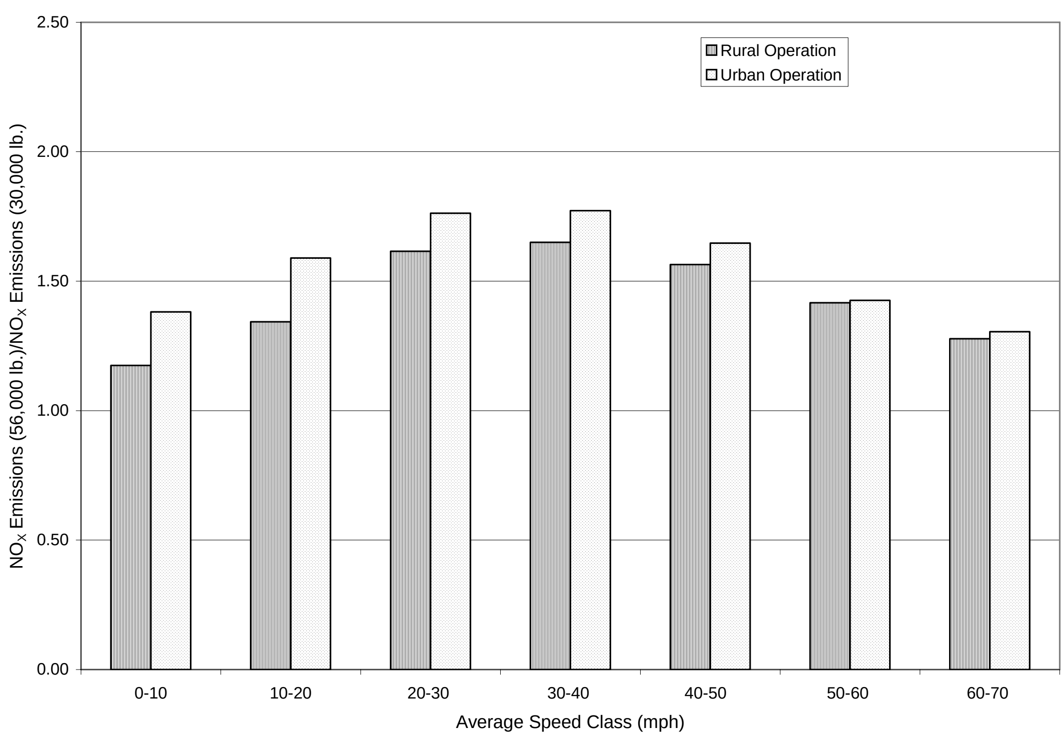


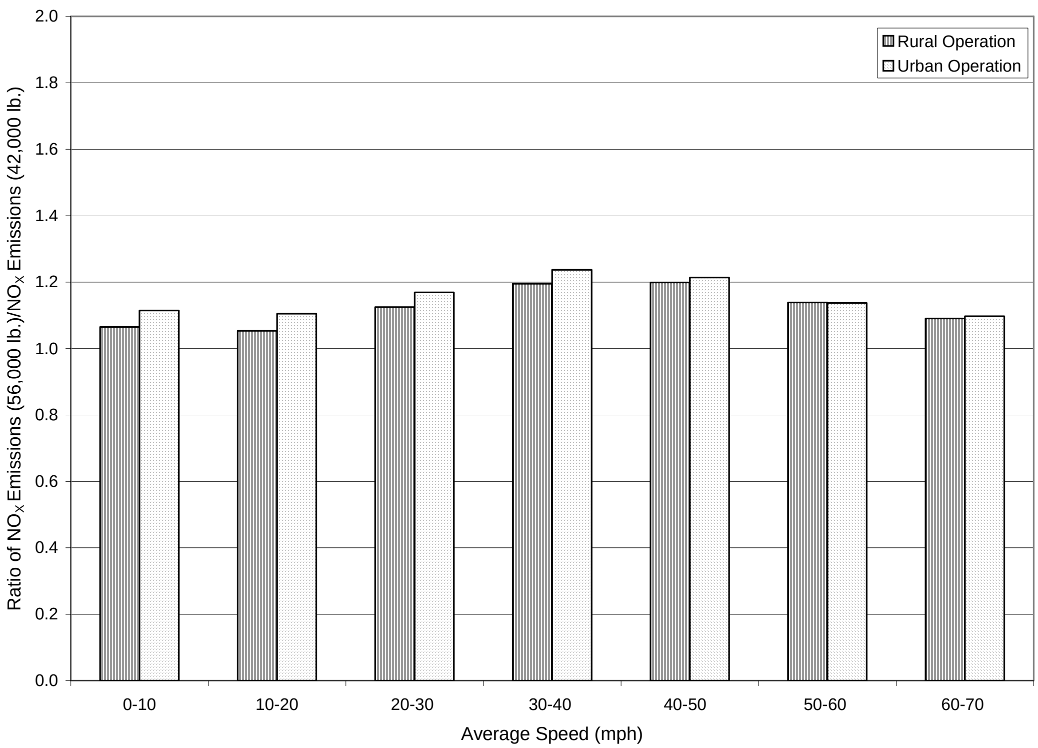
Figure 6.22 Ratio of NO_X emissions at 56,000 lbs. to NO_X emissions at 30,000 lbs. for the 1998 and newer model year group.



It can be seen from Figures 6.16 through 6.22 that vehicle weight has a significant effect on the NO_X emissions. The ratio of NO_X at 56,000 lbs. to NO_X emissions at 30,000 lbs. varies with the average speed class for both rural and urban operation. For the earlier model year vehicles: 1974-77, 1978-81, and 1982-85. The NO_X emission ratio decreases with average speed until 35 mph and then increases at high speeds. For the 1974-77 model year group, the ratio was 1.6 at 5 mph and dropped to 1.5 at a speed of 35 mph and then increased to 1.92 at 70 mph. The point of lowest NO_X ratio increased with the model year group. The results support the theory presented earlier in this chapter and also correlate with the experimental results discussed. For the 1978-81 group, the minimum occurred at 45 mph. For the 1982-85 group the point moved further toward higher speed, which in this case was 55 mph. For the model year group 1986-89, the trend changed, the ratio dropped constantly with average speed. The later model year groups: 1990-93, 1994-97, and 1998 and newer, showed a different trend altogether. The NO_X ratio increased with average speed and then dropped at higher speeds. The high point occurred at 25 mph, 45 mph and 35 mph for the model year groups 1990-93, 1994-97, 1998 and newer respectively.

Figure 6.23 shows the variation of the NO_X emissions ratio at 56,000 lbs. to NO_X emissions at 42,000 lbs. for the Test Vehicle 1 on a dual map. The trends are similar to that of the later model years in Figure 6.20, 6.21 and 6.22 with the maximum occurring at a speed of 35 mph.

Figure 6.23 Ratio of NO_X emissions at 56,000 lbs. to NO_X emissions at 42,000 lbs. for the Test Vehicle 1 on dual map.



It was found from the present study that the vehicle weight had a significant effect on the emissions. From the theoretical approach, the NO_X emissions were found to have a nearly linear correlation with the vehicle weight and did not vary much from vehicle to vehicle. NO_X emissions were also found to be insensitive to the transients. Hence, the NO_X emissions can be predicted reasonably accurate using the theory presented in this dissertation. As a rule of thumb, the data suggest that a weight increase of X% will result in a NO_X increase of roughly about X/2% in most cases.

Hydrocarbon emissions were insensitive to the vehicle weight. There was not much variation in the HC emissions with either the vehicle weight or the test cycle used. CO and PM emissions were found to be a strong function of the transient operation. There was a significant increase in the CO and PM emission production with the vehicle weight during transient operation. Transient operation increased the CO emissions value by 36%. However, CO and PM were found to be insensitive to the vehicle weight during nearly steady state operation.

6.2 Effect of Test Cycles on Heavy-Duty Diesel Vehicle Emissions

The test cycles have a significant effect on the emissions from heavy-duty diesel vehicles. To study this aspect, the data available from a prior study was used. A 1995 box truck (described in Chapter 4) had been tested on 16 different cycles. The continuous emissions data available from these tests were used to generate the emissions factors table as described in Chapter 5. Table 6.4 presents the emissions factors table in grams/mile as a function of average speed class for all of the 16 test schedules.

Table 6.4 Emissions factors in g/mile for the 1995 Box Truck over 16 different cycles.

Emissions in grams/mile for the 1995 Box Truck on 16 different cycles

			Average Speed Bin in mph				
Emissions Species	**0-10**	**10-20**	**20-30**	**30-40**	**40-50**	**50-60**	**60-70**
Rural							
NO_X	24.98	15.56	11.97	9.87	8.65	8.30	8.33
HC	2.65	1.33	0.76	0.45	0.29	0.26	0.34
CO	5.86	4.13	2.77	1.78	1.15	0.83	0.80
Urban							
NO_X	28.18	18.83	14.44	10.11	8.73	8.39	8.38
HC	2.87	1.53	0.98	0.49	0.28	0.26	0.33
CO	6.12	4.64	3.56	2.09	1.20	0.88	0.85

The vehicle was tested at 22,000 lbs. Figure 6.24 and Figure 6.25 show the plots of the variation of emissions factors with average speed class for rural and urban operation. It can be seen from Table 6.5 that the model predicts the NO_X emissions reasonably well for most of the cycles except for the NYBUS, CSC and Yard cycle. The NYBUS and Yard cycle represent typical stop-and-go urban operation and their average speeds are less than 4 mph. Table 6.4 was generated using the average of the emissions data for all the 16 cycles.

Table 6.5 Actual and predicted NO_X emissions for the Box Truck over 16 different cycles.

Test Schedule	Average Speed (mph)	Actual NO_X Emissions (g/mile)	Predicted NO_X Emissions Using Polynomial Fit(g/mile)	Predicted NO_X Emissions Using Linear Interpolation (g/mile)	Percentage Error - Polynomial Fit (%)	Percentage Error - Linear Interpolation(%)
CBD	12.6	17.1	17.0	17.8	**-0.3**	**3.6**
CBD ROUTE	13.1	17.2	16.7	17.3	**-2.8**	**-10.6**
14-C	11.8	18.3	17.6	18.6	**-3.7**	**0.4**
NYBUS	3.7	41.9	27.0	26.2	**-35.5**	**-37.5**
ARTERIAL	24.8	13.3	12.0	12.0	**-9.9**	**-9.5**
5-PEAK CYC	20	13.1	13.4	13.8	**2.2**	**5.1**
MILE ROUT	23.7	11.2	12.3	12.4	**9.6**	**12.0**
CSR	15.5	13.5	15.3	15.7	**13.4**	**16.6**
CSC	13.5	13.3	16.5	17.0	**23.7**	**27.6**
ALT 1	13.4	15.3	16.5	17.1	**8.0**	**11.6**
ALT 2	14.2	14.9	16.0	16.3	**7.6**	**9.5**
TEST_D	18.9	12.1	13.8	14.2	**14.0**	**18.0**
YARD	3.3	36.5	27.7	26.6	**-24.0**	**-27.0**
HIGHWAY	34	9.3	10.1	10.1	**8.4**	**8.4**
CITY	8.5	20.9	20.6	21.7	**-1.6**	**3.7**
FIGE	36.6	9.7	9.7	9.7	**-0.5**	**-0.3**

Figure 6.24 Variation of emissions factors with average speed class for the 1995 box truck. – Rural mode.

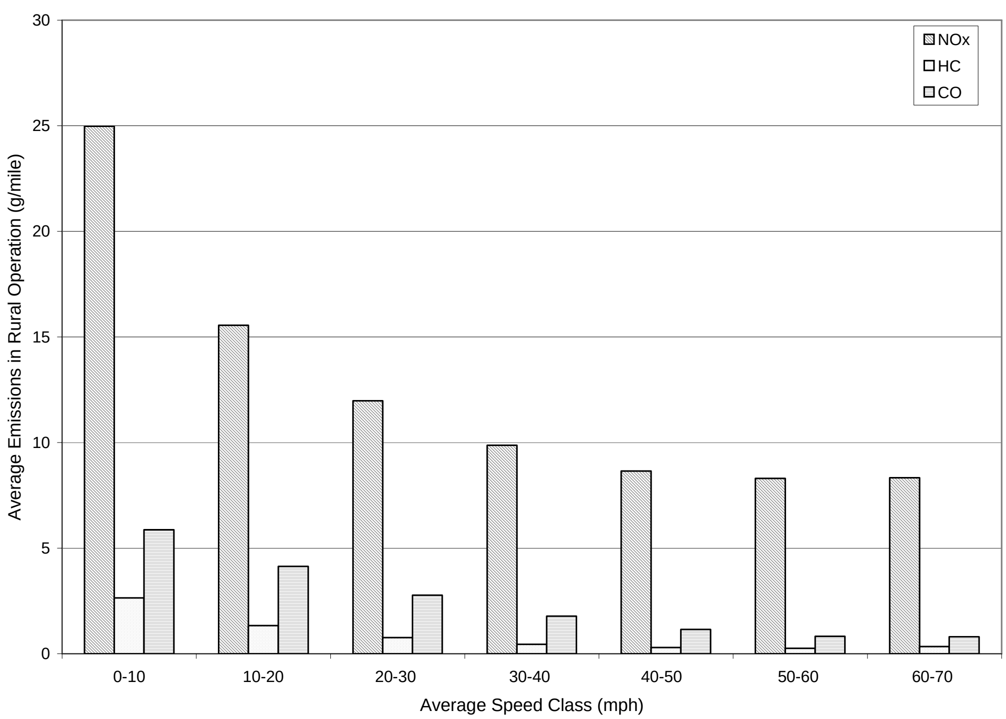
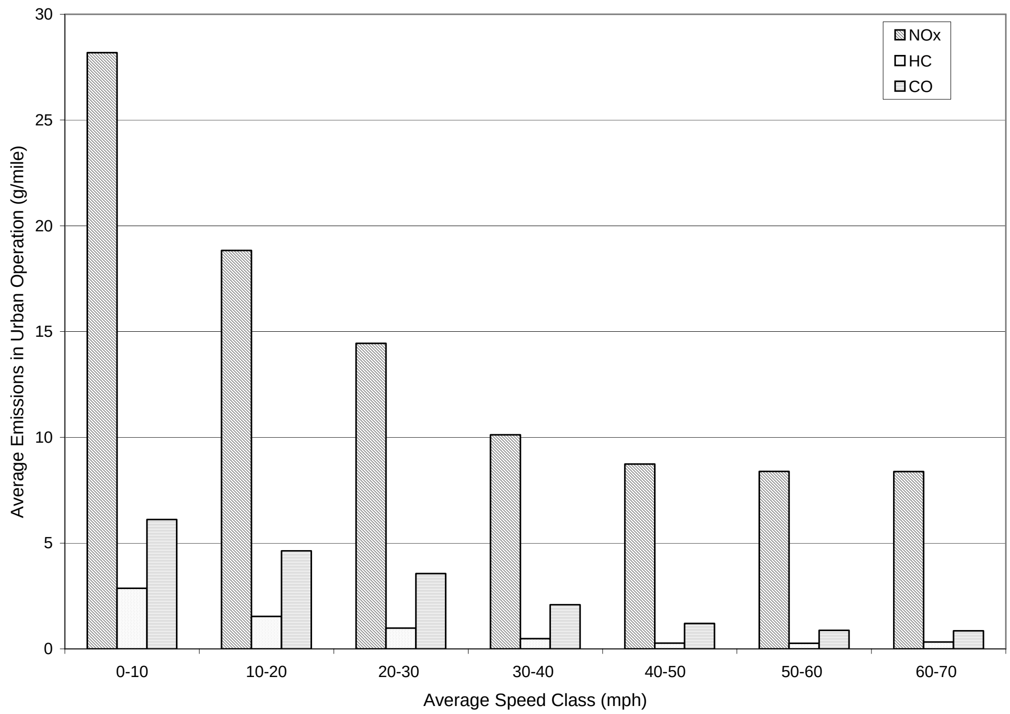


Figure 6.25 Variation of emissions factors with average speed class for the 1995 box truck. – Urban mode.



The effect of driving schedule on emissions is clearly evident from the results presented in Table 6.5. The speed acceleration based model predicts the emissions over a wide range of cycles reasonably accurately. The emissions were predicted using a best-fit polynomial and also using a linear interpolation between neighboring points to the NO_X emissions factors from Table 6.4 as explained in Chapter 5. It can be seen that both methods predict the NO_X emissions reasonably well, however, the best-fit polynomial predicted better than using the linear interpolation. It can also be seen that six out of the 16 predicted values had a percentage error less than 5%, and 11 out of the 16 predicted values had a percentage difference below 10%.

6.3 Effect of Off-Cycle Operation on Emissions

The off-cycle fuel injection timing strategy practiced commonly during the 1990's to facilitate improved fuel economy, but also to improve cold start in some circumstances. The effect is that emissions of NO_X are increased, due to the earlier combustion and higher in-cylinder temperatures, while more complete combustion implies that levels of particulate matter, hydrocarbons, and carbon monoxide will be reduced. However, it is acknowledged that the effect is most profound with respect to the NO_X.

In the case of the heavy-duty vehicles, the excess NO_X emissions that were produced during off-cycle operation mostly occurred during steady state operating modes such as cruising down the freeway, and rarely occurred during transient operation.

In this section the results from the tests conducted on the "Test Vehicle 1" on single map (without off-cycle) and dual map (with off-cycle) operation are discussed in detail. Let us assume that the off-cycle (Rural or Highway) emissions and on-cycle (Urban or City) emissions are separate and discrete, based upon existing data. In order to predict the NO_X inventory, it is necessary to know both the difference between the on-cycle and off-cycle NO_X mass emission rates, and the fraction of time (or mileage) for which the two modes are enacted. Algorithms used by the engine manufacturers to implement the advanced timing strategy are not in the public domain, so that a simulation approach cannot be used to infer the incidence or fraction of high NO_X operation

Figures 6.26 and 6.27 show the continuous plots of NO_X emissions as a function of time for the 1995 truck "Test Vehicle 1" in dual (with off-cycle) and single (without off-cycle) maps.

Figure 6.26 Continuous NO_X emissions in g/s for the Test Vehicle 1 on single map over the Inventory Highway Cycle (IHC) at 56,000 lbs.

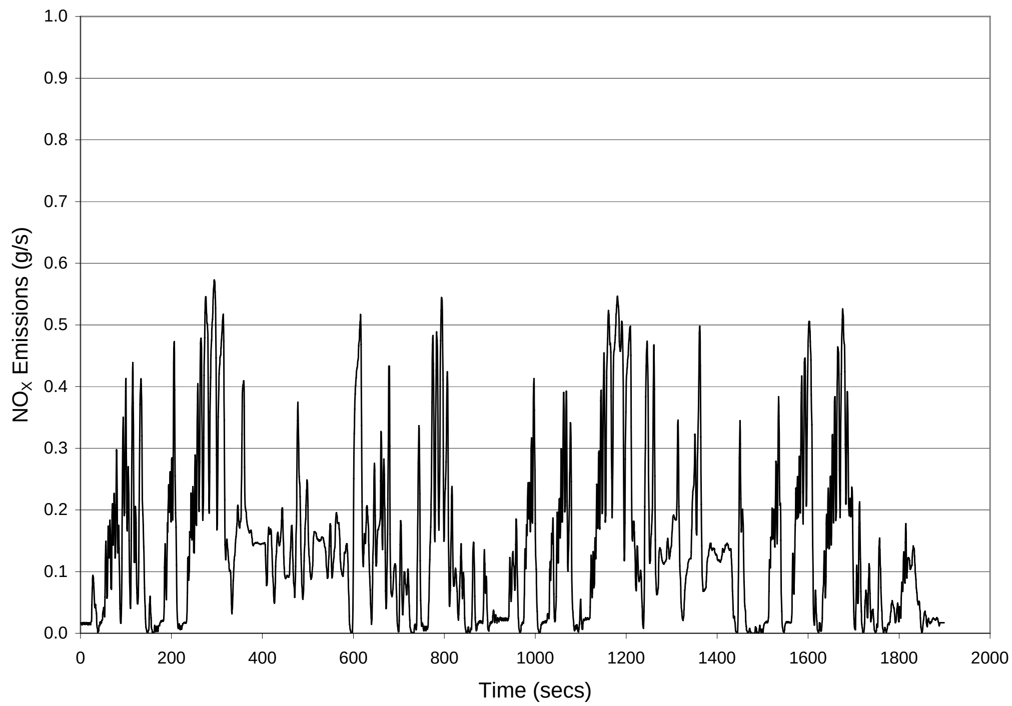
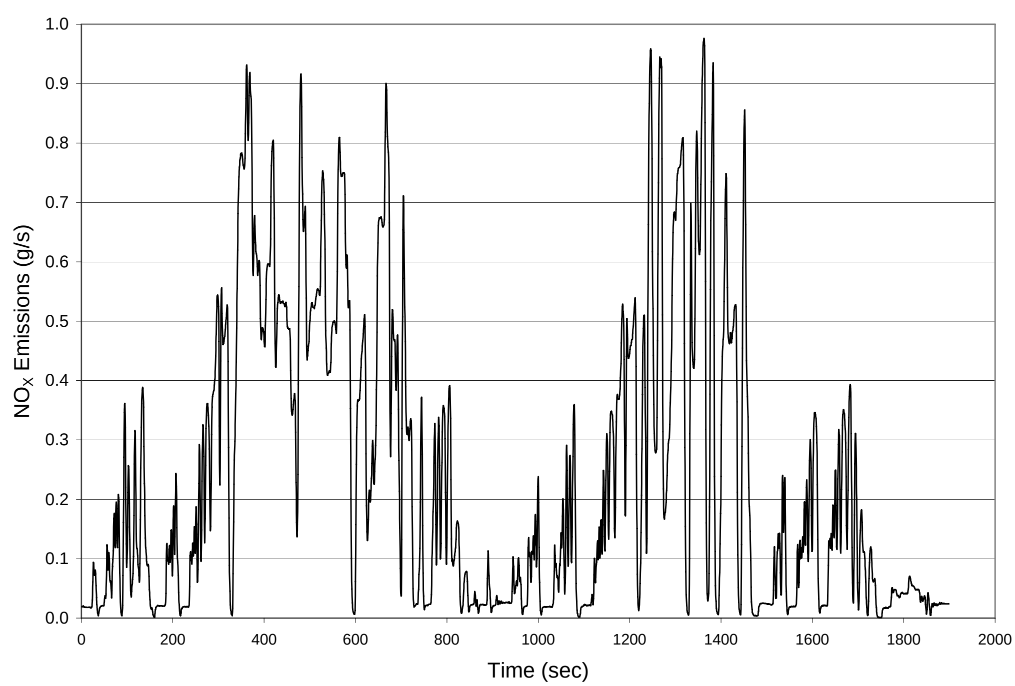


Figure 6.27 Continuous NO_X emissions in g/s for the Test Vehicle 1 on dual map over the Inventory Highway Cycle (IHC) at 56,000 lbs.



It is evident from Figures 6.26 and 6.27 that NO_X emissions are higher on the dual map due to the effect of "off-cycle" operation. Figures 6.28 and 6.29 below show the plots of NO_X versus power for these two cases. The off-cycle emissions in the dual map can be seen as the upper "arm" in the bifurcated data (Figure 6.29).

Figure 6.28 Plot of NO_X vs. power for the Test Vehicle 1 (56,000 lbs.) on the single map (low NO_X) over the Inventory Highway Cycle (IHC). No "off-cycle" emissions are evident.

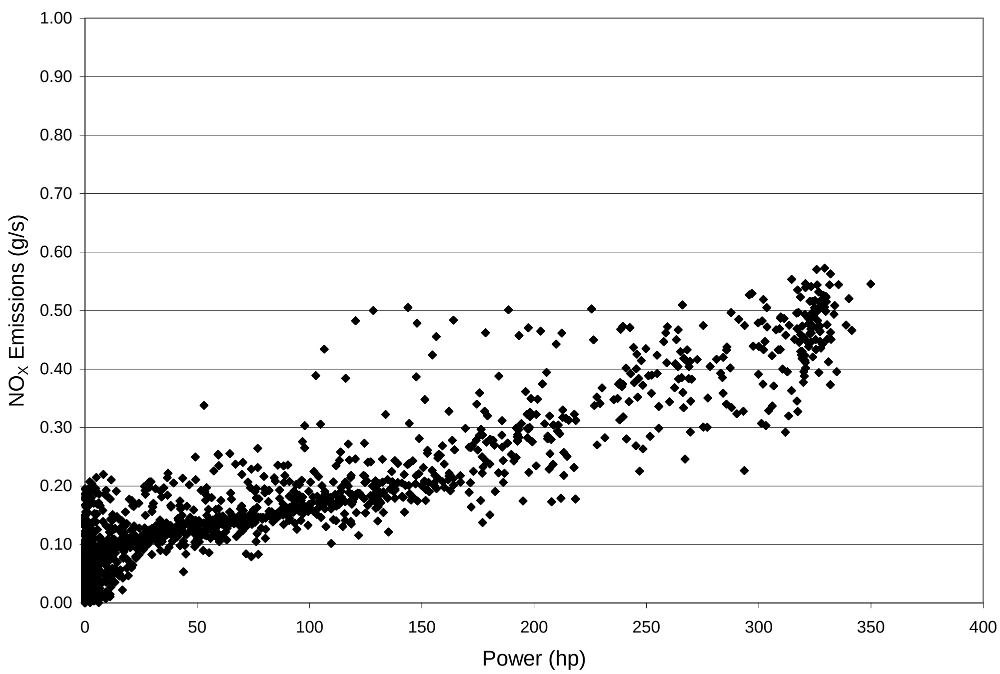
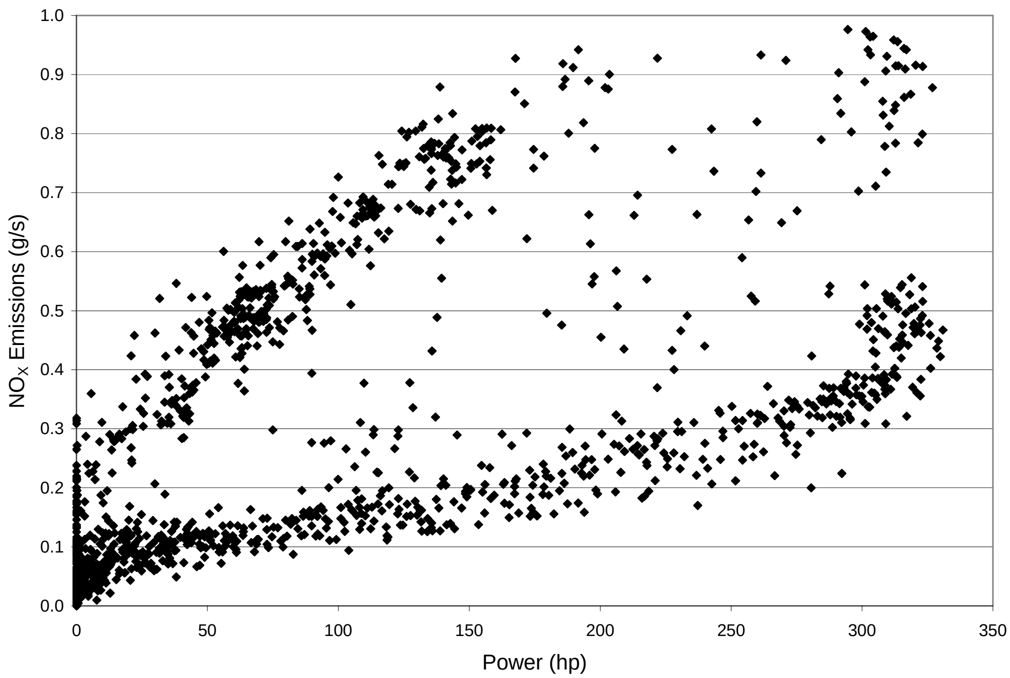


Figure 6.29 Plot of NO_X vs. power for the Test Vehicle 1 (56,000 lbs.) on the dual map (high NO_X) over the Inventory Highway Cycle (IHC). The "off-cycle" emissions are shown.



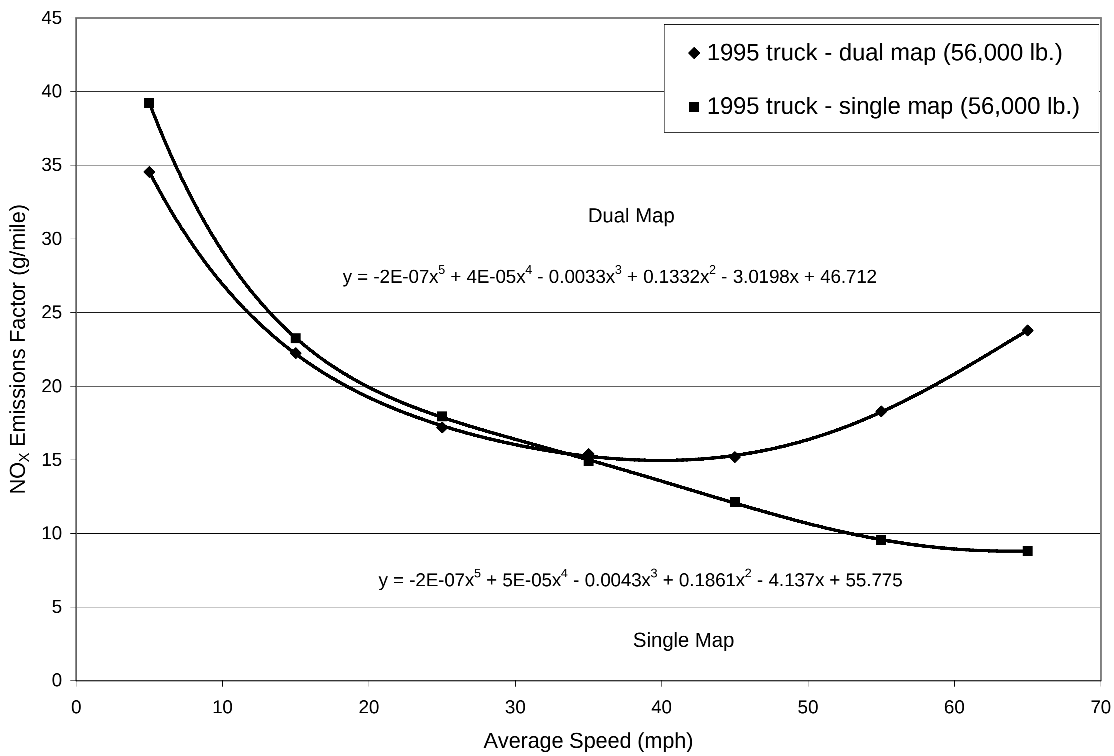
NO_X emissions factors as a function of average speed class for the Test Vehicle 1 is presented for the single and dual map operation at a test weight of 56,000 lbs. in Table 6.6. These values are also presented in Table 5.39 in Chapter 5.

Table 6.6 Variation of NO_X emissions factor in grams/mile with average speed class for Test Vehicle 1.

			Average Speed Bin in mph				
Test details	0-10	10-20	20-30	30-40	40-50	50-60	60-70
Rural							
1995 truck - 56000 lbs. Dual Map	34.55	22.24	17.20	15.40	15.18	18.30	23.79
1995 truck - 56000 lbs. Single Map	39.24	23.25	17.95	14.92	12.12	9.56	8.82
Urban							
1995 truck - 56000 lbs. Dual Map	36.22	26.54	21.43	15.23	13.65	18.31	22.77
1995 truck - 56000 lbs. Single Map	41.79	28.74	23.29	16.53	11.66	9.14	8.61

As can be seen in Table 6.6, the NO_X emissions increase in the dual map for speeds above 40 mph for both Rural and Urban modes. Using Table 6.6, NO_X emissions for a 1995 truck at a specific average speed can be predicted with and without off-cycle operation. For example consider the rural mode if we plot the NO_X emissions factors against the average speed class, as in Figure 6.30. A curve fit can be obtained for the data, and the equation obtained from the curve fit can be used to estimate the NO_X emissions factor for any average speed value. It is clear from Figure 6.30 that the dual and single map curves deviate after an average speed of approximately 35 mph.

Figure 6.30 Plot of NO_X emissions factor with average speed class for Test Vehicle 1 in dual and single maps for the rural mode of operation.



Using the equations shown in Figure 6.30, for an average speed of 58.3 mph, the NO_X emissions for a 1995 truck will be estimated to be 19.87 g/mile in dual map (with off-cycle) and 9.13 g/mile in single map (without off-cycle). For the same average speed, NO_X emissions with off-cycle are more than twice the value of NO_X emissions without off-cycle.

The NO_X emissions value with off-cycle and without off-cycle, and the ratio of NO_X emissions with and without off-cycle are tabulated in Table 6.7 for a range of average speed values chosen arbitrarily. The NO_X emissions values were estimated using the equations from Figure 6.30. It is clear that the NO_X emissions ratio between dual and single maps increase with increasing speed. Higher average speed means longer periods of operation in the high-speed region and hence, higher off-cycle emission values. With knowledge of amount of time spent by a truck in different average speed class, one can estimate the total NO_X emissions for that vehicle which may include both dual and single map operation.

Table 6.7 Variation of NO_X emissions in g/mile and ratio of NO_X emissions with and without off-cycle for different average speed values.

Average Speed (mph)	NO_X (g/mile) emissions with off-cycle	NO_X (g/mile) emissions without off-cycle	Ratio of NO_X withoff-cycle/without off-cycle
5	39.23	39.23	1.00
10	29.15	29.15	1.00
15	23.28	23.28	1.00
20	19.92	19.92	1.00
25	17.89	17.89	1.00
30	16.39	16.39	1.00
35	15.00	15.00	1.00
40	14.96	13.55	1.10
45	15.30	12.06	1.27
50	16.38	10.67	1.53
55	18.25	9.58	1.90
60	20.83	8.94	2.33
65	23.80	8.81	2.70

Figure 6.31 shows the variation of the ratio between NO_X emissions with off-cycle and NO_X emissions without off-cycle operation as a function of average speed. Figure 6.25 was plotted using the data presented in Table 6.7. A 6^{th} degree polynomial curve was fitted to the data and the resulting equation obtained is presented in the Figure 6.31. Now this equation can be used to predict the NO_X emissions for the Test Vehicle 1 without off-cycle operation if the

emissions values are known for that vehicle with off-cycle operation or vice versa. Table 6.8 presents the actual and predicted NO_X emissions for Test Vehicle 1 without off-cycle operation using the ratio presented in Table 6.7 and the actual measured NO_X emissions for the vehicle with off-cycle operation.

Figure 6.31 Variation of ratio of NO_X emissions with and without off-cycle operation as a function of average speed.

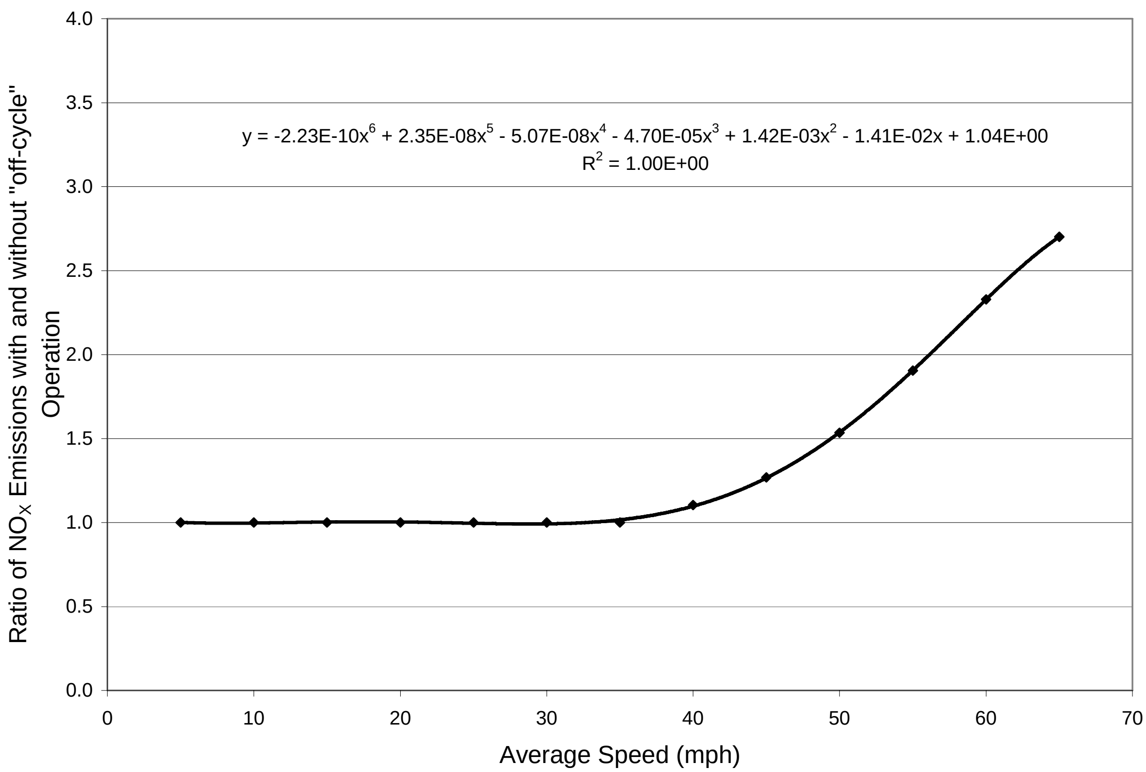


Table 6.8 Actual and Predicted NO_X emissions in g/mile for dual map (with off-cycle) operation for the Test Vehicle 1.

Average Speed (mph)	Measured NO_X Emissions with Off-Cycle (g/mile)	Predicted Ratio of NO_X Emissions with and without Off-Cycle (g/mile)	Predicted NO_X Emissions with Off-Cycle (g/mile)	Percentage Difference between Predicted and Actual NO_X Emissions with Off-Cycle
5	34.55	1.00	39.26	**13.66**
15	22.24	1.00	23.32	**4.87**
25	17.20	1.00	17.87	**3.91**
35	15.40	1.02	15.16	**-1.55**
45	15.18	1.27	15.34	**1.01**
55	18.30	1.91	18.22	**-0.45**
65	23.79	2.70	23.81	**0.09**

Off-cycle injection timing strategies have a significant effect on the NO_X emissions. Off-cycle emissions are evident at higher speeds typical of freeway speeds. Results show that the test vehicle entered off-cycle mode after a speed of a little over 35 mph. There is an increase in NO_X emissions with increase in the speed. This variation of NO_X emissions with speed is not linear. For an average speed of 45.8 mph the ratio between NO_X emissions with off-cycle and NO_X emissions without off-cycle was 1.3. For an average speed of 65 mph, this ratio was found to be 2.7. The approach proposed in this dissertation can be used to predict the off-cycle emissions from heavy-duty trucks. One must remember, however, that the results presented were obtained from a single truck on three different test runs and two driving cycles. Accuracy of prediction can be improved with additional data from many trucks tested over a wide range of test schedules covering a range of model year groups.

7 Conclusions and Recommendations for Future Research

7.1 Conclusions

Prediction of heavy-duty diesel vehicle emissions inventory is substantially less mature than the prediction of gasoline passenger car emissions. Diesel vehicles are now receiving great attention, because they are acknowledged to be significant contributors to the atmospheric inventory of PM and NO_X. Heavy-duty diesel vehicle emissions are affected by a wide variety of factors and there is a need for thorough understanding of various factors that affect emissions and to develop methodology to accurately predict heavy-duty diesel vehicle emissions for inventory purpose.

Various factors that affect heavy-duty diesel vehicle emissions were studied in detail to understand the extent to which they affect emissions. Different emissions prediction methodology were reviewed and speed-acceleration based emissions prediction methodology was analyzed in detail and presented as an emissions predictive tool.

To address the lack of high-speed emissions data additional data were acquired using a high-speed chassis dynamometer cycle that was developed as a part of this dissertation. A large body of data was analyzed in great detail and a suite of emissions factors tables were produced to be used with the emissions predicting approach proposed.

The speed-acceleration based emissions prediction model predicts the emission values with reasonable accuracy. It was found that cycle-to-cycle variations could be minimized if a large set of data is used to generate the emissions factors tables. A technique was also developed to smooth and extrapolate the emissions factors tables to fill in unpopulated cells and minimize any anomalies observed in the emissions factors tables.

With the initial data that was gathered by conducting tests on two over the road tractor trucks, the speed-acceleration based emissions method enabled prediction of NO_X emissions fairly well even though there was some over prediction in some cases. NO_X emissions were predicted for a 1995 model year vehicle within 15% error in rural mode and under 6% error for urban mode. It was found that the speed-acceleration model could predict the NO_X emissions fairly well for the CSHVR cycle on the rural operation. The model also predicts fairly well on both the cycles for the 1995 truck on single map and the 1982 model year vehicle, which does not have the capability to operate on the dual map (off-cycle mode). It is clear that the off-cycle operation has a profound effect on the emissions, especially for a high average speed typical of freeway operation. The accuracy of the model improved with the inclusion of additional data available form different studies.

Analysis of additional data resulted in a suite of emissions factor tables in g/mile covering a wide range of model year groups. The vehicle model year was found to have a significant effect on the emissions. From a deeper analysis of the second-by second raw data, it was found that gearshift could affect the emissions factors tables to some extent. Careful analysis is necessary in generating the emissions factors tables.

When the emissions factors obtained for the 1994-97 model year group was used to predict the NO_X emissions for the two test vehicles, the percentage error was within 3% for both rural and urban operation. For the CSHVR, the rural mode prediction was within 10%. However, the urban mode value was over predicted by 25%. This could be due to the presence of some “off-cycle” operation in the data used to generate the emissions factors table. This shows that the model can predict the NO_X emissions for any truck fairly accurately using the emissions factors tables presented for different model year groups.

When the model was used to self-predict for a special case (1974-78 model year group), It was found that the model predicts the NO_X emissions fairly well for all the cycles except for the cruise part of CARB hddt cycle, which has an average speed of about 40 mph. It can also be seen that for lower average speeds, the urban prediction is better than the rural as would be expected because the low average speeds typically represent urban stop and go driving pattern.

The speed-acceleration approach was compared with CARB's EMFAC 2002 model. It was found from the analysis that the shape of speed correction factors for NO_X emissions employed by EMFAC is not supported by the results. EMFAC showed that the speed correction factor increased both at lower and higher than 35 mph.

When compared with ANN, the proposed approach did fairly well in predicting the NO_X emissions from a single truck that was driven on 16 different test schedules. Eleven out of the total sixteen predictions by the speed-acceleration method were within a 10% error band. ANN did very well with self-prediction, but under predicted when trained on Yard cycle and consistently over predicted when trained on the FIGE and CBD cycles respectively

Heavy-duty diesel vehicle emissions are affected by many parameters such as the vehicle weight, driving cycle, injection timing strategy, vehicle age and terrain effects. It was found that vehicle weight had a profound effect on NO_X emissions. There was a nearly linear relationship between NO_X and vehicle weight. In general for every X% increase in vehicle weight, there was a X/2% increase in NO_X emissions. This conclusion was also supported by the theoretical analysis performed to understand the weight effects. NO_X emissions were insensitive to the transients. However, PM and CO emissions were affected very much by transients. Using the theoretical approach, it was found that transients could emphasize the weight effects for NO_X emissions. As an example, for Test-D cycle with an average speed of 18.9 mph, the ratio of NO_X

emissions at 30,000 lb to that at 80,000 lb was found to be 1.79. If the same truck were operated at steady state speed of 18.9 mph, the ratio would be 1.56, a 15% increase.

The experimental results correlated well with the theoretical approach on vehicle weight effects. It was found that the ratio of NO_X emissions at two different weights, varied significantly with the average speed. The trend in the variation of NO_X emissions ratio with average speed was also affected by the model year group to a great extent. For a 1994 truck that was tested at three different weights, doubling of the vehicle weight increased NO_X emissions by 54%.

Driving schedule was found to have significant effect on the emissions. The Speed-acceleration model under predicted the NO_X emissions for the NYBUS cycle and the YARD cycle. These two cycles have average speeds of 3.7 and 3.3 mph respectively and represent typical urban stop-and-go operation.

The speed-acceleration based emissions prediction methodology was found to predict the emissions with reasonable accuracy. The method showed better prediction for NO_X than any other emission species. CO and hence PM are hard to model as they are very strong function of the transients. HC emissions are very low in diesel engines and they exhibit erratic behavior.

Off-cycle emissions resulting from injection timing control strategy affected NO_X emissions. The effect was profound during highway speed operation exceeding 35 mph. NO_X emissions almost doubled when the same vehicle was operated in the dual map (high NO_X mode) as opposed to single map (low NO_X mode).

Using the equations obtained from a theoretical approach discussed in Chapter 6, considering an average speed of 58.3 mph, the NO_X emissions for a 1995 truck was estimated to be 19.87 g/mile in dual map (with off-cycle) and 9.13 g/mile in single map (without off-cycle). For the same average speed, NO_X emissions with off-cycle are more than twice the value of NO_X

emissions without off-cycle. Off-cycle emissions were not evident up to a speed of around 35 – 40 mph.

The proposed speed-acceleration approach was found to be promising in developing emissions factors for heavy-duty diesel vehicles for emissions predictions for inventory purpose.

7.2 Recommendations for Future Research

Effect of vehicle operating weights on emissions needs further research. Comprehensive testing of heavy-duty vehicles on chassis dynamometer at various test weights would help understand the extent to which the emissions are affected by vehicle weight.

The accuracy of the speed-acceleration model can be greatly improved if emissions data were available for a large number of different vehicles covering wide range of model year groups, vehicle weight and test schedules. The E-55/59 and Gasoline/Diesel PM Split studies undergone at WVU are producing those data for future analysis.

Off-cycle operation has a significant effect on NO_X emissions. Collection of emissions data for many trucks that are capable of operating without off-cycle operation (single map) will enable to improve the accuracy of the speed-acceleration model for predicting off-cycle emissions.

Some anomalies present in the emissions factors tables were attributed to the gearshift effect. Even though these anomalies were dealt with smoothing of the emissions factors tables, a detailed study of effect of gearshift on emissions would greatly improve the emissions factors development.

7.3 Publications based on Present Research

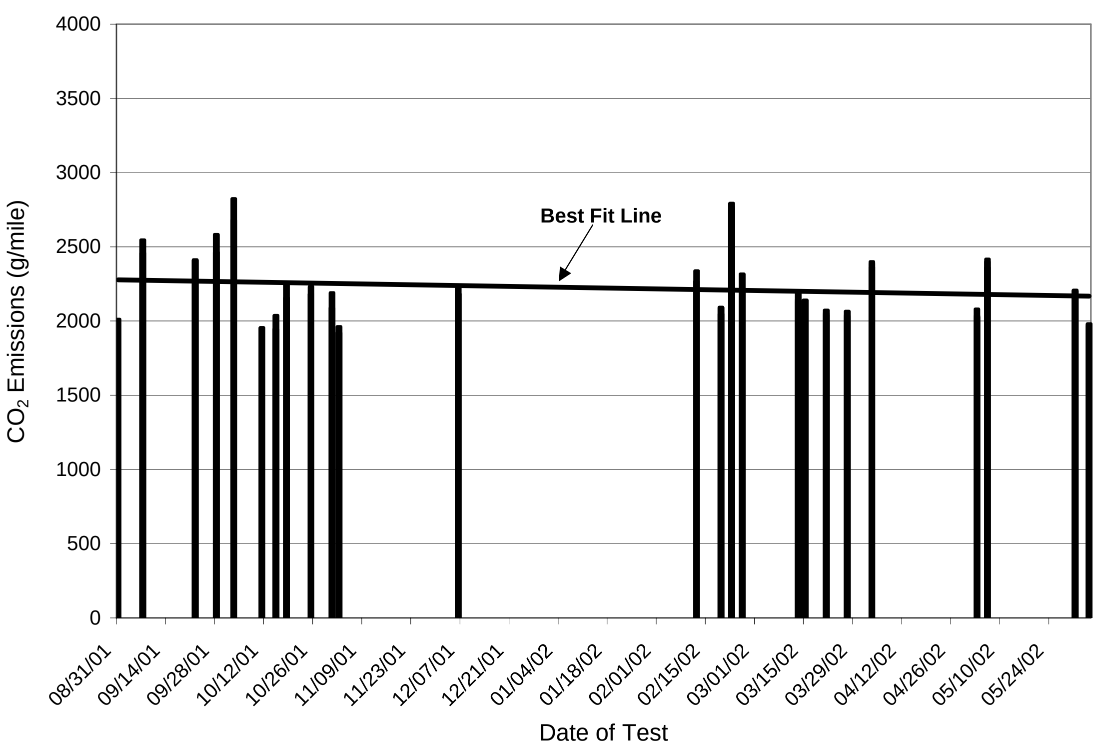
A paper titled "A predictive Tool for Emissions from Heavy-Duty Diesel Vehicles" has been published in Environmental Science & Technology, 2003, 37(1), pg 7-15.

A paper titled "Effect of Truck Operating Weight on Heavy-Duty Diesel Emissions" has been published in Environmental Science and Technology, 2003, 37(18), pg 4309-4317.

Appendix A Error Analysis of Translab

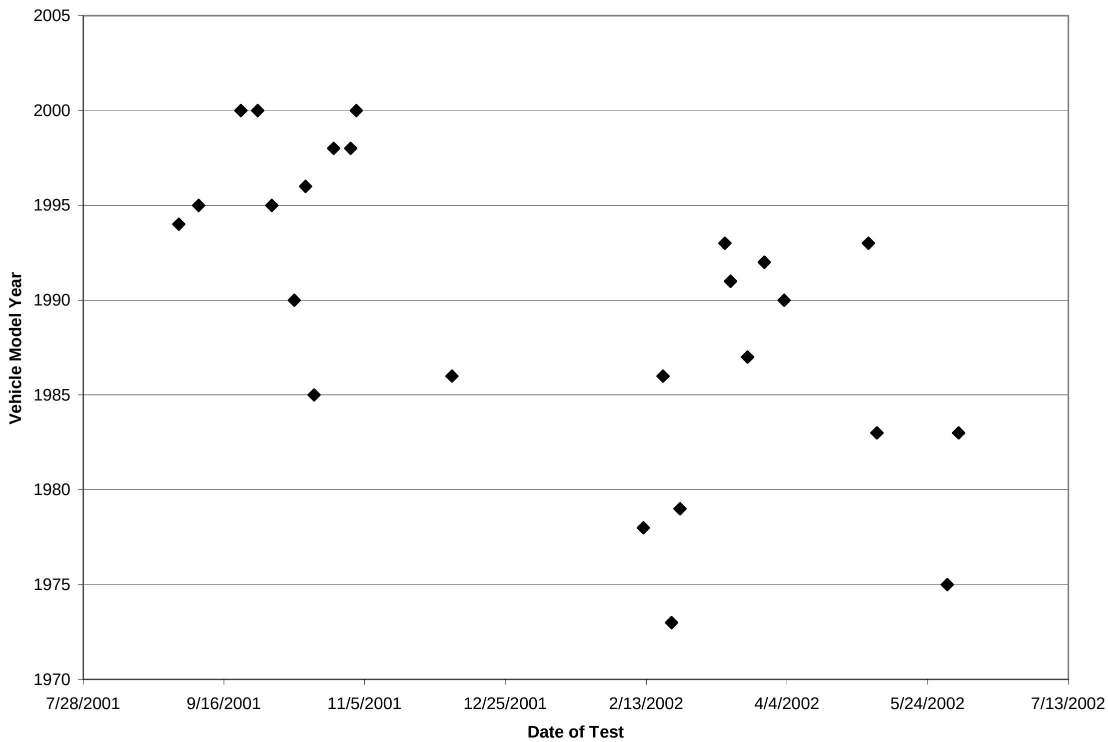
A good way to understand if there is any systematic drift over time is to plot the repeat data for a single vehicle over time. Unfortunately such data were not available in the existing database. However, data were available for 25 different vehicles as a part of the CRC E55 study (discussed in Chapter 4). These vehicles were tested over a period of 11 months. Figure A.1 shows the plot of CO_2 emissions in grams/mile as a function of test date for these 25 vehicles tested over UDDS cycle.

Figure A.1 Variation of CO_2 emissions with UDDSate for 25 Class 8 trucks tested on UDDS cycle at a test weight of 56,000 lbs,. A best fit curve is also plotted for these data.



It can be seen from Figure A.1 that there is a slight downward drift in the best-fit trend line. Figure A.2 shows the model year distribution of the 25 vehicles as a function of test date. The best-fit line shows a 5.15% drop in CO_2 emissions over a period of 11 months. This variation is well within the day to day variation, which may arise due to test conditions and atmospheric conditions. In addition, trucks recruiting may have been biased with respect to model year over time, provoking a fuel economy trend.

Figure A.2 Model year distribution of the 25 class 8 trucks tested on UDDS cycle at a test weight of 56,000 lbs,.



References

ARB, "Proposed Identification of Diesel Exhaust as a Toxic Air Contaminant," Report by the staff of the California Air Resources Board and the Office of Environmental Health Hazard Assessment, April 22, 1998.

ARB, "Mobile Sources Emission Inventory Program," http://www.arb.ca.gov/msei.html, accessed September 2002.

ARB, http://www.arb.ca.gov/msei/msei.htm, accessed November 19, 2004.

Atkinson, C. .M., Clark, N. N., Long, T. L., and Hanzevack, E. L., "Neural Network based Vehicle Emissions Modeling for Inventory Applications – An Update on Virtual Sensing," Eighth CRC On-Road Vehicle Emissions Workshop, San Diego, CA, April 1998.

Battelle,"Heavy-Duty Truck Activity Data," final report prepared for Office of Highway Information Management, Office of Technology Applications, Federal Highway Administration, Washington, D.C. 20590, by Battelle Memorial Institute, Columbus, OH 43201, April 30, 1999.

Barth, M., An, F., Younglove, T., Scora, G., and Levine, C., "Development of a Comprehensive Modal Emissions Model: Final Report," Prepared for National Cooperative Highway Research Program under NCHRP Project 25-11, April 2000.

Butler, J. W., Kornisk, T. J., Reading, A. R., and Kotenko, T. L., "Dynamometer Quality Data On-board Vehicles for Real-World Emission Measurements," Proceedings of the Ninth CRC On-Road Vehicle Workshop, San Diego, CA, April 19-21 1999.

Clark, N. N., McKain, D. L., Messer J. T., and Lyons, D. W., "Chassis Test Cycles for Assessing Emissions from Heavy Duty Trucks," SAE Paper 941946, 1994.

Clark, N. N., and McKain, D. L., "Transient Chassis Cycles for Heavy Duty Trucks and Tractors," Int. Jour. of Vehicle Design (Heavy Vehicle Systems), Vol.2, pg.143-159, 1995.

Clark, N. N., Messer D. J., McKain, D. L., Wang, W. G., Bata, R. M., Gautam, M., and Lyons D.W., "Use of the West Virginia University Truck Test Cycle to Evaluate Emissions from Class 8 Trucks," SAE Paper 951016, 1995.

Clark, N. N., Lyons, D. W., Bata, R. M., Gautam, M., Wang, W. G., Norton, P., and Chandler, K., "Natural Gas and Diesel TB Emissions: Review and Recent Data," SAE Paper 973203, 1997.

Clark, N. N., Nine, R. D., Daley, J. J., Atkinson, C. M., Tennant, C. J., and Lyons, D. W., "Heavy Duty Truck Emissions: Vehicle Activity, Driving Routes, and NO/NO_2 Ratios," Proceedings of Eighth CRC On-Road Vehicle Emissions Workshop, San Diego, CA, April 20-22, 1998.

Clark, N. N., Atkinson, C. M., Thompson, G. J., and Nine, R. D., "Transient Emissions Comparisons of Alternative Compression Ignition Fuels," SAE Paper 1999-01-1117, 1999.

Clark, N. N., Daley, J. J., Nine R. D., and Atkinson C. M., "Application of the New City-Suburban Heavy Vehicle Route (CSHVR) to Truck Emissions Characterization," SAE Paper 1999-01-1467, 1999.

Clark, N. N., Jarrett R. J., and Atkinson C. M., "Field Measurements of Particulate Matter Emissions, Carbon Monoxide, and Exhaust Opacity from Heavy-Duty Diesel Vehicles," Journal of the Air & Waste Management Assoc: Vol. 107, pg. 84-93, 1999.

Clark, N. N., Azadeh Tehranian., Jarret R. P., and Nine R. D., "Translation of Distance-Specific Emissions rates between Different Heavy Duty Vehicle Chassis Test Schedules," SAE Paper 2002-01-1754, 2002.

Clark, N. N., Kern J. M., Atkinson C. M., and Nine R. D., "Factors Affecting Heavy-Duty Diesel Vehicle Emissions," Journal of the Air & Waste Management Association, Vol. 52. pg 174-185, January 2002.

Code of Federal Regulations, "Protection of the Environment," Title 40, Part 86, Subpart N, U.S. Government Printing Office, 1996.

Code of Federal Regulations, Title 40, Part 86, Subpart N, 1998.

"COPERT," http://vergina.eng.auth.gr/mech/lat/copert/copert.htm, accessed January 2003.

Dementhon, J. B., "Influence of Various Diesel Traps on Particulate Size Distribution," SAE Paper 97299, 1997.

DETR, "Transport Statistics Bulletin- Road Traffic Statistics: 1999," United Kingdom Department of Environment, Transport and the Regions (DETR), London, UK, SB (00) 20 August 2000.

Dieselnet, "Diesel Particle Size Distribution," http://www.dieselnetcom/tech/dpm_size.html, accessed April 2000.

Dieselnet, "Diesel Emission Inventory," http://www.dieselnetcom/tech/env_inv.html, accessed September 2002.

Dieselnet, "Heavy-duty Truck and Bus Engines," http://www.dieselnetcom/standards/us/hd.html, accessed September 2002.

Dietzman, H. E., and Warner-Selph, M. A., "Comparison of Emissions from Heavy-duty Engines and Vehicles During Transient Operation," Energy Sources and Technology Conference, Dallas, TX, ASME Paper 85-DGP-10, 1985.

EPA, “Heavy-duty Vehicle Cycle development,” Environmental Protection Agency, Office of Air and Waste management, Office of Mobile Source Air Pollution Control, Emission Control Technology Division, Ann Arbor, Michigan, EPA-460/3-78-008, 1978.

EPA Document, “Emissions Standards reference Guide for Heavy-Duty and Nonroad Engines,” Report EPA 420-F-97-014, 1997.

EPA, “Development and Use of heavy-Duty Defeat Device Emission Effects for Mobile5 AND Mobile6,” EPA Report Number M6.HDE.003, EPA420-P-99-030, October 1999.

EPA, “National Air Quality and Emissions Trends Report, 1999,” U. S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Report EPA 454/R-01-004, March 2001.

EPA, “National Air Quality and Emissions Trends Report,” U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Report EPA 454/R-01-004, March 2001.

EPA, “EPA’s New Generation Mobile Source Emissions Model: Initial EPA, Proposal and Issues,” Report EPA420-R-01-007. Office of Air and Radiation, Ann Arbor, MI, April 2001.

EPA, "EPA's Plan for MOVES: A Comprehensive Mobile Source Emissions Model,” presented at the CRC On-Road Vehicle Emissions Workshop, San Diego, April 2002.

EPA, "Methodology For Developing Modal Emission Rates For EPA's Multi-Scale Motor Vehicle & Equipment Emission System,” produced by North Carolina State University EPA420-R-02-027, August 31, 2002.

EPA, "Mobile Source Observation Data (MSOD) Database Update, Interim Report,” produced by Eastern Research Group, EPA420-R-02-033, October 31, 2002.

Fuel Economy Measurement Test (Engineering Type) for Trucks and Buses - SAE J1376, SAE Handbook, Vol. 4, 1993.

Gamo, O. S., Ouladrine, M., and Rachid, A., “Diesel Engine Exhaust Emissions Modeling using Artificial Neural Networks,” SAE Paper 1999-01-1163, 1999.

Ganesan, B., and Clark, N. N., “Relationships Between Instantaneous and Measured Emissions in Heavy Duty Applications,” SAE Paper 2001-01-3536, 2001.

Graboski, M. S., Ross, J. D., and McCormick, R. L., “Transient Emissions from No. 2 Diesel and Biodiesel Blends in a DDC Series 60 Engine,” SAE Paper 961166, 1996.

Graboski, M. S., McCormick, R. L., Yanowitz, J., and Ryan, L., “Heavy-Duty Diesel Vehicle Testing for the Northern Front Range Air Quality Study,” Fort Collins, CO, February 1998.

Hackman, J. D., Hassel, R., Joumard, Z., and Sorenson, S., "Methodology for Calculating Transport Emissions and Energy Consumption," TRL Report PR/SE/491/98, Crowthorne, U.K., 362 p., and European Commission, DG VII, ISBN 92-828-6785-4, Luxembourg, 362 p.

Harris, D. B., King, F., Brown, J. E., Nine, R. D., Clark, N. N., and Kopasko, J., "Comparison of On-Road and Chassis Dynamometer Emissions Results," Seventh CRC On-Road Vehicle Emissions Workshop, San Diego, pg.. 5-93 to 5-111, April 1997.

Health Effects Institute, "Diesel Exhaust: A Critical Analysis of Emissions, Exposure, and Health Effects," April 1995.

Japar, S. M., "Motor Vehicles and Particle Air Pollution: an Overview," Particulate Matter: Health and Regulatory Issues, VIP. 49, Air & Waste Management Association, Proceedings of an International Specialty Conference, Pittsburgh, PA, pg. 577-599, April 4-6 1995.

Johnson V. T., "Diesel Emission Control – Last 12 Months in Review," SAE Paper 2000-01-2817, 2000.

Kihara, N., Tsukamoto, T., Matsumoto, K., Ishida, K., Kon, M., and Murase, T., "Real-Time On-Board Measurement of Mass Emission of NO_X, Fuel Consumption, Road Load, and Engine Output for Diesel Vehicles," SAE Paper 2000-01-1141, 2000.

Krijnsen H. C., Van Kooten, W. E. J., Calis, H. P. A., Verbeek, R. P., and Vanden Bleek, C. M., "Evaluation of an Artificial Neural Network for NO_X Emission Prediction from a Transient Diesel Engine as a Base for NO_X Control," Canadian Journal of Chemical Engineering, pg. 408-417, April 2000.

Kwan, S., Parker D., and Nolan K., "Effectiveness of Engine Calibration Techniques to reduce Off-Cycle Emissions," SAE Paper 971602, 1997.

Long, T. R., "Design and Construction of a Transportable Heavy-duty Vehicle Emission Testing Laboratory," Annual Automotive Technology Development Contractors' Coordination Meeting, Dearborn, MI, Oct. SAE Special Publication P-256, 1991.

Lloyd, A. C., and Cackette, T. A., "Diesel Engines: Environmental Impact and Control," Journal of Air & Waste Management Association, Vol. 51, pg. 809-847, 2001.

Lyons, D., Bata, R., Wang, W., Clark, N., Palmer, M., Gautam, M., Howell, A., Loth, J., and Long Jr., T., "Design and Construction of a Transportable Heavy Duty Vehicle Emission Testing Laboratory," Annual Automotive Technology Development Contractors' Coordination Meeting, Dearborn, MI, pg.. 593-598, SAE P-256, October 28-31 1991.

Machiele, P. A., "Heavy-Duty Vehicle Emissions Conversion Factors II," EPA-AA-SDSB-89-01, October 1988.

McKain, D. L., Clark N. N., McDaniel T. I., and Hoppie, J., "Chassis Test Cycle Development for Engine Test Compliance on Heavy Duty Engines," SAE International Congress, Detroit, SAE Paper 980407, February 1998.

Nine, R. D., Clark, N. N, Norton, P., "Effect on Emissions of Multiple Driving Test Schedules Performed on Two Heavy-Duty Vehicles," SAE Paper 2000-01-2818, 2000.

Ntziachristos, L., and Samaras, Z., "Computer Programme to Calculate Emissions from Road Transport - Methodology and Emission Factors (Version 2.1)," COPERT III, European Topic Centre on Air Emissions, European Environment Agency, November 2000.

Okrent, D. A., "Optimization of a Third Generation TEOM Monitor for Measuring Diesel Particulate in Real-Time," SAE Paper 980409, 1998.

Perkins, G. C. H., "Analytical Process to Develop a Local Truck Driving cycle," SAE Paper 821256, 1982.

Quenou Gamo, S., Ouladsine M., Rachid, A., "Diesel Engine Exhaust Emissions Modeling Using Artificial Neural Networks," SAE Paper 1999-01-0163, 1999.

Ramamurthy, R., Clark, N. N, Atkinson, C. M., and Lyons, D. W, "Models for Predicting Transient Heavy-Duty Vehicle Emissions," SAE Paper 982652, 1998.

Ramamurthy, R., and Clark, N. N., "Atmospheric Inventory Data for Heavy-Duty Vehicles," Environmental Science &Technology, Vol. 33 pg. 55-62, 1999.

Tehranian, Azadeh., "Effects of Artificial Neural Networks Characterization on Prediction of Diesel Engine Emissions," Master's Thesis, West Virginia University, 2003.

Thompson, G. J., Atkinson, C. M., Clark, N. N., Long, T. W., and Hanzevack, E., "Neural Network Modelling of the Emissions and Performance of a Heavy-Duty Diesel Engine," Proc Instn Mech Engrs, Vol. 214, Part D, No. D04499, 2000.

Walsh, M. P., "Global Trends in Diesel Emissions Control – A 1999 Update," SAE Paper 1999-01-0107, 1999.

Wang, W., Sun, X., Bata, R., Gautam, M., Clark, N. N., Palmer, M., and Lyons, D., "Emissions Comparisons of Twenty-Six Heavy Duty Vehicles Operated on Conventional and Alternative Fuels," International Truck and Bus Meeting and Exposition, Detroit, MI, November 1-4, SAE Paper 932952, 1993.

Weinblatt, H., Dulla, R. G., and Clark, N. N., "A Vehicle Activity Based Procedure for Estimating Emissions of Heavy-Duty Vehicles," Transportation Research Board Meeting, Hilton Energy and Environmental Analysis, Poster Session 309 (03-3962), January 13, 2003.

Watson, H. C., Milkins, E. E., Preston, M. O., Chittleborough, C., and Alimoradian, B., "Predicting Fuel Consumption and Emissions—Transferring Chassis Dynamometer Results to Real World Driving Conditions," SAE Paper 830435, 1983.

Yanowitz, J., McCormick, R. L., and Graboski, M. S., "In Use Emissions from Heavy-Duty Diesel Vehicles" Environmental Science & Technology, Vol. 34, pg. 729-740, 2000.