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Inventory and Prediction of Heavy-Duty Diesel Vehicle Emissions

By

Justin M. Kern

A THESIS

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in
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ABSTRACT

INVENTORY AND PREDICTION OF HEAVY-DUTY DIESEL VEHICLE EMISSIONS

By Justin M. Kern

A vehicle emissions inventory is an account of emissions produced by all vehicles in an area. Many different factors can affect the emissions and the measurement of the emissions that are used to create an emissions inventory. These factors for heavy-duty diesel vehicles have been addressed and their relative affect on emissions was evaluated from test data and analytical analyses. These elements can affect the emissions by a factor of 15 depending on testing conditions.

One purpose that an emissions database serves is to provide a source for predicting future emissions for a specific vehicle or many vehicles in a general area. Using a database directly for prediction is ideal, but no comprehensive data set currently exists that covers all of the different vehicle and component combinations that exist in current use. Numerical models can be used to take the existing information about vehicle emissions and calculate the emissions that would be produced by all the vehicles in an inventory. The Transportable Heavy-Duty Vehicle Emissions Testing Laboratories at WVU have collected emissions data from heavy-duty vehicles for approximately 8 years. This existing data were used in an analysis to develop a method that can produce emissions factors in grams per mile for all heavy-duty vehicles from a small database of measured emissions. The method developed categorizes the emissions according to the vehicle speed and acceleration. The WVU emissions data were combined with truck activity data derived by Battelle Memorial Institute to create emissions factors in grams per mile that reflects actual driving patterns. These factors were then compared to measured emissions from the THDVETL and errors were found to be as low as 5%.

Acknowledgements

Many people deserve a lot of thanks and credit for helping me complete this research and thesis. First, I thank Nigel for giving me the opportunity to attend graduate school and for all the help and guidance provided during the course of my stay here. Next, I thank the rest of my committee, Chris Atkinson, Greg Thompson, and Ralph Nine for their help and the time they've devoted to this. Special thanks goes to Ralph for teaching me how the system works, all the technical help, and for being a good friend.

The Los Alamos National Laboratory and the NCHRP research projects are responsible for funding the research that led to this monstrosity and they deserve thanks for that.

Thanks to the mobile lab crew for their efforts in collecting the data used for this research, and thanks to the guys at the ERC for their technical assistance and cynical pessimism.

I couldn't have endured the this ordeal without the support of the friends I've made along the way, and for that I owe a special thanks to John, Dave, Marcus, Steve, Amy and many more I've failed to mention. The heckling and guidance were both appreciated.

My family has provided support in many ways and for that, thank you very much, Mom and Dad especially.

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Nomenclature

AAMA	American Automotive Manufacturers Association
ASAE	American Society of Agriculture Engineers
ASME	American Society of Mechanical Engineers
BD	Biodiesel
BSFC	Brake Specific Fuel Consumption
CARB	California Air Resources Board
CBD	Central Business District
CFR	Code of Federal Regulations
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CRT	Continuously Regenerating Trap
CSHVR	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
F-T Fuel	Fischer-Tropsch Fuel
FTP	Federal Test Procedure
GVW	Gross Vehicle Weight
GVWR	Gross Vehicle Weight Rating
HC	Hydrocarbons
IB	Isobutanol
MG	Moss Gas Fuel
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
NYGTC	New York Garbage Truck Cycle
PART5	EPA’s PM emissions factor program
PM	particulate matter
ppm	parts per million
SAE	Society of Automotive Engineers
SAP	speed - acceleration profile
SOF	soluble organic fraction
TEOM	Tapered Element Oscillating Microbalance
TEST-D	Urban Dynamometer Driving Schedule defined by 40 CFR 86
THDVETL	Transportable Heavy-Duty Vehicle Emissions Testing Laboratory
VMT	vehicle miles traveled
WVU	West Virginia University

1. Introduction

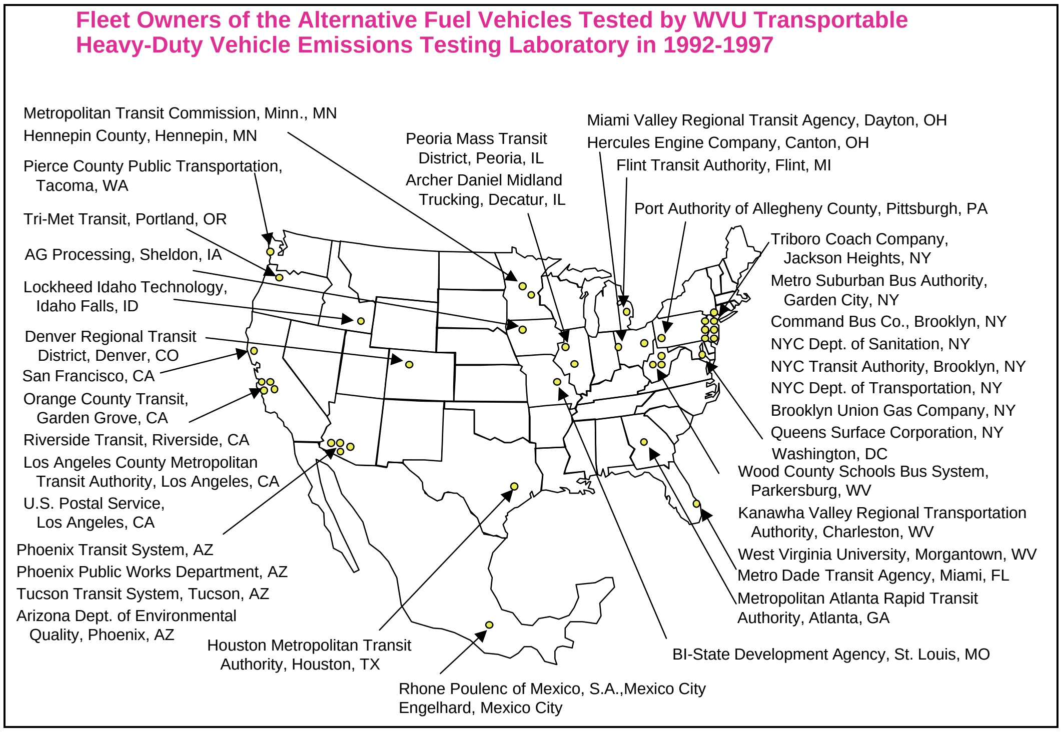
1.1 Exhaust Emissions

Diesel engines are the most efficient internal combustion engine available today and are currently the main power source for heavy-duty on-road and off-road vehicles. Recent concerns about personal and environmental health have brought the subject of exhaust emissions of these vehicles to public awareness. The United States Environmental Protection Agency (EPA) has set regulations limiting the production of certain chemical species that emit from diesel engines. The two species of primary interest are oxides of nitrogen (NO_X) and particulate matter (PM). NO_X contributes to the production of smog in urban areas and PM has been targeted as a carcinogen. Heavy-duty diesel engines are the largest source of diesel PM in the United States. The total diesel PM emissions for 1997 have been estimated by the EPA at 516 thousand tons nationwide. Emissions inventories are employed to gain an accurate estimate of the extent of emissions impact on the environment. Emissions inventories use existing data about different emissions sources, and the existing data for heavy-duty vehicle emissions is not comprehensive, which makes accurate inventories from these mobile sources difficult when limited by this data. A mathematical prediction scheme to predict emissions missing from the measured data replaces comprehensive testing needed to complete an inventory.

1.2 Origin of Data

The heavy-duty vehicle emissions data used in this analysis were acquired using West Virginia University's Transportable Heavy-Duty Vehicle Emissions Testing Laboratories (THDVETL). These two laboratories have collected data across the nation (see Figure 1.1) primarily to gather data on performance of alternately fueled trucks and buses for the U.S. Department of Energy, Office of Transportation Technologies. In doing so, substantial information was gathered from diesel control vehicles. Vehicles were characterized using a variety of driving cycles, including the CBD Cycle, 5-Peak Cycle, 5-Mile Route, NY Bus Cycle and the CSHVR (SAE J1376, Clark et al. 1994, Clark and Lyons 1998, EPA 1978, Clark et al. 1999). A description of the laboratory follows.

Figure 1.1 Map showing data collection sites.



1.3 Technical Description of Laboratory

The two transportable laboratories (THDVETL) are heavy-duty chassis dynamometer systems that can be moved from site to site with a dedicated semi-trailer and a laboratory trailer. These laboratories were constructed with funding from the U.S. Department of Energy, Office of Transportation Technologies, and emissions data gathered by the laboratories are added to a database (http://www.afdc.nrel.gov/web_view/emishdv.html) maintained by the National Renewable Energy Laboratory (NREL), in Golden, Colorado. Using selectable flywheels and air-cooled eddy current power absorbers, both inertia and road load losses, including wind drag and rolling resistance, are simulated by the laboratories. Power is taken directly from the drivewheels of the tested vehicle via hub adapters while the vehicle runs on free-spinning rollers. Hub torque, vehicle speed, engine speed, and gaseous emissions data can be logged continuously during a test through use of a full scale exhaust dilution tunnel, with heated probes and sample lines and analyzers for carbon monoxide (CO), oxides of nitrogen (NO_X) and hydrocarbons (HC). Particulate matter (PM) is determined gravimetrically by collecting the PM on 70mm diameter filters. The two laboratories have previously been correlated with one another, and both laboratories were used to collect data that were used in this analysis.

Figure 1.2 Refuse truck being tested on the WVU THDVETL showing exhaust routed into dilution tunnel inside the analyzer trailer.

Figure 1.3 Transit bus being tested on the WVU THDVETL with flywheels and power absorber in foreground and dilution tunnel atop analyzer trailer at the rear of the bus.

2. Objectives

The objectives of this analysis include identifying the factors, vehicle components, and testing procedures that effect the measured exhaust emissions of heavy-duty vehicles. These observations were made from chassis dynamometer data and were meant to provide guidelines for processing this data into a useful form for emissions prediction. Data comparisons and analytical modeling were used to determine the relative effect of each factor on the measured exhaust emissions. Next, a method to predict emissions for a wide variety of vehicles from the measured data available from the WVU THDVETL was determined. This multidimensional study used the information that was gathered from the previous effort to identify the factors that influenced the measured exhaust emissions. Some verification comparisons of the predictive model were made with the base emissions measured on the chassis dynamometer. The incorporation of representative activity data enabled the prediction method to produce emissions factors in grams per mile suitable for inventory use.

3. Literature Review: Previous Prediction Methods

3.1 Current EPA Heavy-Duty Inventory Method

There are many heavy vehicles used across the country to haul goods (such as tractor trucks), and render services (such as refuse trucks and buses). The majority of these vehicles is powered by diesel-fueled internal combustion engines that produce undesirable exhaust gas emissions. Since 1985 there have been restrictions imposed on these engines by the United States Government to limit the emissions of designated exhaust gas components and limit emissions of particulate matter. To determine the contribution of heavy vehicles to overall loss of atmosphere quality, an emissions inventory is employed. To enable a complete and accurate inventory of mobile emissions, each vehicle would need to be tested for emissions using a test cycle that is typical of its real world use, and have the total vehicle miles traveled (VMT) recorded. This is obviously impractical, so a simplified inventory model is used. The inventory models currently used by the United States EPA and the Air Resources Board of the California EPA (CARB) are titled MOBILE5, PART5, and EMFAC. These computer models use engine emissions certification data and information about vehicle activity to produce an emissions factor for a set of vehicles, usually expressed in grams of emissions per mile traveled (g/mile). The emissions factor is generated by incorporating changes in calendar year, ambient temperature and driving situation, which are then used to determine emissions inventories in various localities. Since heavy-duty engine certification testing provides emissions in terms of grams per brake horsepower-hour (g/bhp-hr), conversion factors of brake horsepower-hour per mile (bhp-hr/mile) are needed to convert the brake-specific emission levels into units of g/mile. This is shown in the following equation.

$$\text{g/mile} = \text{g/bhp-hr} * \text{bhp-hr/mile}$$

The bhp-hr/mile conversion factors are calculated from tabulated brake-specific fuel consumption (BSFC), fuel density (ρ), and fuel economy (FE), because it is difficult to measure bhp-hr/mile directly. These measurable parameters were implemented in the following equation to calculate the conversion factor (CF).

$$\text{CF (bhp-hr/mile)} = \rho \text{ (lb/gal) / BSFC (lb/bhp-hr) / FE (mile/gal)}$$

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 some certain speed, there is a minimum emissions rate and higher or lower speed operation increases the emissions.

To provide a better understanding of the factors affecting heavy vehicle emissions, the parameters that may be used to calculate future inventories need to be evaluated. These parameters include vehicle class, driving test cycle, vehicle vocations, fuel type, engine exhaust aftertreatment, vehicle age, and terrain traveled. In addition, the effects of injection timing strategies on measured emissions are discussed. 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 Other Variations of Heavy-Duty Prediction

Recently, the newest version of EMFAC, CARB's emissions factor software, has been released. The previous method used by this program was very similar to EPA's MOBILE software. This newest version now incorporates some chassis measured emissions factors to scale the engine dynamometer based emissions factors.

3.3 Light-Duty Methods

Light-duty emissions regulations are placed on the vehicle itself rather than the engine, like heavy-duty vehicles. This creates a large database of emissions factors that, combined with in-use vehicle activity data, can produce a complete and accurate inventory. The problems that are addressed in this research for converting measured emissions to an inventory for heavy-duty vehicles are not present in light-duty inventory modeling.

4. Factors Affecting Compression Ignition Engine Emissions

4.1 Vehicle Class

The American Automotive Manufacturers Association (AAMA) classifies trucks from class 1 (light-duty trucks) to class 8 (heavy-duty trucks). A complete listing of vehicle classifications can be seen in Table 4.1 [Merrion, 1994]. For heavy-duty vehicles, emission regulations are imposed on the engine regardless of the size or specific use of the vehicle in which the engine may be installed. The FTP transient test used to establish certification to emissions standards is based upon maximum power, unlike in light-duty applications where the test uses a chassis dynamometer and is affected by road-load power and vehicle weight. Some class 1 and 2 trucks may be emissions certified using the light-duty automotive approach (GVWR < 8500 lbs.). Table 4.2 shows the emission standards for heavy-duty engines from 1985 to 1998. Table 4.3 shows the emission standards for model year 2004 and later heavy-duty diesel engines. Either option of combined non-methane hydrocarbons (NMHC) and NO_X can be used. The standards for CO and PM in 2004 have not been changed from previous years. Following an investigation in 1998, selected heavy-duty diesel engine manufacturers were subject to a consent decree by the EPA requiring the 2004 emissions standards to be met in 2002. Other penalties to the manufacturers were part of this ruling.

Table 4.1 American Automotive Manufacturers Association (AAMA) Vehicle Classifications. [Merrion, 1994]

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

Table 4.2 Heavy-duty engine emission standards [EPA, 1997].

Model Year	HC (g/bhp-hr)	CO (g/bhp-hr)	NOx (g/bhp-hr)	PM (trucks) (g/bhp-hr)	PM (buses) (g/bhp-hr)
1985-1987	1.3	15.5	10.7	No standard	No standard
1988-1989	1.3	15.5	10.7	0.6	0.6
1990	1.3	15.5	6.0	0.6	0.6
1991-1992	1.3	15.5	5.0	0.25	0.25
1993	1.3	15.5	5.0	0.25	0.1
1994-1995	1.3	15.5	5.0	0.1	0.07
1996-1997	1.3	15.5	5.0	0.1	0.05
1998	1.3	15.5	4.0	0.1	0.05

Table 4.3 EPA emission standards for model year 2004 and later heavy-duty diesel engines.

Option	NMHC + NO_X (g/bhp-hr)	NMHC (g/bhp-hr)
1	2.4	n/a
2	2.5	0.5

The effect of vehicle class on emissions will first be addressed from an analytical point of view. To compare two vehicles of different class (weight), a theoretical model of a vehicle operating at a steady state was employed. A simple road load relation considering aerodynamic drag, tire rolling resistance, and grade is shown in Equation 4.1.

Equation 4.1 $$P = \frac{1}{2} \rho_a C_d A V^3 + \mu M g V + M g V \sin \theta$$

where P is the power required to maintain a steady speed, ρ_a is the density of air, C_d is the aerodynamic drag coefficient of the vehicle, A is the frontal area of the vehicle, V is the speed at which the vehicle is traveling, μ is the tire rolling resistance coefficient, M is the mass of the vehicle, g is the acceleration due to gravity, and θ is the angle of inclination of the road grade. From the equation, it can be seen that the three main factors that cause a vehicle to require more power are speed, weight, and incline traveled. Note that this is for a steady-state (constant speed) case only. As the required power increases, the amount of fuel burned to produce that power also increases, and the mass of emissions will generally increase. (Note, however, that brake specific emissions levels may be higher at low power ratings than at higher power ratings.) This implies that emissions directly vary with truck class. The higher truck classes are heavier which require more power, and thus produce more exhaust gas and regulated components. See Section 4.3 for a comparison of vehicle weights.

Another problem arises, however, which is acceleration. The above analysis disregards the fact that the vehicle has to accelerate to this steady state condition. Under acceleration, it is assumed that a heavy vehicle is customarily using the maximum power available from its engine, thus producing the maximum amount of exhaust gas and typically high rates of NO_X and PM. So then, over a typical day of use for any vehicle, one that stops, and then accelerates more often, will produce higher emissions in units of grams per mile, providing all else is held constant.

Results from the analytical modeling of truck class are shown in Table 4.4. For this simulation, a class 2 pick-up truck and a class 8 tractor truck are assumed to be operating at a steady speed of 40 mph ascending a two percent grade. It is obvious that the heavier vehicle will require a significantly larger amount of power to maintain this speed. The class 8 truck will be consuming more fuel, and therefore have a higher flow rate of exhaust gases than the class 2 truck.

Table 4.4 Power required for a pick-up truck and a tractor truck at 40 mph steady speed on a 2% grade.

	Class 2 Pick-up Truck	Class 8 Tractor Truck	Ratio (class 8/class 2)
Weight (GVWR lbs.)	8,000	80,000	10
Required Power (hp.)	50	275	5.5
Fuel Economy (mpg)	16	3	1/5.3

It is evident that if two trucks employ the same engine, all else being equal, that the heavier vehicle will demand a higher energy (as axle-hp-hr or ahp-hr) to cover a similar mileage. [Energy at the rear wheels (in ahp-hr) differs from engine energy (in bhp-hr) by the factor of transmission efficiency and accessories demand.] Such variation would be accounted for if emissions variations were linear with power (as is NO_X, more or less if "off-cycle" injection timing is not encountered (Ramamurthy and Clark, 1998)) 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 5.5. The fuel economy values shown in the table were calculated using BSFC information and the required power for the comparison.

For a comparison of truck classes from test data, the emissions of two different heavy vehicles with the same engine are compared, noting that these two vehicles have different vocations, transmissions, and horsepower ratings. Table 4.5 shows the data for the engine and fuel used by these vehicles.

Table 4.5 Engine data for class comparison.

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

Table 4.6 Test results for two different vehicles with the same engine (with different power ratings).

Vehicle Type	Transit Bus	Tractor Truck	
Model Year	1993	1992	
Rated Power (hp.)	277	300	
GVWR (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 %
CO_2 (g/mile)	3593	2789	- 25 %
Fuel Economy (mpg)	2.80	3.61	+ 25 %

* Difference/average as a percentage.

Table 4.6 shows the vehicle information and chassis dynamometer based emissions results for a transit bus and a tractor truck with the same engine. These vehicles have different engine power ratings of 300 hp for the tractor truck and 277 hp for the transit bus. Each vehicle was tested on a different test cycle. The two different cycles are 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, and the tractor truck 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 (tractor truck) can follow the scheduled speed.

The tractor truck exhibited lower emissions in NO_X (oxides of nitrogen), HC (hydrocarbons), and PM (particulate matter) of 26%, 8.2% and 30%, respectively. The total emissions of CO (carbon monoxide) were higher for the tractor truck 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.

4.2 Driving Test Schedules

4.2.1 Review of Driving Schedules

Driving test schedules are used in the measurement of vehicle emissions with a chassis dynamometer. The traffic conditions and the routes traveled by each vehicle affect driving operation. In a similar way, test schedules vary widely in that they attempt to mimic specific driving behavior. Consequently, measured vehicle emissions are largely affected by the driving schedule. For comparison, existing test schedules have been divided into two groups for description below, namely synthesized and actual test schedules. Synthesized schedules are geometric in nature and usually consist of constant acceleration and constant speed phases. The actual or realistic driving schedules are derived or created from data collected as a vehicle performs its tasks. Most chassis test schedules are defined by a speed versus time trace, with load implied by a road load equation with no gradient assumed. Emissions testing was 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 [Merrion, 1994]. The actual speeds and torques are derived using the maximum torque curve and rated and idle speeds of the engine.

Relevant schedules, presented and discussed below, include four synthesized for chassis testing, two from the engine certification test, three cycles developed from actual truck data, and three engine test cycles. Speed versus time plots of every test cycle and route discussed were included for visual comparison.

Synthesized Chassis Schedules

Central Business District

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], which also includes arterial and commuter phases. These are not addressed here as they are not often used for heavy vehicle emissions testing. 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 4.1 shows a speed versus time plot of the entire CBD Cycle. Figure 4.2 shows the speed versus time trace of a bus actually following the CBD Cycle.

Figure 4.1 Central Business District Cycle speed versus time plot.

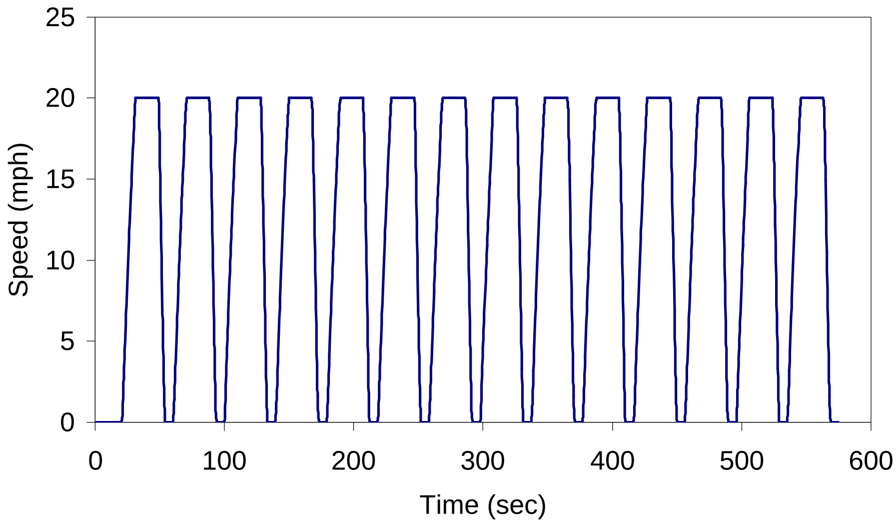
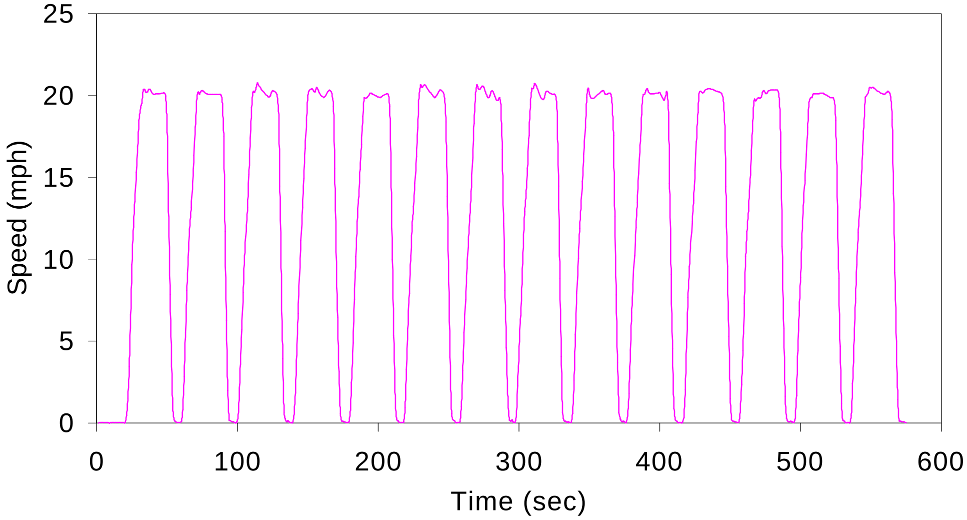


Figure 4.2 Plot of speed versus time for a Flint transit bus following the CBD cycle. The simulated test weight was 33,000 lbs. The vehicle was powered by a 275 hp. DDC Series 50 engine and was equipped with a 5 speed automatic transmission.



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 is designed for general truck chassis testing for comparison of diesel and alternate fuels. Figure 4.3 shows a speed versus time plot for this cycle. 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, and the cycle covers a distance five miles. Figure 4.4 shows the speed versus time trace of a bus driving the cycle.

Figure 4.3 Speed versus time plot for the WVU 5-Peak cycle.

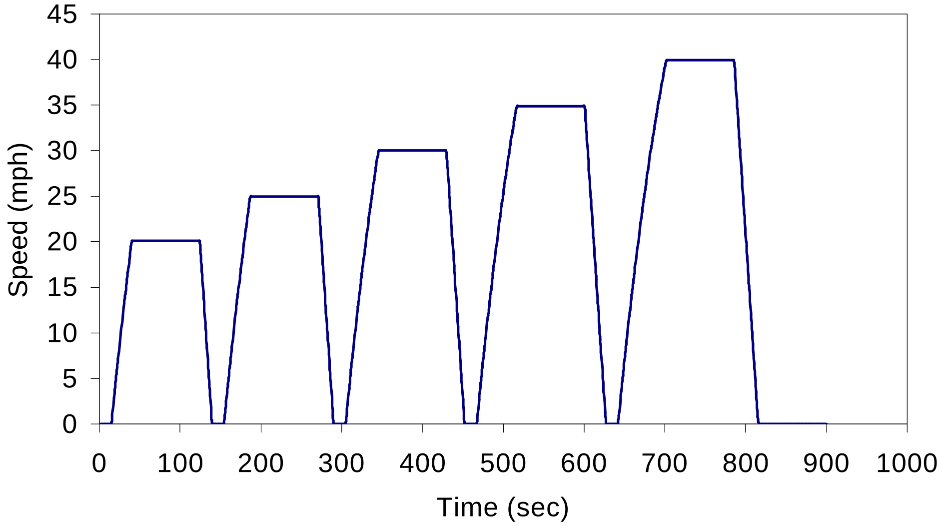
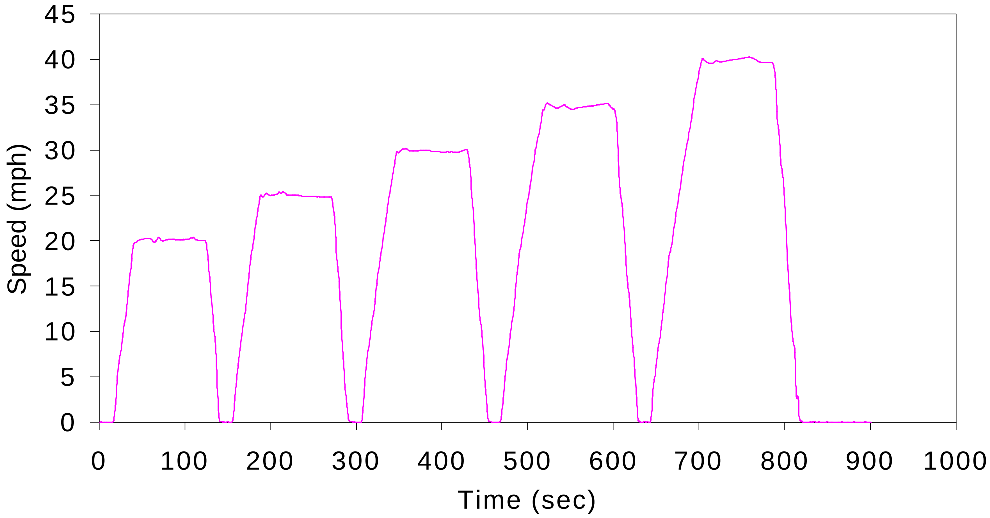


Figure 4.4 Plot of speed versus time for a Flint transit bus following the WVU 5-Peak Cycle. The simulated test weight was 33,000 lbs. The vehicle was powered by a 275 hp. DDC Series 50 engine and was equipped with a 5-speed automatic transmission.



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 controlled always 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 and a more powerful vehicle will be able to complete the driving portion in less time. An example of a transit bus driving this cycle is shown in Figure 4.5 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 WVU 5-Mile Route. Figure 4.6 shows an example of a truck driving the WVU 5-Mile Route. The target cycle cannot be illustrated on a speed-time plot, but can be illustrated on a speed-distance plot.

Figure 4.5 Plot of speed versus time for a Flint transit bus driving the WVU 5-Mile Route. The simulated test weight was 33,000 lbs. The vehicle was powered by a 275 hp. DDC Series 50 engine and was equipped with a 5-speed automatic transmission.

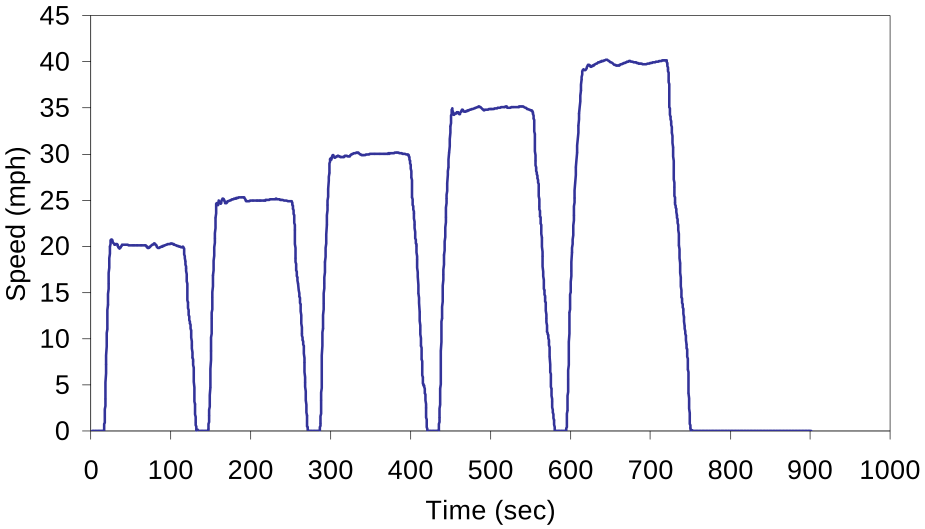
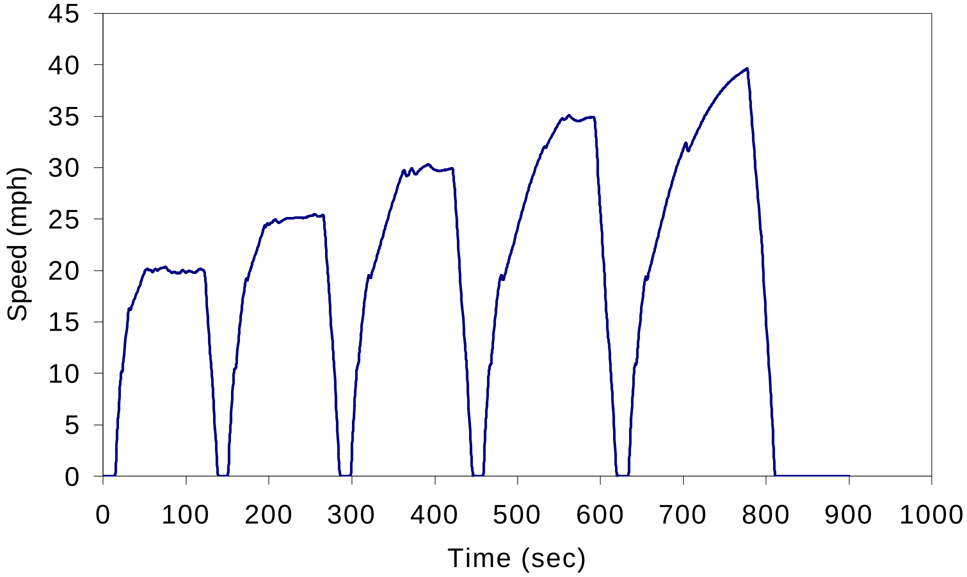


Figure 4.6 Speed versus time for a truck with an unusually low power-to-weight ratio driving the WVU 5-Mile Route. The simulated test weight was 27,800 lbs. The vehicle was powered by a 120 hp. Mercedes engine and was equipped with a 5-speed manual transmission.



New York Garbage Truck Cycle

WVU researchers developed the New York Garbage Truck Cycle (NYGTC) by following refuse trucks and recording the characteristics of their typical operation [Clark and Lyons, 1997]. Although not statistically derived, this cycle mimics real refuse truck use better than the CBD Cycle. This cycle incorporates three compactions of the loaded garbage while the truck is not moving. The acceleration ramps in this cycle are at a fixed rate rather than at the maximum acceleration the vehicle can attain. A speed versus time plot of the NYGTC, with compactions noted, is shown in Figure 4.7. An example of a refuse truck driving the NYGTC can be seen in Figure 4.8.

Figure 4.7 New York Garbage Truck Cycle speed versus time plot.

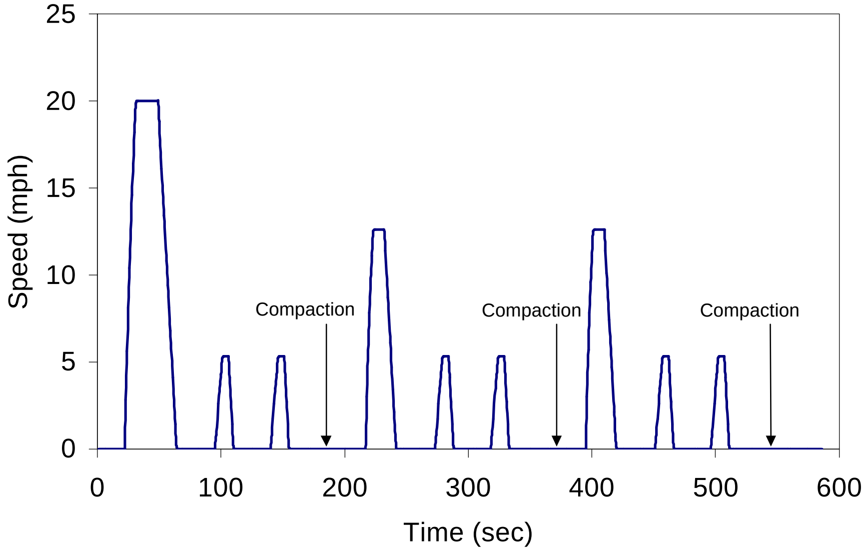
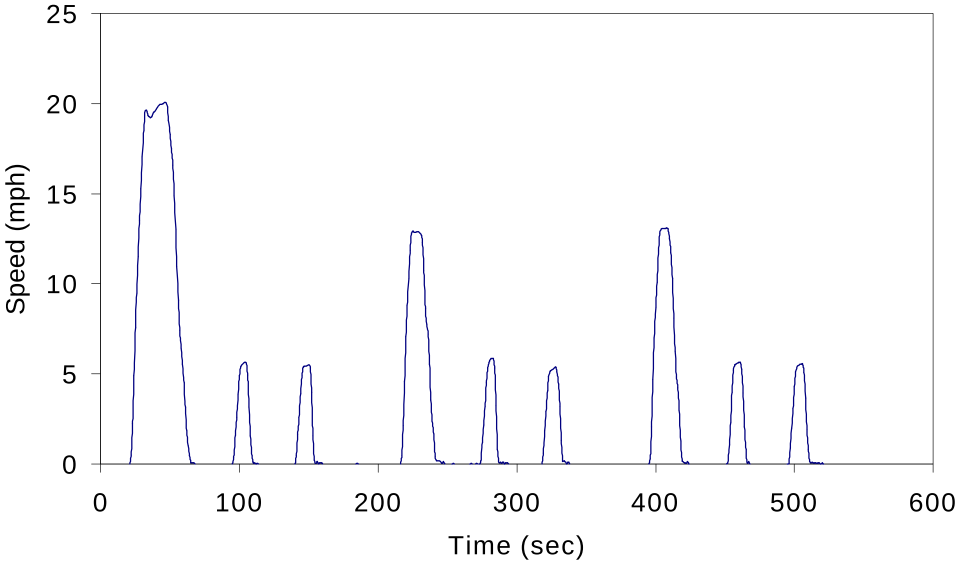


Figure 4.8 Example of a refuse truck driving the New York Garbage Truck Cycle, speed versus time plot.



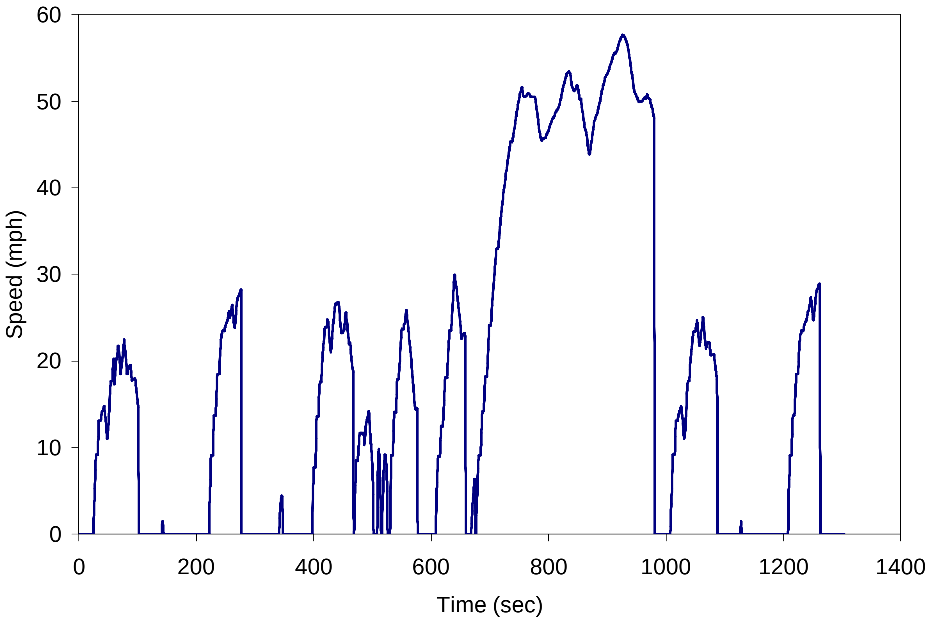
Chassis Cycles Derived from the Engine Certification Cycle

Two synthesized chassis test cycles have been derived from the engine certification test. The first employed an energy conservation method, used with precise knowledge of the engine torque curve and prescribed shifting points to yield a speed-time cycle specific to individual trucks [Clark and McKain, 1995]. This approach has subsequently been employed by the EPA group in Research Triangle Park [Harris et al., 1997], who have termed the cycle the "Road Certification Test." An example of this cycle can be seen in Figure 4.9.

The second approach, treating the whole truck with a single gear engaged as if it were an engine alone, has been demonstrated recently by McKain et al. [1998] for CARB.

Both of these approaches are geared toward screening for, or mimicking, an engine certification test and are not directly suitable as a basis for developing a mobile source inventory.

Figure 4.9 Engine cycle known as the Road Certification Test, [Clark and McKain, 1995; Harris et al., 1997], speed versus time plot.



Comparison of Synthesized Chassis Cycles

From the plots of each cycle, it can be seen that the CBD Cycle favors the one speed of 20 mph, while the WVU 5-Peak Cycle and the WVU 5-Mile Route incorporate a variety of speeds, with the maximum being 40 mph. Favoring a single speed through a cycle can bias emissions measurement through gear selection. The WVU 5-Peak Cycle has the highest average speed of 21.2 mph shown in Table 4.7. The two examples for the WVU 5-Mile Route are from WVU test data. The bus example is from a 1996 New Flyer bus with a 37,920 lbs. GVW and a DDC Series 50 engine rated at 275 hp. The truck example is a 1986 Famsa International truck with a 39,683 lbs. GVW and a Perkins Phase 2 engine rated at 120 hp. The bus had a fast completion of the WVU 5-Mile Route, while the truck had a slow completion. The 5-Mile Route appears twice, using actual behavior of a bus and a truck respectively. The CBD, WVU 5-Peak Cycle and the NYGT Cycle statistics have been calculated from the target cycle.

Table 4.7 Calculated parameters of the various synthesized cycles and routes.

Cycle or Route:	CBD	WVU 5-Peak Cycle	WVU 5-Mile (Bus)	WVU 5-Mile Route (Truck)	NYGT
Total Duration (s)	574	900	900	900	600
Idle (%)	17.8	17.3	25.0	17.3	68.5
Acceleration (%)	26.6	23.4	9.7	38.7	9.7
Cruise (%)	43.5	46.3	52.2	30.0	12.0
Deceleration (%)	12.1	12.9	13.3	14.4	9.8
Maximum Accel. (mph/s)	1.93	0.80	4.08	2.16	3.00
Average Accel. (mph/s)	1.93	0.72	1.74	0.43	1.31
Maximum Decel. (mph/s)	-3.73	-1.33	-3.05	-1.78	-1.40
Average Decel. (mph/s)	-3.73	-1.33	-1.24	-1.16	-1.29
Max. Speed (mph)	20	40	40	40	20
Average Speed (mph)	12.6	21.2	20.0	19.3	2.3
Total Distance (miles)	2.0	5.0	5.0	4.8	0.38

Realistic Chassis Cycles

New York Bus Cycle

This cycle was derived from in-use vehicle data from the CAPE-21 survey [EPA, 1978]. The CAPE-21 project also yielded the data used to formulate the present heavy-duty engine certification test schedule, as presented in the Code of Federal Regulations, Title 40, Part 86, Subpart N. This survey collected data from buses, trucks, and tractor trailers in New York and Los Angeles. This cycle is intended to simulate very low average speed operation in dense city traffic [EPA, 1978]. Figure 4.10 shows a speed versus time plot for the NYB Cycle and Figure 4.11 shows an example of a bus following this cycle.

Figure 4.10 New York Bus Cycle scheduled speed versus time plot.

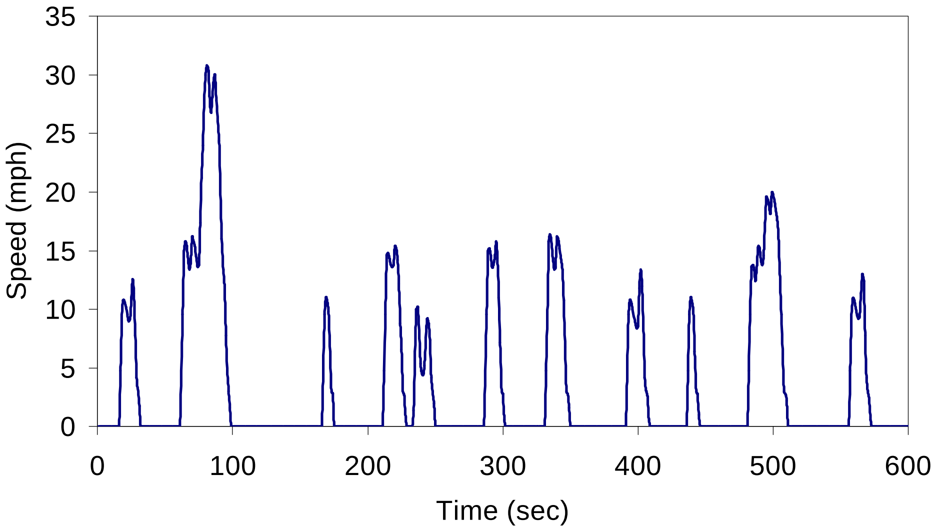
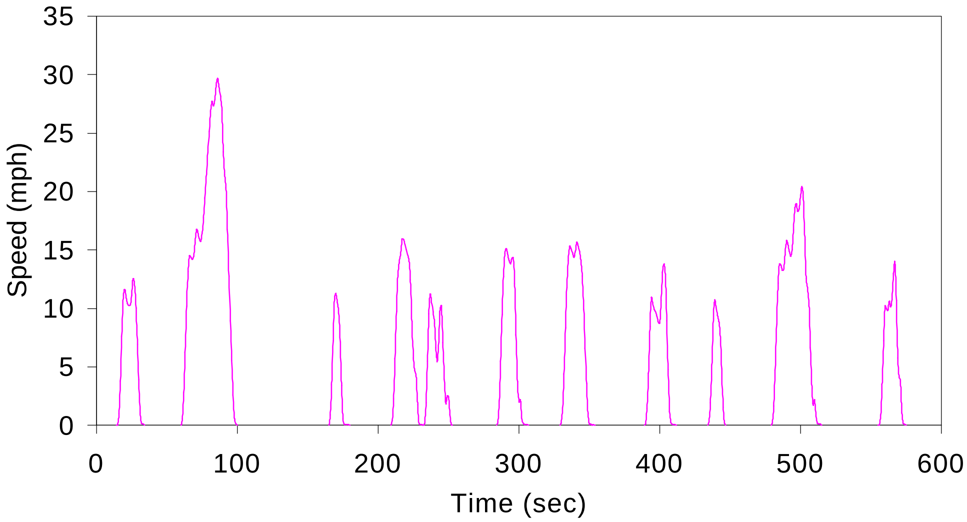


Figure 4.11. Speed versus time for the Flint transit bus following the New York Bus Cycle. The simulated test weight was 33,000 lbs. The vehicle was powered by a 275 hp. DDC Series 50 engine and was equipped with a 5-speed automatic transmission.



EPA Urban Dynamometer Driving Schedule for Heavy-Duty Vehicles

The EPA Urban Dynamometer Driving Schedule for Heavy-Duty Vehicles is also referred to as “Test-D.” It is another 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 [CFR Title 40, 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 peen employed occasionally as a “best attempt” basis to simulate vehicle activity and emissions by most heavy-duty chassis emissions laboratories in North America. Figure 4.12 shows the scheduled speed versus time plot for Test - D, and Figure 4.13 shows an example of a bus following the cycle.

Figure 4.12 EPA Urban Dynamometer Driving Schedule for heavy-duty vehicles (Test-D) speed versus time plot.

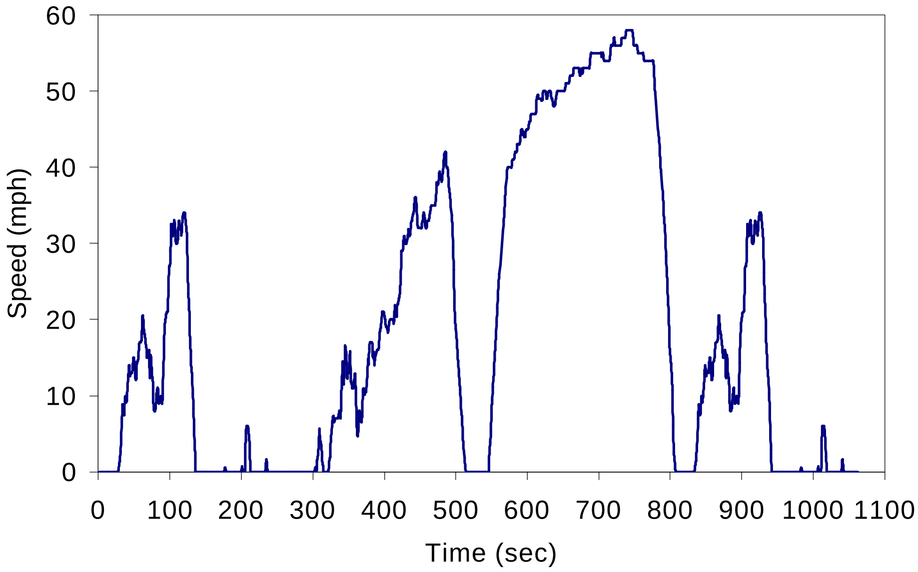
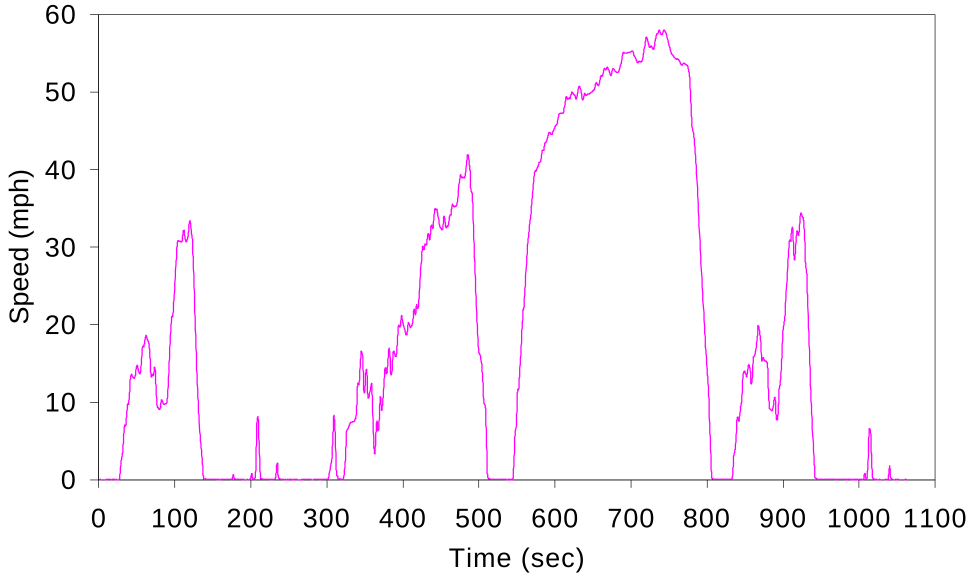


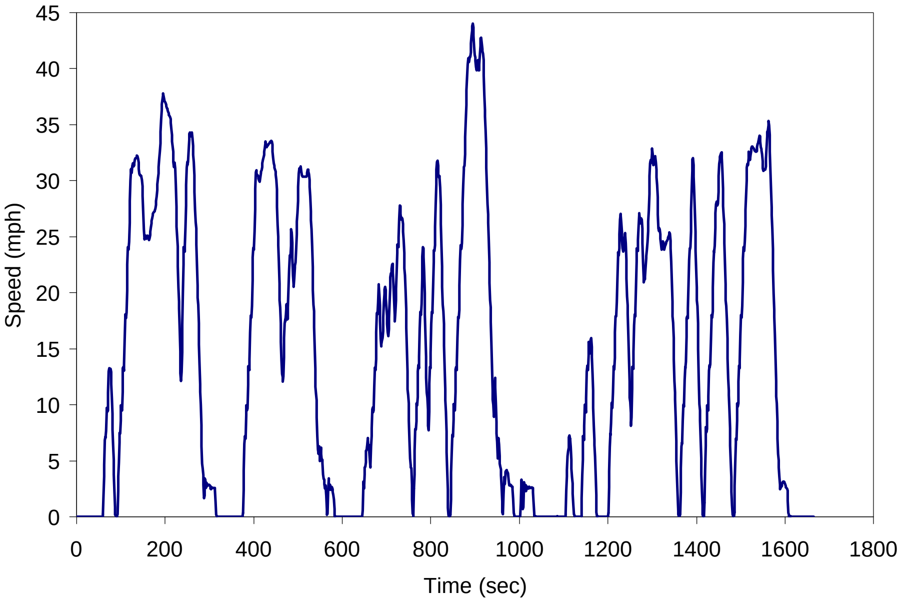
Figure 4.13 Speed versus time for the Flint transit bus following Test-D. The simulated test weight was 33,000 lbs. The vehicle was powered by a 275 hp. DDC Series 50 engine and was equipped with a 5-speed automatic transmission.



City Suburban Heavy Vehicle Route (CSHVR)

The City Suburban Heavy Vehicle Route was developed by 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., 1998b]. A speed versus time plot of a tractor truck driving the CSHVR is show in Figure 4.14.

Figure 4.14 City Suburban Heavy Vehicle Route speed versus time plot.



Comparison of Actual Chassis Cycles

Table 4.8 shows the demographics of the actual cycles. The CSHVR statistics are taken from operation of a truck over the route while Test-D and the NY Bus cycles were analyzed using the target speed-time data.

The NY bus cycle has a long percentage of idle time (58%) and a relatively large maximum acceleration (4.43 mph/s). The low average speed (3.69 mph), and maximum speed (31 mph) along with the short travel distance are representative of bus traffic with many short trips between stops. Even though difficult to follow, Test-D is more suited for testing trucks due to its lower maximum acceleration (2.80 mph/s) and longer cruise time (~25%). The truck used for the CHSVR example was a 1998 International Eagle with a Cummins N14 engine rated at 435 hp. The simulated vehicle test weight was 46,400 lbs.

Table 4.8 Calculated parameters of the actual cycles.

Cycle:	NY Bus	Test - D	CSHVR (truck)
Total Duration (s)	600	1062	1664
Idle (%)	58.0	27.4	22.8
Acceleration (%)	15.3	29.3	28.8
Cruise (%)	8.2	24.6	19.3
Deceleration (%)	18.5	18.8	29.2
Maximum Acceleration (mph/s)	4.43	2.80	3.00
Average Acceleration (mph/s)	1.79	0.75	1.06
Maximum Deceleration (mph/s)	-3.35	-3.19	-2.70
Average Deceleration (mph/s)	-1.51	-1.17	-1.02
Maximum Speed (mph)	31	58	44
Average Speed (mph)	3.69	18.8	14.5
Total Distance (miles)	0.615	5.55	6.69

The values for acceleration, deceleration, idle, and cruise presented in Table 4.8 were determined from cut-off values. For speeds below 10 mph, the vehicle was considered accelerating if the rate exceeded 0.4 mph/s and decelerating if the rate was below –0.4 mph/s. For speeds above 10 mph, the vehicle was considered accelerating if the rate exceeded 0.1 mph/s and decelerating if the rate was below -0.18 mph/s. Idle condition was when the vehicle was not moving.

Engine Cycles

Heavy-duty engine test cycles are defined by a speed and torque (load) schedule over a period of time. Generally, the specified speed and torque are defined as percent of maximum rated speed, and percent of maximum rated torque. The certification cycle for engine testing is also referred to as the Federal Test Procedure (FTP) cycle. Figure 4.15 shows the scheduled speed versus time for this cycle, and Figure 4.16 shows the scheduled torque versus time. Table 4.9 is an example of three repeat hot FTP tests that were performed by researchers at WVU on a Navistar T444E engine.

Figure 4.15 Engine speed versus time for FTP engine cycle.

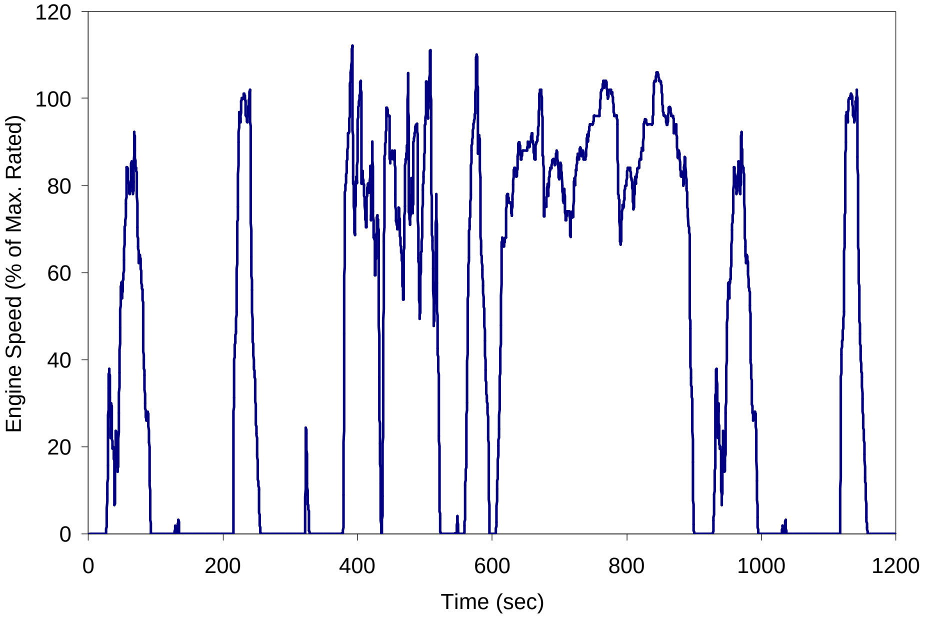


Figure 4.16 Torque versus time for the FTP.

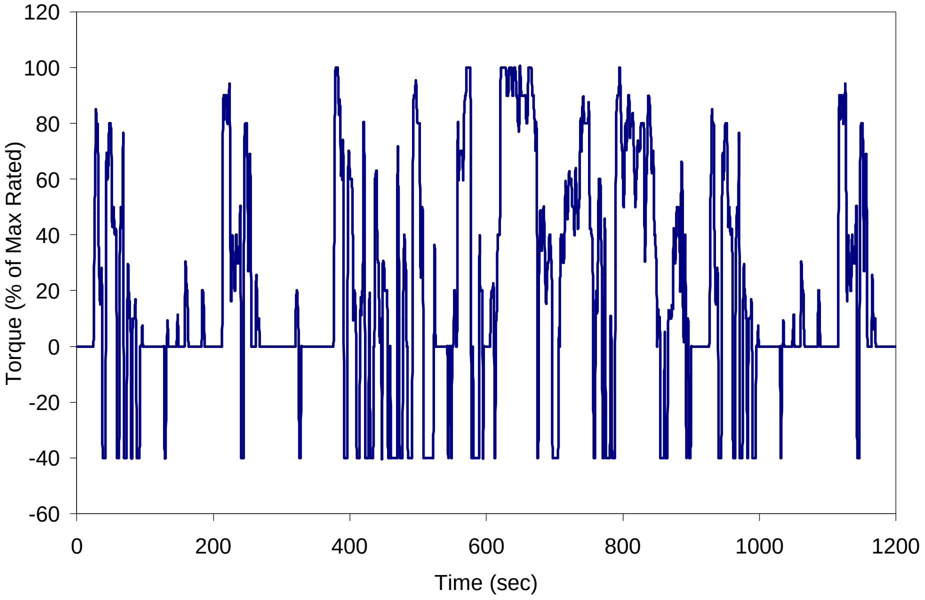


Table 4.9 Engine test data from the FTP cycle on a Navistar engine.

Test No.	NO_X (g/bhp-hr)	CO (g/bhp-hr)	HC (g/bhp-hr)	PM (g/bhp-hr)
1	5.35	1.39	0.20	0.12
2	5.25	1.40	0.24	0.12
3	5.15	1.43	0.25	0.12
Average	5.25	1.41	0.23	0.12
Std. Dev.	0.10	0.02	0.03	0
COV %	1.9 %	1.3 %	11.5 %	0

4.2.2 Test Cycle Emissions Comparison

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 5-Peak Cycle, Test-D, and the CBD Cycle. One particular heavy-duty diesel powered vehicle that was tested on all three cycles was “vehicle # 17.” This was a telephone truck of 19,500 lbs. curb weight and 80,000 lbs. GVWR. It was a 1983 model year vehicle powered by a Cummins NTC400 with the odometer showing 80,876 miles. Results from this testing can be seen in Table 4.10.

Table 4.10 NFRAQS test vehicle #17 emissions test results.

Cycle	NO_x (g/mile)	CO (g/mile)	HC (g/mile)	PM (g/mile)	Fuel Economy (mile/gal)
WVU 5-Peak	18.8	18.4	3.42	1.96	4.56
Test –D	24.7	50.7	4.31	3.50	3.75
CBD	31.2	62.4	7.08	5.99	2.39

A sequence of tests performed by the WVU Transportable laboratory was considered to evaluate the effect of driving test cycles on the emissions produced. Previous testing performed using a bus from the Flint Mass Transit Authority in Flint, MI will be used for the comparison. This testing was completed before this study was chartered, and was part of a program funded by the United States Department of Energy, Office of Transportation Technologies. This testing was performed on a single bus and different driving test cycles were run consecutively. The bus was outfitted with a Detroit Diesel Series 50 engine coupled to a 5 speed automatic transmission. The engine was a four-cylinder unit, having 8.5 liters of displacement rated at 275 bhp operating on D2 diesel. Results of this testing are shown in Tables 4.11 through 4.14. Bar graphs of this data are provided in Figures 4.17 through 4.20. Although this is data from just one bus, many other similarly equipped busses were tested at this Flint site, and showed consistent bus-to-bus correlation of emissions data for operation on the CBD Cycle. For the comparison, a range of emissions parameters was employed to show the difference in emissions based on various measures (such as miles, cycle, time). In addition to the conventional use of g/mile in chassis testing, data were also expressed as a total mass per cycle, as an average mass flowrate, as a mass ratio with CO_2 and as grams per gallon of diesel. In addition, since axle speed and torque were known continuously for each of these tests, it was possible to express the data in mass per total axle energy delivered, with units of g/axle-hp-hr (or g/ahp-hr). Occurrences of negative torque during deceleration were not added to the ahp-hr summation.

Table 4.11 NO_X emissions for each cycle (Flint Bus).

Cycle	g/mile	g/cycle	Avg. g/sec	g/ahp hr	g/g CO_2	g/gal fuel
CBD	30.70	62.01	0.1080	11.59	0.01145	116.05
WVU 5-Peak Cycle	28.60	143.00	0.1682	19.38	0.02238	227.37
WVU 5-Mile Route	24.70	123.75	0.1375	16.39	0.01868	189.70
NY-Bus	70.00	44.10	0.0735	21.20	0.01301	130.90
Test-D	26.80	148.47	0.1398	13.58	0.01536	155.71

Table 4.12 CO emissions for each cycle (Flint Bus).

Cycle	g/mile	g/cycle	Avg g/sec	g/ahp hr	g/g CO_2	g/gal fuel
CBD	6.90	13.94	0.0243	2.61	0.0026	26.08
WVU 5-Peak Cycle	1.30	6.50	0.0076	0.88	0.0010	10.34
WVU 5-Mile Route	2.50	12.53	0.0139	1.66	0.0019	19.20
NY-Bus	44.30	27.91	0.0465	13.42	0.0082	82.84
Test-D	6.20	34.35	0.0323	3.14	0.0036	36.02

Table 4.13 Total HC emissions for each cycle (Flint Bus).

Cycle	g/mile	g/cycle	Avg g/sec	g/ahp hr	g/g CO_2	g/gal fuel
CBD	0.14	0.28	0.000493	0.053	0.000052	0.53
WVU 5-Peak Cycle	0.07	0.35	0.000412	0.047	0.000055	0.56
WVU 5-Mile Route	0.06	0.30	0.000334	0.040	0.000045	0.46
NY-Bus	0.61	0.38	0.000641	0.185	0.000113	1.14
Test-D	0.06	0.33	0.000313	0.030	0.000034	0.35

Table 4.14 Total PM emissions for each cycle (Flint Bus).

Cycle	g/mile	g/cycle	Avg g/sec	g/ahp hr	g/g CO_2	g/gal fuel
CBD	0.34	0.69	0.00120	0.128	0.000127	1.29
WVU 5-Peak Cycle	0.08	0.40	0.00047	0.054	0.000063	0.64
WVU 5-Mile Route	0.17	0.85	0.00095	0.113	0.000129	1.31
NY-Bus	1.33	0.84	0.00140	0.403	0.000247	2.49
Test-D	0.37	2.05	0.00193	0.188	0.000212	2.15

Figure 4.17 Visual comparison of vehicle NO_X emissions from various test cycles.

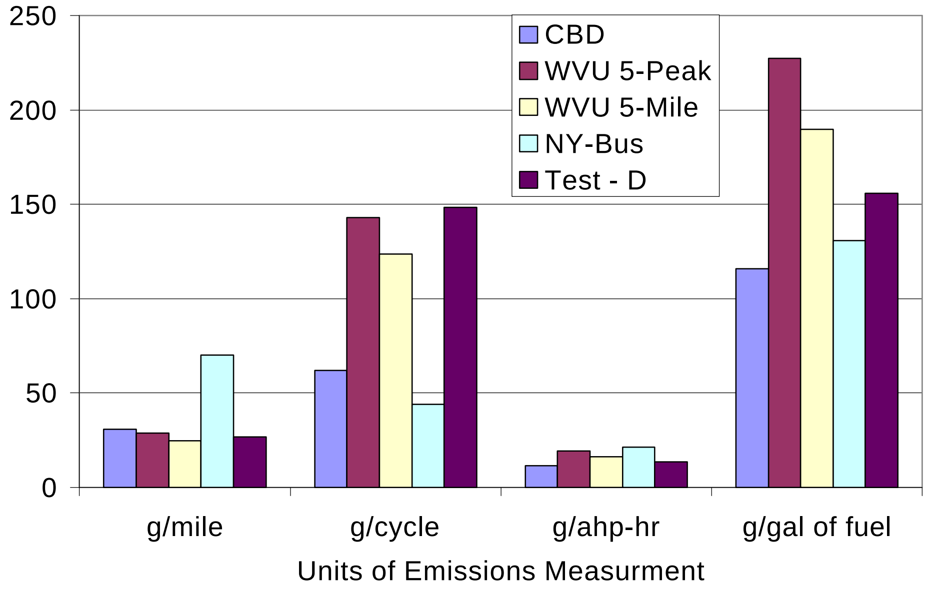


Figure 4.18 Visual comparison of vehicle CO emissions from various test cycles.

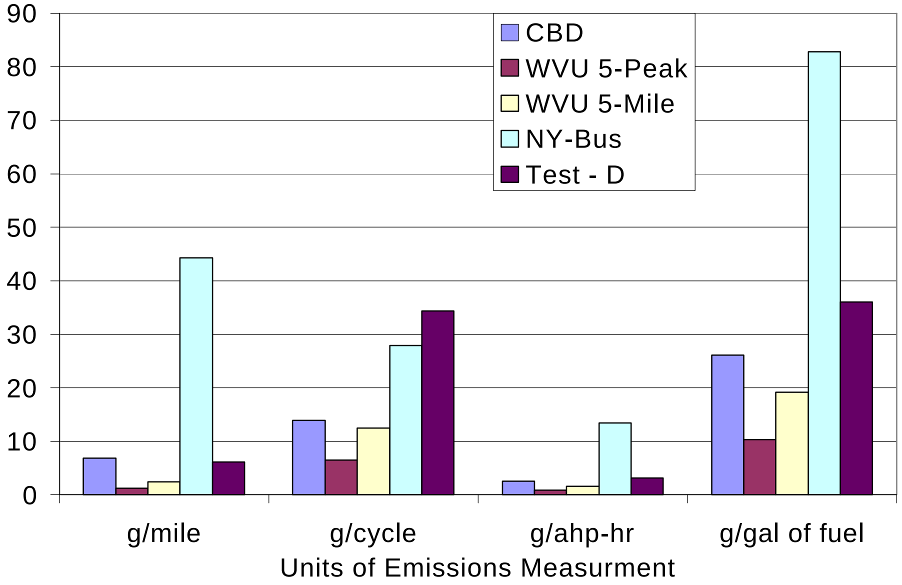


Figure 4.19 Visual comparison of vehicle HC emissions from various test cycles.

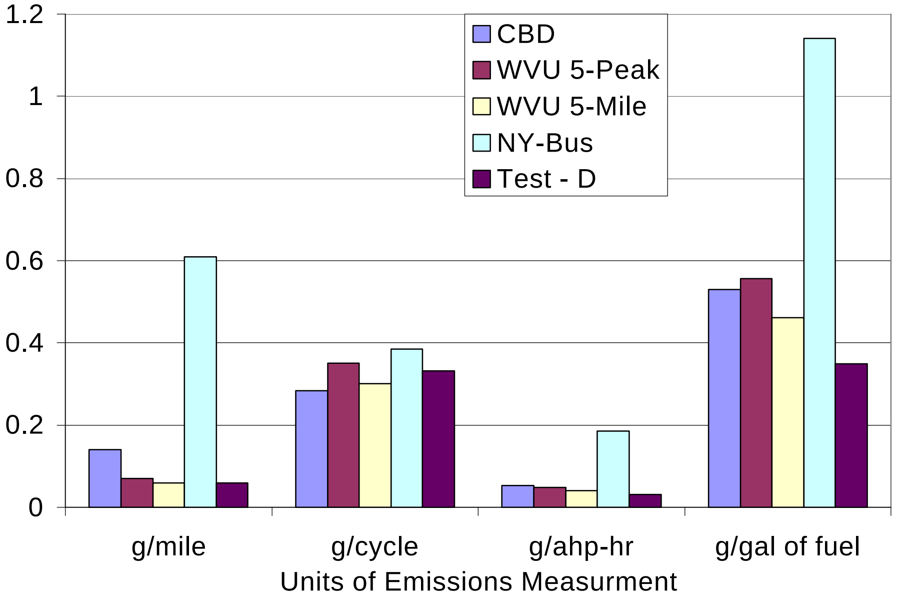


Figure 4.20 Visual comparison of vehicle PM emissions from various test cycles.

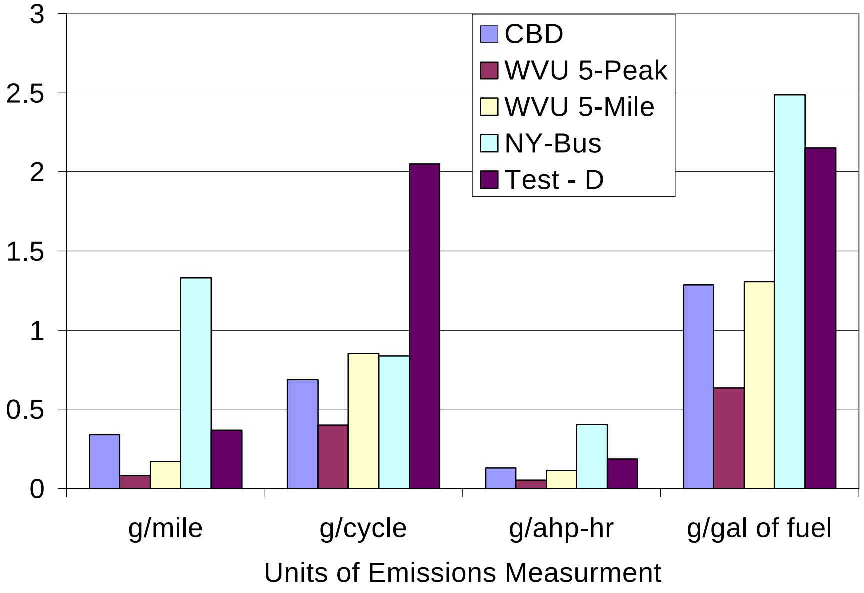


Table 4.15 shows data collected by the WVU Transportable laboratory comparing the New York Garbage Truck (NYGT) cycle, and the CBD cycle on various refuse trucks. It is evident that the emissions in g/mile are highly dependent on the cycle used in this case.

Table 4.15 NYGT Cycle and CBD Cycle emissions test results.

Vehicle	cycle	date	NO_X (g/mile)	CO (g/mile)	HC (g/mile)	PM (g/mile)	Fuel Economy (mpg)	Engine
1	CBD	10/96	34.7	2.92	1.92	0.45	2.65	CAT 3306
	NYGT	10/96	94	10.2	5.94	0.95	1.36	CAT 3306
Difference*			92%	111%	102%	71%	64%	
1	CBD	10/97	33.37	3.1	2.21	0.48	2.81	CAT 3306
	NYGT	10/97	79.13	11.8	6.73	1.23	1.45	CAT 3306
Difference*			81%	118%	101%	88%	64%	
2	CBD	11/96	31.1	2.39	1.78	0.36	3.14	CAT 3306
	NYGT	11/96	101	8.88	5.46	0.95	1.32	CAT 3306
Difference*			106%	115%	102%	90%	82	
3	CBD	11/96	31.2	2.33	2.07	0.41	3.36	CAT 3306
	NYGT	11/96	90.2	11.7	6.09	0.82	1.51	CAT 3306
Difference*			97%	134%	98%	67%	76%	
4	CBD	11/96	30.1	5.82	4.27	1.87	2.87	Cum. L-10
	NYGT	11/96	116	15.8	9.64	4.76	1.27	Cum. L-10
Difference*			117%	92%	77%	87%	77%	
5	CBD	10/97	42.62	3.5	0.38	0.31	2.88	DDC 50
	NYGT	10/97	120	11.9	1.29	1.24	1.30	DDC 50
Difference*			95%	109%	110%	119%	76%	

* Difference/average as a percentage.

Table 4.16 shows emissions levels of a truck using the recently devised City Suburban Heavy Vehicle Route (CSHVR), discussed in section 4.2.1, and the CBD cycle. The vehicle was a Mack refuse truck with a 350 hp Mack E7 diesel engine and an automatic transmission. WVU tested this vehicle under funding from the U.S. Department of Energy. NO_X emissions were observed to be comparable in units of g/mile, while the PM and CO emissions reflect the high engine loads required by the CBD cycle.

Table 4.16 CSHVR and CBD Cycle emissions test results.

Cycle or Route	NOx (g/mile)	CO (g/mile)	HC (g/mile)	PM (g/mile)	Fuel Economy (mpg)
CBD	29.6	6.98	0.62	1.22	2.93
CSHVR	24.5	3.93	0.42	0.66	3.49
Difference*	19%	56%	39%	60%	17%

* Difference/average as a percentage.

Conclusions from Emissions Data

In Tables 4.11 to 4.14, the emissions in g/g CO_2 and g/gal fuel need not be discussed separately, as they are linked by carbon balance and fuel consumption. In this unit conversion analysis, the diesel density was taken as 3028 g/gal, diesel carbon-hydrogen ratio was 0.59 and no mass loss due to blow-by past the rings was assumed.

From the WVU data on the Flint bus, it is evident that the units in which the emissions are expressed are significant. For example, considering NO_X, the NY Bus Cycle is highest of all the cycles in g/mile, but lowest in average g/sec. This is to be expected due to its low speed and high idle content. Also, the CBD Cycle and WVU 5-Peak Cycle yield similar emissions in g/mile, but emissions differing by a factor of two in g/ahp-hr. This is to be expected because the vital ratios of the cycles, such as ahp-hr/mile, vary widely, as supported by the data in Tables 4.7 and 4.8.

In currency of g/mile, the WVU bus data show that all cycles yield NO_X in the range of 24.7 to 30.7 g/mile, with the NY bus cycle an outlier at 70 g/mile. This is because the NY bus cycle covers a short distance over its duration relative to other cycles. One may conclude that NO_X data, in g/mile, remain fairly consistent for most cycles in current use. For the NFRAQS telephone truck data, NO_X ranged from 18.8 to 31.2 g/mile for the three cycles used, which is a wider relative variation than for the WVU bus data.

Variations in both CO and PM are acknowledged to be higher than for NO_X, all else being equal. This is borne out by the data of both the NFRAQS and WVU studies. For the WVU bus, excluding the NY Bus Cycle as an outlier, emissions of CO in g/mile varied by a factor of three over the four cycles used, and the NFRAQS data yielded a similar ratio. For PM in both studies the range was a factor of three to four, in g/mile. In the NFRAQS study the ratio of PM in g/mile of the CBD to the WVU 5-Peak Cycle was three, while in the WVU study it was 4.25. One must conclude that the cycle chosen has profound effect on PM and CO levels, if they are expressed in g/mile. The WVU data showed that choice of units in g/ahp-hr did not improve cycle-to-cycle agreement by much. This criticizes the present inventory approach of MOBILE and EMFAC with respect to CO and PM.

Hydrocarbon emissions from diesel engines are customarily low and are of less interest than NO_X and PM emissions. Both the NFRAQS and the WVU data showed cycle-to-cycle variations of a factor of two, when the units were in g/mile, and when the NY Bus Cycle was excluded.

Of specific interest is the comparison of the WVU data for the bus using the WVU 5-Peak Cycle and the WVU 5-Mile Route. Both cycles are similar except that the 5-Peak Cycle does not demand full power from the bus engine upon acceleration. PM values in g/mile for the full power operation (route) are slightly more than twice as high as for the cycle. This confirms the sensitivity of CO and PM emissions to engine loading, in contrast to the relative stability of the NO_X emissions in units of g/mile.

The diesel emissions from the CSHVR testing were lower than the CBD Cycle emissions in every exhaust gas component in the case of the Mack refuse truck. The fuel economy produced with the CSHVR was better than that recorded from the CBD Cycle.

The conclusions from Graboski et al. [1998] indicate the trend of the CBD Cycle producing the highest emissions, and the WVU 5-Peak Cycle producing the lowest emissions with the Test-D in between them. This trend was attributed to the CBD Cycle being the most aggressive cycle with more acceleration ramps and more sustained high acceleration than the other cycles.

4.3 Vehicle Vocations, Weight, and Local Driving Activity

The particular vocation or specific use of a vehicle can have an effect on the emissions produced. The transients and cruise behavior of each vehicle vocation, along with the load carried, can be reproduced in testing by changing the testing weight and the driving cycle. A driving cycle for a bus will produce the characteristics of a bus route (frequent stops, high acceleration, and low speeds) and produce representative values of the exhaust emissions. This would also be true for a particular truck vocation, either a local delivery, long haul, or a shipping yard route would be used where applicable. Research at WVU, funded by NREL, and leading to the development of the CSHVR, included recording data from Roadway and Overnite tractor trucks as the drivers performed their respective tasks. Table 4.17 shows the data collected from this survey. It is evident that the primary difference between operation in yard, city, suburban, and interstate service lies in the average speed, whereas average accelerations are similar, most likely requiring full engine power. The average acceleration for the interstate type of activity is lower due to the higher power required to maintain the higher average speed, thus leaving less engine power available for acceleration as compared to lower average speed operation.

Table 4.17 Combined survey data from Roadway and Overnite tractors.

Microtrip Type	Total distance (miles)	Average Speed (mph)	Average Acceleration (mph/s)	Average Deceleration (mph/s)
Interstate	198	32.6	0.61	-0.89
Suburban	153	17.8	0.82	-1.20
City	26	10.2	0.75	-1.12
Yard	5.5	6.3	0.73	-0.87
Sub. and City	179	16	0.80	-1.19

The data collected from the Flint Mass Transit Authority bus, as described above, also contained one portion where the test weight of the bus was varied. The CBD cycle and D2 diesel was used for the tests, and Table 4.18 shows the emissions results.

Table 4.18 Emission results from varied test weights for a bus.

Test Weight	38,000 lbs.	32,825 lbs.	27,650 lbs.
NO_x (g/mile)	30.7	32.2	28.7
CO (g/mile)	6.91	4.51	4.56
HC (g/mile)	0.14	0.14	0.14
PM (g/mile)	0.34	0.22	0.21

For the test weight set at 38,000 lbs. (max GVW for the vehicle), the CO and particulate matter were both considerably higher than for the lighter test weights. However, NO_X was relatively insensitive over the range of test weights (in units of g/mile).

The preceding discussion examined the effect of test weight on emissions from the same vehicle. When the effect of test weight is considered over the spectrum of vehicles in service, the following logic based on existing energy-specific approaches, may by applied. If all engines are certified to a similar emissions level in g/bhp-hr, then their emissions in g/mile will be influenced solely by the ratio bhp-hr/mile. In this case, one would argue that in regular service a light-heavy-duty pickup truck would emit at approximately 40% of the rate, in g/mile, of a tractor-trailer. This is the argument embodied in the present inventory process, but is flawed if the emissions rates are non-linear with respect to power demand (as CO and PM are known to be) or if "off-cycle" operation induces NO_X emissions rates that differ from certification rates, in g/bhp-hr.

The NFRAQS testing also compared the GVWR of the vehicles against the emission results. The conclusion by Graboski et al. [1998] 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.

The issue of the effect of vehicle vocation is difficult to tackle, but is also covered in part by the discussion of test cycles above. It is evident that a line haul tractor may be expected to emit at lower levels in g/mile than an inner-city refuse truck because long idle periods and stop-and-go operation will increase emissions in g/mile. This is the basis for the development of the New York Garbage Truck Cycle that has previously been discussed.

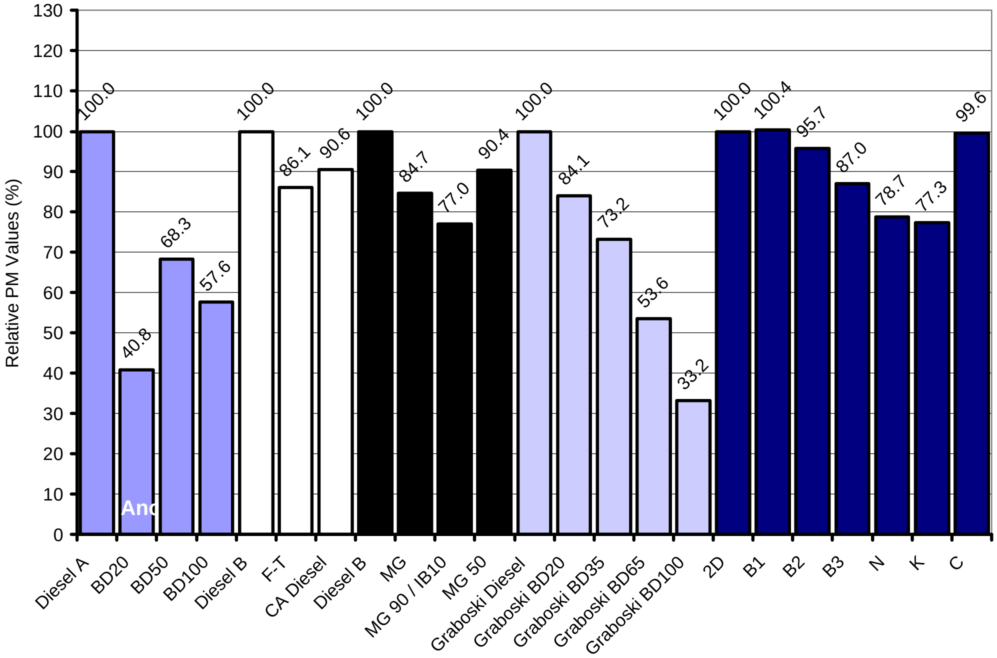
Local driving activity also affects heavy vehicle emissions, but is difficult to quantify. A simple definition of local driving activity would be the differences that occur when a vehicle is driven or used differently, mainly due to the driving attitudes of different geographic locations. This is very close to the definition of vehicle vocations, and also impacts the discussion on test cycles. Local driving habits will also affect the vehicle emissions due to driver-to-driver variations. The effect that these factors have on vehicle emissions is comparable with different driving cycles that mimic the particular driving patterns or vehicle uses.

4.4 Fuel Type

Fuels other than conventional diesel provide a means of reducing heavy-duty engine emissions. Fuels such as compressed natural gas (CNG), liquefied petroleum gas (LPG), and various alcohols have been used, but require engine modifications for operation. However, using a reformulated diesel or a diesel equivalent fuel that does not require engine modifications can produce significant reductions in engine emissions while avoiding the expense of vehicle modifications. Complete fuel reformulation would affect all heavy-duty diesel vehicles and has the potential to reduce NO_X and PM significantly [Health Effects Institute, 1995]. Diesel fuel additives have also been used for reduction of emissions as shown by Lange et al. [1997], and Green et al. [1997]. The most common additive has been a cetane number enhancer. The results show that a fuel with a higher cetane number ignites earlier and thus uses less fuel to produce the same power. This increase in fuel economy leads to lower emissions and the earlier ignition generally reduces NO_X production during the premix burn.

Clark et al. [1998a] recently compared a variety of diesel fuels and diesel fuel substitutes. Testing for this study included available diesel fuels, biodiesel blends (eg. BD20 is 20% biodiesel), fuels from the Fischer-Tropsch process (termed F-T, and MG) and a blend of the MG fuel with isobutanol (IB). The results of the testing were then compared with similar studies by Graboski et al. [1996], and Schaberg et al. [1997]. The PM results are shown in Figure 4.21. The fuels tested by Schaberg et al. are conventional diesel, a fuel from the Sasol slurry phase distillate process, and blends of the two, and are termed 2D, B1, B2, B3, N, K, and C. The comparison shows a maximum decrease of 66% in PM emissions for the fuels tested.

Figure 4.21 Normalized PM emissions results comparison for different fuel types. Data are from studies by Schaberg et al. [1997], Graboski et al. [1996], and Clark et al. [1998]. For each study, the low sulfur diesel results were set at 100%. The Clark et al. BD20 results appear anomalous, but no corrective explanation can be found.



In the study by Graboski et al. [1996], the transient emissions from D2 diesel and biodiesel blends in a DDC Series 60 engine were investigated. The fuels tested were a reference diesel, 20%, 35%, and 65% biodiesel (methyl soy ester) blends in the reference diesel, as well as 100% biodiesel. This testing was performed on an engine dynamometer with NO_X, CO, HC, and PM recorded in g/bhp-hr. The results are shown in Table 4.19.

Table 4.19 Emissions comparison of varied concentrations of biodiesel. [Graboski et al., 1996]

Biodiesel Content	0 %	20 %	35 %	65 %	100 %
NO_X (g/bhp-hr)	4.58	4.63	4.63	4.79	5.11
CO (g/bhp-hr)	4.27	3.86	3.48	3.01	2.24
HC (g/bhp-hr)	0.154	0.130	0.139	0.110	0.085
PM (g/bhp-hr)	0.295	0.248	0.216	0.158	0.098

The biodiesel showed a strong trend of reduction in CO, HC, and PM, but an increase in NO_X emissions. This is to be expected due to the effect of oxygen in the fuel.

Recent testing by West Virginia University included a fuel from Malaysia produced using a Fischer-Tropsch (F-T) process. This fuel is produced from natural gas and has similar properties to diesel fuel, but usually with zero sulfur and low aromatic levels. Two separate vehicles were tested consecutively on a base California specification diesel and the F-T fuel. Table 4.20 shows the results from this comparison.

Table 4.20 Chassis emissions comparison of D2 diesel and F-T fuel.

Fuel	D2	F-T	Difference*	D2	F-T	Difference*
Vehicle	1	1		2	2	
NO_x (g/mile)	12.0	10.7	-11 %	14.0	13.7	-2 %
CO (g/mile)	4.0	3.5	-13 %	5.0	3.9	-22 %
HC (g/mile)	0.6	0.4	-33 %	0.5	0.3	-20 %
PM (g/mile)	0.47	0.33	-30 %	0.5	0.3	-20 %

*Using D2 as baseline.

The F-T fuel produced emissions that were lower than the D2 diesel for each exhaust gas constituent. HC was reduced the most at 33%, and NO_X was reduced the least at 2% for the second vehicle. Alternate heavy-duty engine fuels such as natural gas and alcohol fuels have not been addressed in this section because they require radically different engine technologies. Data on these fuels have been published elsewhere [Clark et al., 1995, Clark et al., 1997, Sharp et al., 1993, and Wool et al., 1996].

Transient engine tests were performed at West Virginia University using the F-T fuel along with D2 and California D2 diesel. Table 4.21 shows the averaged results of three tests using these fuels on a Navistar 444 engine using the FTP engine cycle.

Table 4.21 Engine emissions comparison of various fuels.

Fuel	D2	CA D2	Difference*	F-T	Difference*
NO_x (g/bhp-hr)	5.25	4.76	-9.3 %	4.47	-15 %
CO (g/bhp-hr)	1.41	0.92	-35 %	0.76	-46 %
HC (g/bhp-hr)	0.23	0.15	-35 %	0.08	-65 %
PM (g/bhp-hr)	0.12	0.11	-8.3 %	0.10	-17 %

* Using D2 diesel as baseline.

Both the California diesel and the F-T fuel showed a substantial decrease of each exhaust gas component over U.S. federal diesel fuel. The F-T fuel produced the greatest gain of 65% reduction in HC. From this comparison, one can conclude that fuel type has the potential to provide a substantial reduction in emissions.

4.5 Exhaust Aftertreatment

The three primary types of diesel exhaust aftertreatment are diesel oxidation catalyst, particulate traps, and continuously regenerating traps (CRT), although further technologies are currently emerging. These have been tested in various studies and show promising results. An oxidation catalyst works by using the excess oxygen in the exhaust to oxidize the gaseous hydrocarbons and carbon monoxide into water vapor and carbon dioxide [Galey, 1997]. Some of the soluble organic fraction (SOF) of the PM will also be eliminated. While this type of aftertreatment is effective in reducing HC, and CO, these are not the specific diesel exhaust pollutants that are desirable to eliminate. The quest for a NO_X reduction catalyst for diesel engines remains an unattained grail.

A particulate trap is a device where the PM is collected or filtered out of the exhaust and is regenerated by some external means. This is usually accomplished by either heating the trap to burn the PM, or using a fuel additive that causes regeneration or having a catalytic substrate on the filter. These are sometimes not effective in regenerating at low loads and low exhaust temperatures [Bach et al., 1998].

The most recent type of exhaust aftertreatment developed is the CRT. This type of system combines an oxidation catalyst and a particulate trap filter that reduces both gaseous and particulate emissions. The exhaust gases first pass through the catalyst to oxidize CO and HC, and also convert the majority of NO_X to NO_2 which is then used to oxidize the PM in the particulate trap [Galey, 1997]. This aftertreatment method continuously regenerates with no fuel additives or heater control system. A drawback of this system is that it requires low sulfur diesel, as sulfur inhibits the catalytic reactions in the system. Reductions with this system are as high as 90% for CO, HC, and PM, and 15% for NO_X [Galey, 1997].

The WVU Transportable Laboratory has performed testing on vehicles with and without catalytic converters. A particular test was a refuse truck tested in 1995 with an early technology catalytic converter manufactured by Donaldson. The vehicle was a 1992 model year with 56,515 miles on a Cummins LTA-10 engine supplying power through a 4-speed automatic transmission. This engine was rated at 260 hp operating on D2 diesel. The testing used the WVU 5-Peak cycle and Table 4.22 shows the results of this comparison.

Table 4.22 Emissions results for comparison of exhaust aftertreatments.

Constituent	Without Catalytic Converter (g/mile)	With Catalytic Converter (g/mile)	Difference* (Percent)
NO_x	23.2	21.1	- 9.1
CO	3.02	2.77	- 8.3
HC	1.74	1.42	- 18
PM	0.62	0.47	- 24
Fuel Economy	5.33	5.32	- 0.2

* Without converter used for baseline.

Each of the exhaust gas constituents was lowered by use of the catalytic converter. The total particulate matter was lowered the most at 24 %, and the CO was lowered the least at 8.6 %. One may conclude that oxidation catalytic converters are successful in reduction of hydrocarbons and particulate matter.

4.6 Vehicle Age

There are two separate factors of vehicle age that affect the emissions produced. First, it is assumed that as a vehicle ages and accumulates high mileage, the engine will slowly wear and produce higher emissions, although deterioration factors are usually taken to be small for diesel engines. This would imply that, for example, a 20-year-old vehicle would produce higher emissions after 20 years of use than it did when it was new. The second factor is the change in technology. The changing technology implies that the engines produced today are different than older ones, and must meet more stringent emissions standards. There are few data available for an age comparison of the same truck that was tested new and after some certain useful life, but there is documentation by the EPA on vehicle deterioration factors for heavy-duty vehicles. These deterioration factors are supplied by manufacturers and may be either additive or multiplicative in modifying the baseline emissions from a new engine. Generally, diesel engines are reported to deteriorate little over the first 290,000 miles of use (the useable limit set by the

EPA). However, engines now last 500,000 to 1,000,000 miles until the first rebuild, and no data can be found to clarify deterioration in the final stages before rebuild.

To compare the technology level, two different engines of the same model are compared that were tested by the WVU Transportable laboratory in 1994. The engine was a Detroit Diesel Corporation 6V-92TA burning D2 diesel and was a 6-cylinder unit of 9.05 liters displacement with a 277 horsepower rating. Table 4.23 shows the summary of vehicle information and the measured emissions from each vehicle.

Table 4.23 Vehicle specifications and emissions for vehicle age comparison.

Vehicle	1	2	
Type	Transit Bus	Transit Bus	
Model Year	1988	1993	
Transmission	3-Speed Auto.	4-Speed Auto.	
Test Weight	33725 lbs.	33175 lbs.	
Test Cycle	CBD	CBD	
Test Date	6/4/1994	3/16/1994	
Odometer	178,798 miles	106,748 miles	
			Difference*
NO_x (g/mile)	38.2	25.0	-35 %
CO (g/mile)	22.2	6.44	-71 %
HC (g/mile)	3.20	3.54	+11 %
PM (g/mile)	3.09	1.71	-45 %
Fuel Economy (mpg)	3.11	2.80	-10 %

*Using 1988 bus as baseline.

The newer engine was made five years after the older engine and produced emissions that for NO_X, CO, and particulate matter were lower than the older engine. The largest reduction offered by the newer engine was in CO and was 71%. The total hydrocarbon production was 11% higher on the newer engine. This simple comparison shows that for the majority of the exhaust gas constituents, reduction has occurred in the 5 year time period. Interestingly though, the fuel economy of the newer vehicle was lowered by 10%, most likely due in part to the retarding of the timing to meet NO_X emissions requirements.

Testing at WVU has included testing the same vehicle in yearly intervals. Testing from the Bi-State Development Agency in St. Louis, Missouri funded by the U.S. Department of Energy included a transit bus powered by a DDC 6V-92TA engine operating on D2 diesel. Table 4.24 shows the emissions over a span of two years as the bus accumulated mileage. From these data, the only trend is that the fuel economy decreased as the mileage increased. The emissions show no definite trend of increasing or decreasing.

Table 4.24 Emissions from one vehicle as mileage accumulated.

Odometer Reading (miles)	NO_X (g/mile)	CO (g/mile)	HC (g/mile)	PM (g/mile)	Fuel Economy (mpg)	Test Date
136,541	32.9	14.0	1.7	0.53	3.93	6/7/94
179,543	49.1	7.4	2.3	0.72	3.79	3/20/95
230,395	45.4	7.5	2.1	0.63	3.70	4/17/96

The NFRAQS testing compared the collected emissions data by emissions model year, and mileage since last engine rebuild. A trend of reduced PM emissions was recorded by Graboski et al. [1998] as model year increased, however, no other exhaust gas constituents were noticeably reduced. The conclusions show that there was no change in emissions as the vehicle mileage (since last rebuild) varied, which supports the low degradation factors currently in use.

The reader is also referred to Table 4.2, which shows the engine emissions certifications that an engine must meet, by year of manufacture. Small deviations from these levels may have occurred due to emissions credit banking, but it is evident that levels of NO_X and PM have been forced to decline through use of improved technologies over the years. A recent development of technology towards reducing diesel engine emissions is the use of exhaust gas re-circulation (EGR). EGR provides an effective means of emissions reduction without complicated engine modifications.

4.7 Terrain Traveled

The effects of the terrain traveled by a vehicle are also referred to as grade effects. The chassis testing performed on the WVU Transportable laboratory uses power absorbers and inertial flywheels to provide a load to the vehicle based on a road load equation [Lyons et al., 1991]. For this equation, it is assumed that there are no hills and the load is calculated for a perfectly flat, level terrain. Although testing that includes terrain grade has been used in the evaluation of a hybrid fuel cell bus [Wimmer et al., 1998], this has not been applied to diesel vehicles. For a comparison of emissions produced from a vehicle traveling varying terrain, the theoretical power requirement can be determined. Then, this power can be related to the emissions rate for a particular vehicle from experimental data. A simple, theoretical road load relation considering aerodynamic drag, tire rolling resistance, and grade is shown in Equation 4.2.

Equation 4.2 $$P = \frac{1}{2} \rho_a C_d A V^3 + \mu M g V + M g V \text{SIN } \theta$$

where P is the power required for a steady speed, ρ_a is the density of air, C_d is the drag coefficient based on frontal area, A is the frontal area of the vehicle, V is the speed at which the vehicle is traveling, μ is the tire rolling resistance coefficient, M is the mass of the vehicle, g is the acceleration due to gravity, and θ is the angle of inclination of the hill. The values of each constant are listed in Table 4.26.

Ramamurthy et al. [1998] plotted the relation between axle power and NO_x emissions rates for some typical diesel vehicles. This type of data may be used to project the NO_x emissions from vehicles under different use. From the required power calculated from the road load equation, the NO_x emissions rate can be determined from the regression equation of the data used to make the plots, namely Figure 4.22. The data have a bifurcation implying that there are different operating modes. The full data set is presented in Section 4.8 that discusses injection timing variances, the most probable cause of this bifurcation. A plot of the complete data is shown in Figure 4.23. The bifurcation is further discussed, and for this analysis, the set of data corresponding to the lower level of NO_X emissions was used (Figure 4.22).

For this analysis the incline grade was limited to 7 % (4 degrees above horizontal). The power was determined from the road load equation for constant grades.

Table 4.25 Constants used for terrain modeling.

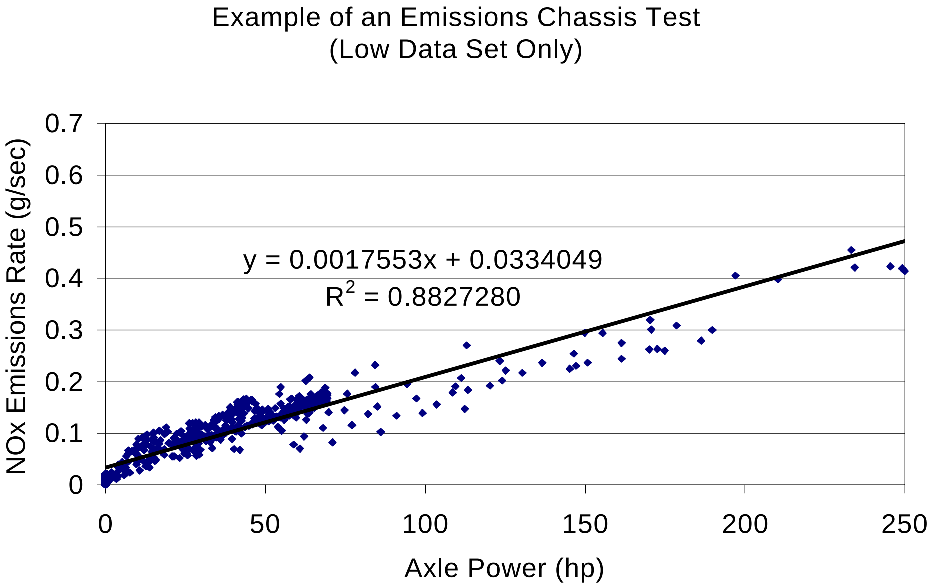
Constant	Value	Source
ρ_a	1.2 kg/m^3	Marks Handbook
C_d	0.7	Marks Handbook
A	7 m^2	Marks Handbook
μ	0.00938	40 CFR Part 86 Subpart N
M	19047 kg	
g	9.807 m/s^2	Marks Handbook

Table 4.26 shows the results of the terrain modeling for a constant ascending grade driven at a steady speed.

Table 4.26 Results of the terrain modeling.

Grade	Speed (mph)	Power (kW)	Interpolated NO_X (g/s)	Interpolated NO_X (g/mile)
0 %	80	197	0.51	23
0 %	48	67	0.19	14
3.5 %	48	207	0.53	40
3.5 %	30	118	0.32	38
7 %	30	205	0.53	64

Figure 4.22 Smoothed axle power versus shifted NO_x as used for terrain modeling.



To climb a 7 % grade, this vehicle would use 205 kW to maintain a steady-state speed of 30 mph. Almost the same power (207 kW) is required for this vehicle to maintain a speed of 48 mph when climbing a 3.5 % grade.

An oscillating terrain simulation would be informative if such factors as vehicle braking and driver shifting patterns were known. Also, knowledge about the emissions produced when the engine is operating in a power absorbing or motoring mode is unavailable. A piecewise analysis of a vehicle traveling an oscillating terrain including these factors and braking requires further investigation. One could also undertake similar modeling for CO, PM, and HC, but nonlinearities make the results less certain.

A simpler method is to assume that a vehicle emits levels that correspond to the emissions standards. Using the axle power values from the model above, PM levels would vary from 11 g/hr to 35 g/hr considering a constant travel speed on level ground and on a 3.5% grade. This is assuming a transmission efficiency of 80%, and shows a difference by a factor of three for PM.

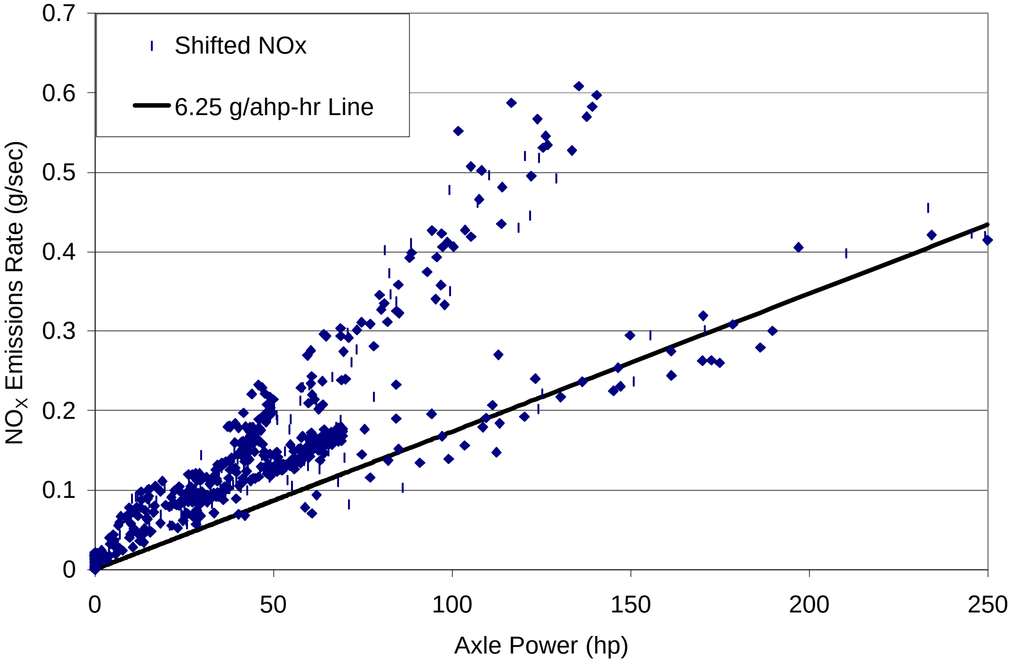
4.8 Injection Timing Variances

Emissions of NO_X and PM are known to be affected strongly by the timing of the in-cylinder fuel injection in diesel engines. Indeed, 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 and higher thermal efficiency.

Many present day electronically controlled engines do not embody timing throughout their operating range that reflects the timing employed during the engine certification test. Deviations in timing during "off-cycle" operation may lead to emissions of NO_X that are higher than those that would occur during the certification test at the same engine speed and load. In some cases available data suggest a binary timing map, with a "high" and "low" NO_X emissions rate. Since history effects may determine which of the two timing choices is in effect, it is not always possible to predict unambiguously the NO_X emissions rate given the engine torque and speed.

Figure 4.23 presents a plot of chassis-based NO_X emissions versus power output at the rear axle for a late model diesel truck. 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. The higher NO_X data set represents the "off cycle" operating points.

Figure 4.23 Smoothed axle power versus shifted NO_x showing bifurcation of data.



All present day truck emissions values used for inventory prediction rely upon the certification data, but Figure 4.23 shows that certification data will underestimate NO_X emissions in off-cycle operation. For example, in Figure 4.23, the whole cycle required 9.94 ahp-hr of energy from the truck, and yielded 110.9 grams of NO_X. This corresponds to an actual emissions rate of 11.2 g/ahp-hr for this cycle, in comparison to the 6.25 g/ahp-hr value (approximately) that might be expected. The real NO_X value in this case was 1.8 times higher than the expected value.

Between the range of 80 hp and 130 hp, there are two noticeably different sets of data points, namely "high NO_X" and "low NO_X" modes. A least squares line was fitted to each set of data in this range and evaluated at the mid-point (105 hp). The results show that in high NO_X mode, 0.44 g/sec of emissions was produced, and in low NO_X mode, 0.18 g/sec. These two modes differ by a factor of 2.4 at the 105 hp point of operation, where the low NO_X mode corresponds well with certification data.

Bifurcations in timing cause accurate emission predictions to be unreasonably difficult. Observations indicate that the choice of injection timing may be triggered in some instances by modest variations in driving style over the same chassis cycle, so that significantly different NO_X emissions may arise for similar truck behavior.

Timing variations influence the overall emissions inventory in two ways. First, the timing variations cause the actual NO_X inventory to be higher than predicted based upon certification data, and second, the timing variations cause the actual PM inventory to be lower than predicted based upon certification data. Timing variations in electronically controlled diesel engines present the single greatest obstacle to present day emissions inventory prediction.

4.9 Summary of Factors Affecting CI Emissions

This analysis included identifying the factors, vehicle components, and testing procedures that effect the measured exhaust emissions of heavy-duty vehicles. These comparisons were made from chassis dynamometer data to provide guidelines for processing this data into a useful form for emissions prediction. Data comparisons and analytical modeling were used to determine the relative effect of each factor on the measured exhaust emissions.

Since diesel engines do not produce relatively large amounts of carbon monoxide (CO) and hydrocarbon (HC) emissions, these emissions are not as important in this discussion as oxides of nitrogen (NO_X) and particulate matter (PM). The data presented here shows that CO and HC exhaust emissions levels from heavy-duty vehicles are typically well below existing certification regulations. A Report by the Health Effects Institute [1995] has predicted that heavy-duty diesel vehicles will produce over 75% of PM emissions from on-road sources by year 2000. Grumet et al. [1997] listed three categories for achieving lower emissions from diesel engines. These are engine modification, aftertreatment of the exhaust gases, and fuel modifications. Identified parameters that affect CI emissions addressed in this paper are Vehicle

Class, Driving Test Cycle, Vehicle Vocations and Local Driving Activity, Fuel Type, Engine Exhaust Aftertreatment, Vehicle Age, Terrain Traveled, and Injection Timing Variances. For each of the factors, the reader is referred to Figures 4.24 and 4.25, which show the relative effect for PM and NO_X respectively, for specific cases discussed in the preceding analyses.

Each one of the bars in these graphs represents a comparison of data or an analytical comparison. Some of these factors are closely related which makes a distinct comparison difficult. For example, the categories of test cycles and vocations are related because each test cycle is supposed to represent accurately the activity that a particular vehicle vocation would require of a vehicle. The comparison of test cycles can be taken as an indication of the difference in vehicle activity as it varies from vocation to vocation. The comparison titled “vocation” included data comparisons of tests performed at different test weights which would indicate the difference in emissions that would be expected if the same vehicle configuration was used in different types of applications.

The factor that has the largest affect on the measured emissions is the test schedule used to evaluate the emissions. This is important to identify so that a suitable method of prediction can be chosen that best eliminates this dependence since the driving schedules used may not accurately represent the activity in use of the particular vehicle for which the vehicle is being made. Vehicle age class also has a significant influence on the emissions produced. A prediction method should distinguish between these.

Figure 4.24 Effect of various factors on particulate matter emissions. Each bar represents a specific comparison discussed in the text and cannot be taken to represent all cases encountered.

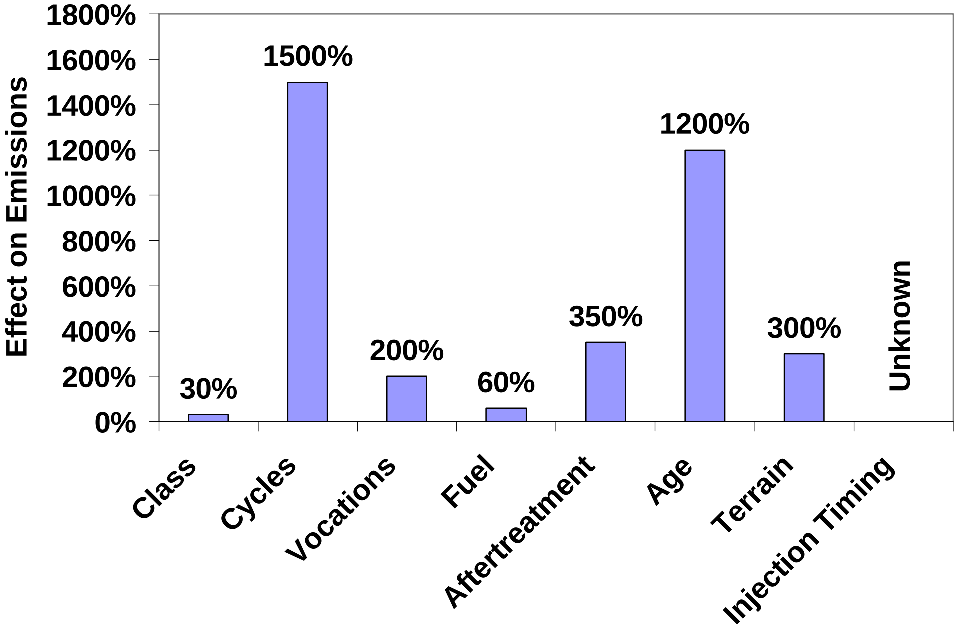
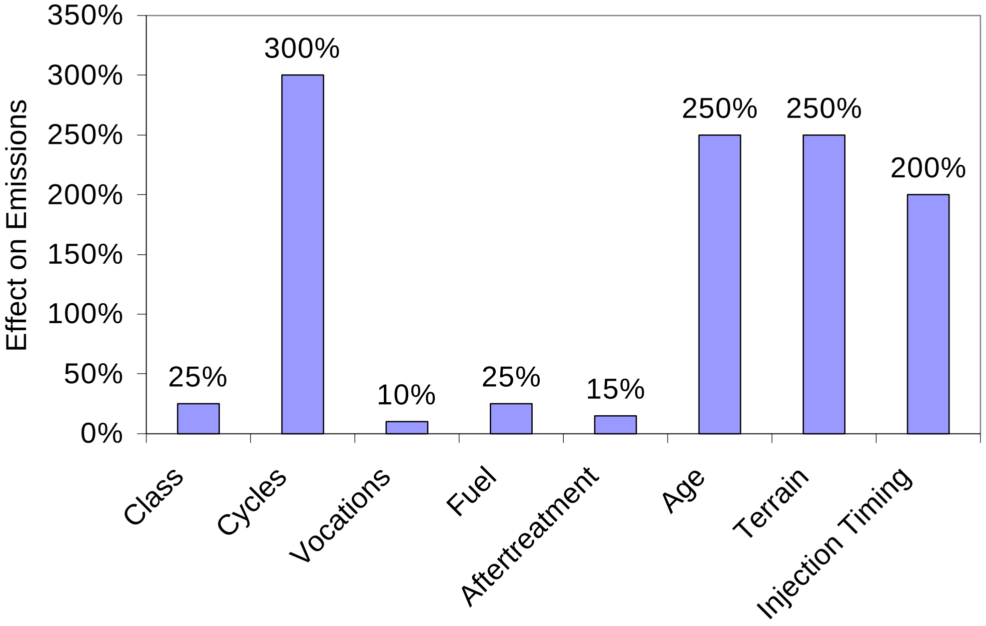


Figure 4.25 Effect of various factors on oxides of nitrogen emissions. Each bar represents a specific comparison discussed in the text and cannot be taken to represent all cases encountered.



5. Methods of Generating Emissions Factors

These methods presented here are similar to research options currently being evaluated by West Virginia University for prediction of heavy-duty truck emissions for NCHRP. Various approaches exist or can be suggested for the prediction of heavy vehicle emissions contribution to the national or 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 hold any approach superior to another. Prediction of emissions is confounded by a lack of detailed data on vehicle activity, a database of heavy-duty vehicle emissions measurements far smaller than that for automobiles, and the unquantified effects of operating parameters on the diesel exhaust produced by vehicles.

5.1 Certification Data

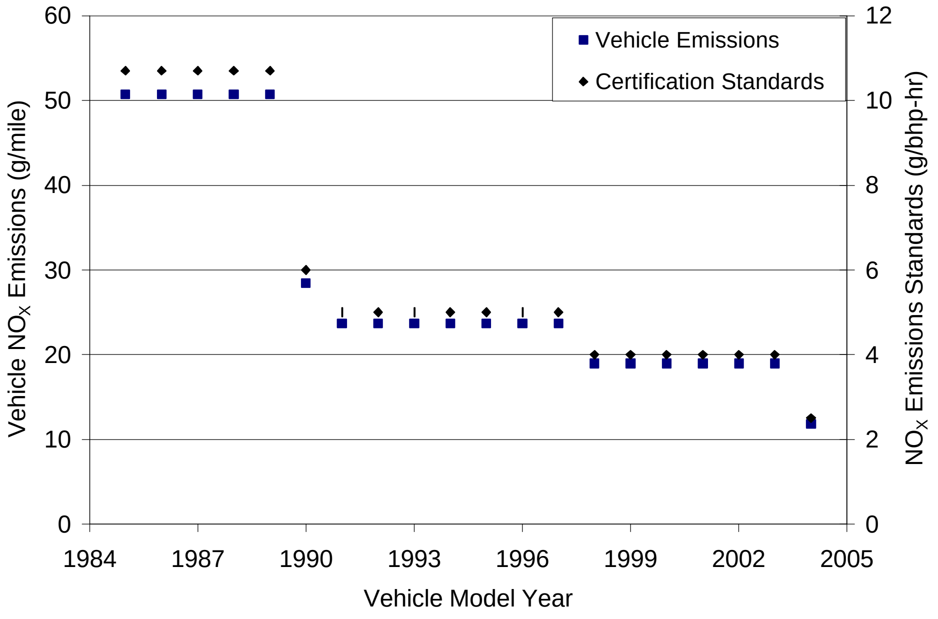
The present approach to prediction of emissions output from heavy-duty vehicles relies on the use of emissions certification data to yield, for each species, an emissions factor with units of g/bhp-hr. The Federal Testing Procedure (FTP) is a transient stationary dynamometer test used to evaluate an engine's emission production level for federal certification. 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, and some vehicles in this study were gasoline powered.

Emissions factors for heavy-duty vehicles are usually expressed in grams per mile (g/mile). The emissions certification data for the engines that power these vehicles are in units of grams per brake horsepower-hour (g/bhp-hr). One method of converting the certification data to vehicle emissions is to use the formula from Machiele (1988). To use this method, the conversion factor of brake horsepower-hour per mile (bhp-hr/mile) of the vehicle needs to be found. This is done using the fuel density, fuel energy content and fuel economy of the vehicle. The formula for vehicle emissions in g/mile is shown in Equation 5.1.

Equation 5.1 $$\frac{g}{mile} = \left(\frac{g}{bhp-hr}\right)\left(\frac{lbs}{gallon}\right)\left(\frac{bhp-hr}{lbs}\right)\left(\frac{gallons}{mile}\right)$$

Figure 5.1 shows the trend 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. These values are from the representative data given in Machiele's report for a 1980's vintage 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.

Figure 5.1 Plot of vehicle NO_X emissions versus model year using the data from Machiele (1988).



This approach may be criticized because the emissions certification test is based on vehicle behavior that is probably not relevant to today's vehicle usage and certainly cannot represent the extremes of freeway cruising and stop-and-go city service vehicle behavior. Also, the emissions test is conducted under closely controlled conditions with respect to intake air temperature and the pressures applied at the engine intake and exhaust. In reality, engines are subject to the vagaries of weather and the influence of altitude and partially blocked air filters. The certification emissions are cycle-specific to the certification cycle which may not be representative of current vehicle use. Certification data may also not reflect emissions in the field if "off-cycle" injection timing strategies are employed in the engine controller. Although off-cycle emissions will be curtailed in the future, they are present in many diesel vehicles manufactured over a decade of model years.

Although degradation factors are provided by the manufacturers to describe the change in certification test emissions with respect to accumulated mileage on engines, very few data exist to show emissions decline in real use. These factors do not account for engines that have endured tampering or malfunction or are approaching retirement or rebuild age. Some effects of tampering have been described by McKain et al. (1998), although the authors expect tampering on transit buses not to be a substantial influence. The emissions factors therefore do not reflect the spectrum of vehicle maintenance conditions in use, although it is the opinion of the authors that diesel engine emissions remain more stable than those from spark-ignited engines as the vehicles age. Concerns over effect of vehicle condition will rise as exhaust aftertreatment devices become prevalent in use.

Further inaccuracies arise in this approach due to the uncertainty in fuel energy content and vehicle fuel consumption. It is evident that fuel consumption is highly dependent on vehicle vocation and on the combination of engine, transmission and vehicle configuration.

5.2 Chassis Dynamometer Data

Heavy-duty vehicles may be subjected to emissions characterization on a chassis dynamometer, as is the present approach for light duty vehicles (Clark et al., 1995; Graboski et al., 1998; Deitzman et al., 1985). The emissions results may 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 present 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 per mile (g/mile).

There is the advantage that vehicles subjected to chassis dynamometer emissions characterization 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, can be obtained.

A problem arises in that no single cycle can hope to represent the real world spectrum of vehicle activities. Although the Urban Dynamometer Driving Schedule (Test-D) (40 CFR, Part 86) exists as a companion to the engine certification test, it does not correlate well with the engine certification test (Deitzman and Warner-Selph, 1985) and does not represent all behaviors. Although future information may be gathered to yield a few representative emissions test cycles for the fleet, these will be applicable only to future testing and existing chassis cycle data will not be useful.

It is certain that the test cycle used has profound effect to the emissions yielded. 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.

A portion of testing at WVU involved testing a single truck on 19 different test cycles. The results of NO_X in g/mile are shown in Figure 5.2. These data are preliminary and details of the testing will be published at a later date. The vehicle was a 1995 GMC box truck with a Caterpillar 3116 engine rated at 170hp. The fuel used was D2 diesel and the vehicle has a GVWR of 22,000 pounds. The engine in this vehicle employed a mechanical fuel-injection system so no off-cycle emissions schemes were possible. There is further data on the influence of cycles on emissions from a city bus in Clark et al. (1997). Figure 5.3 shows the emissions data for the 1996 New Flyer transit bus which was powered by a Detroit Diesel Series 50 engine.

Figure 5.2 NO_X emissions of 19 test schedules on one truck.

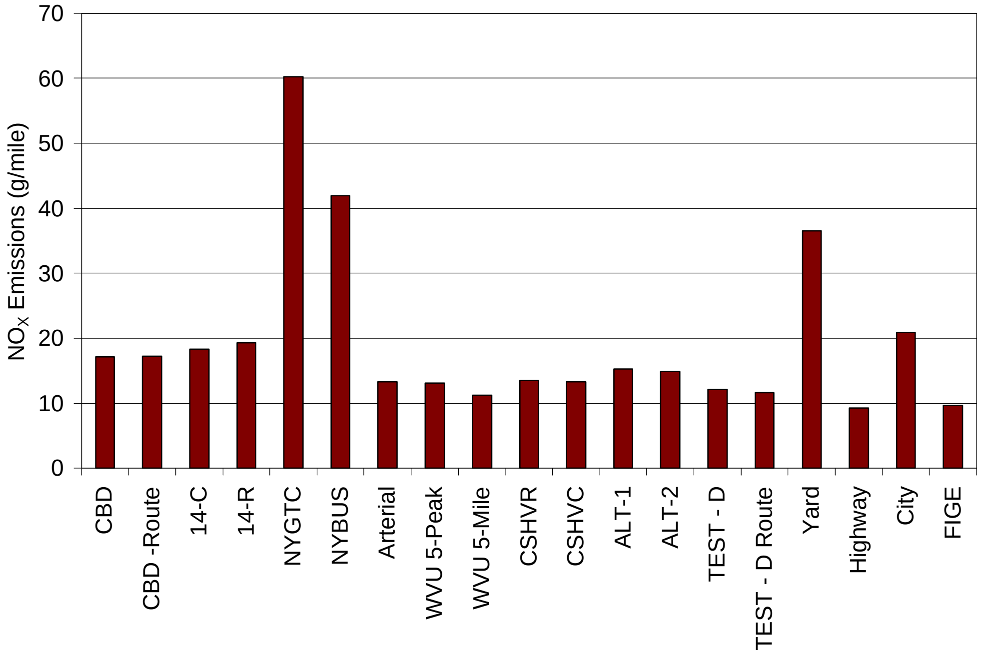
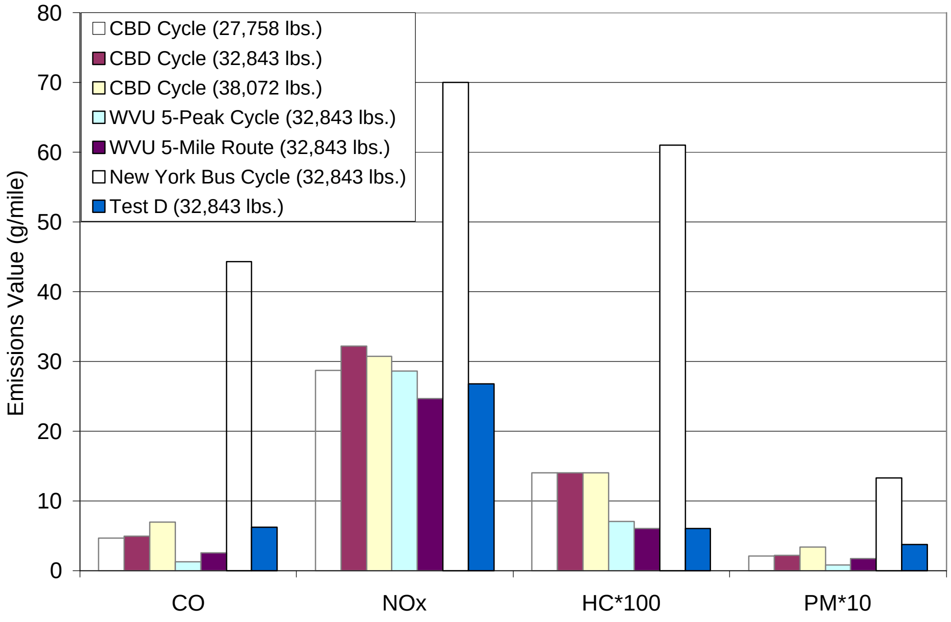


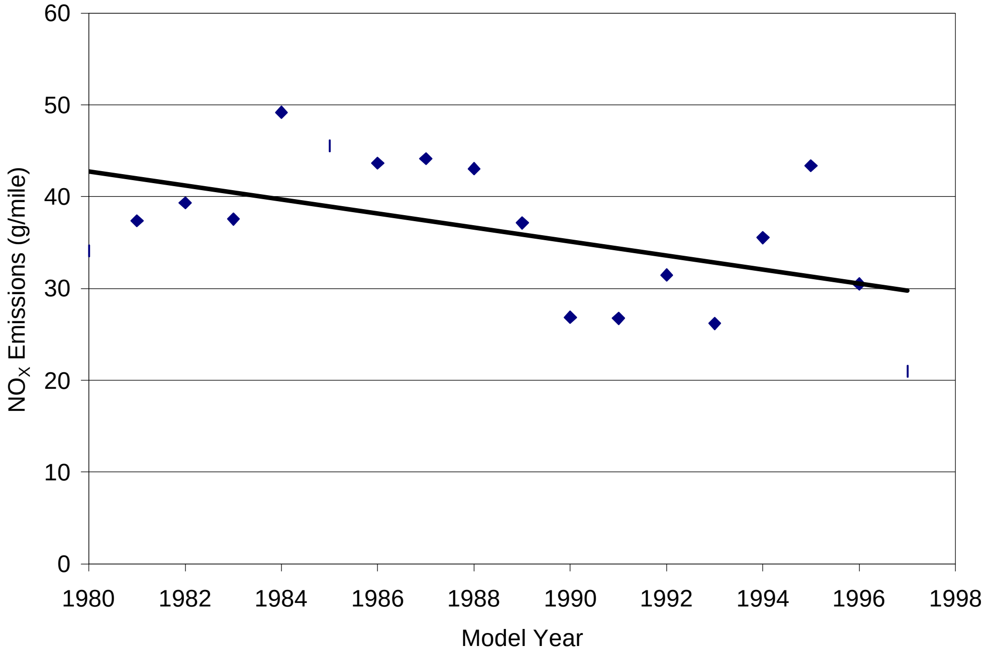
Figure 5.3 Emissions data from the 1996 transit bus on different test weights and test cycles.



Example using Chassis Data

The chassis testing laboratory at WVU reports results for a vehicle driving a test cycle in g/mile of an emissions species. This 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, which is not necessarily true in the data available. Figure 5.4 shows the results of testing of full size transit buses that was performed by WVU on diesel powered buses driving the CBD test cycle described in SAE J1376. The average value of NO_X emissions for each model year is shown. The line shown on the plot shows the trend of bus emissions factors, but this is specific to the CBD behavior.

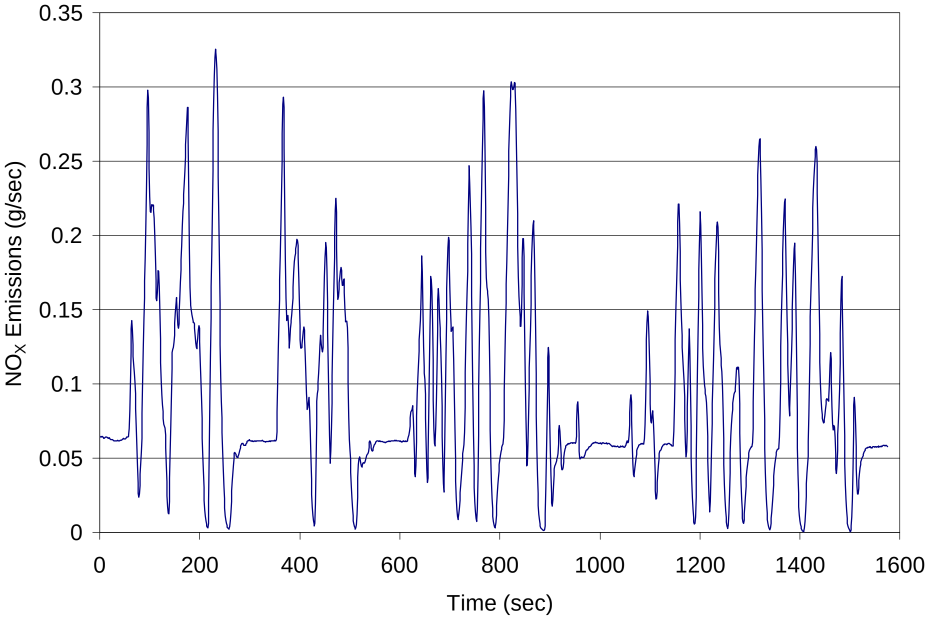
Figure 5.4 Transit bus NO_X emissions versus model year with a linear trend line for CBD Cycle data from chassis laboratory testing.



5.3 Power-Based Emissions Factors

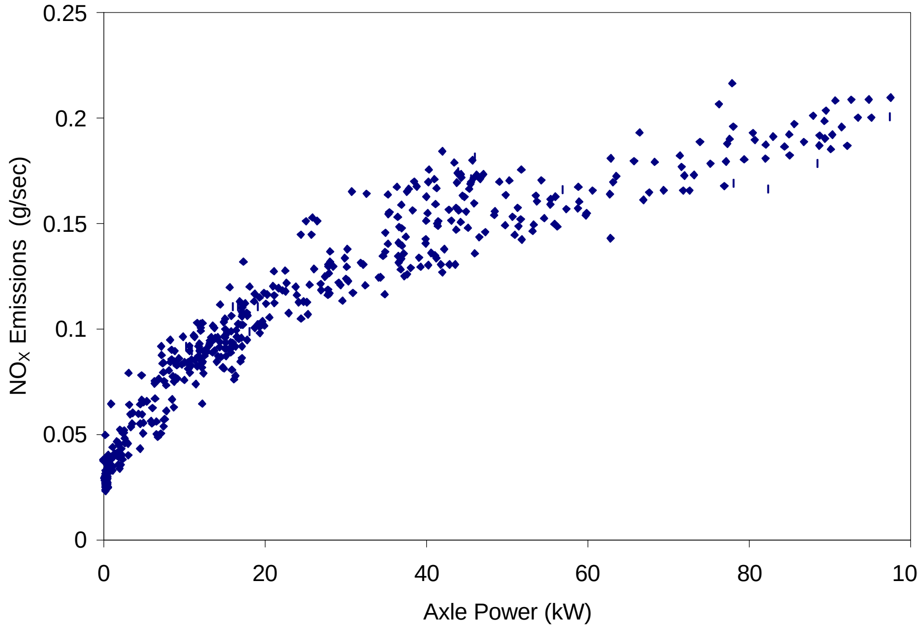
Chassis dynamometer data need not be employed directly as emissions factors. During most chassis dynamometer testing, continuous emissions data are acquired for NO_X, CO and HC and these can be considered in the development of models that can then be used to project the emissions from the vehicle under a broad range of operating conditions. To illustrate the point, Figure 5.5 shows continuous emissions gathered during testing. These data are taken in units of parts per million of species in diluted exhaust, but are readily converted to units of grams per second using the dilution tunnel mass flow rates. In using these factors, one must employ correct time alignment of instantaneous power and the emissions constituent (Messer and Clark, 1995; Ramamurthy and Clark, 1999).

Figure 5.5 Continuous NO_X emisisons for a heavy-duty vehicle following the City/Suburban Heavy Vehicle Route (CSHVR).



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, 1999) have espoused 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 are 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 5.6. In producing this model, it is necessary to consider time shifts that exist between power and emissions measurement and the "smearing" of highly transient emissions by the sampling system and respective emissions analyzers. Work has been completed at WVU to understand the time alignment of instantaneous power and its resulting emission production. The axle power is measured instantaneously yet the resulting emission is measured after a time delay of the gas traveling from the engine to the analysis bench. An effect defined as "smearing" has been observed. Smearing is when a pulse input of emissions from the engine is diffused into a bell-shaped curve when the pulse reaches the analyzers (Ramamurthy and Clark, 1998, 1999).

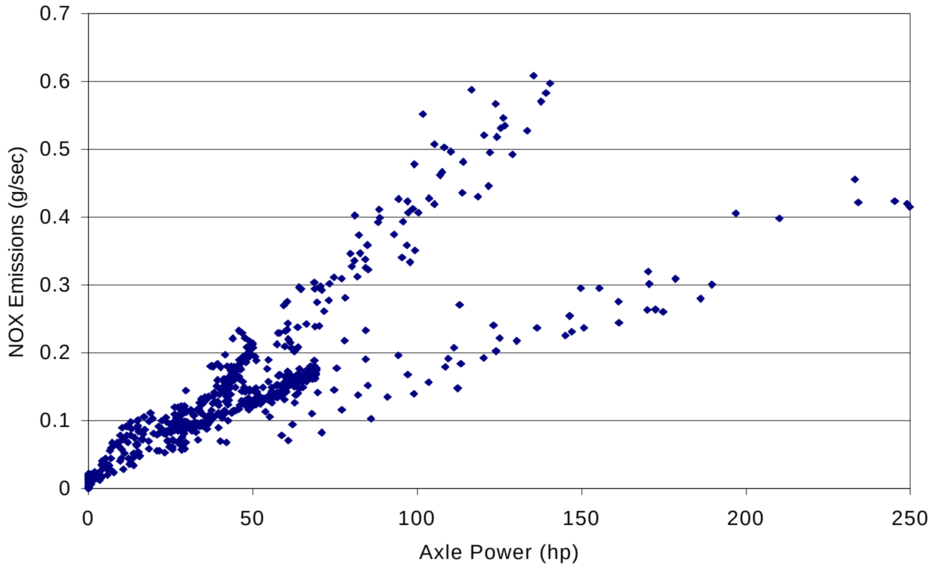
Figure 5.6 Continuous NO_X versus power for a tanker truck tested on the CBD Cycle.



Ramamurthy and Clark (1998) have found this approach 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. Variables that are available include vehicle speed (which is not a likely candidate in combination with axle power), separate axle torque and speed (which is ambiguous to the engine due to gear changing), engine speed, and time derivatives of axle power and engine speed. These issues will be explored in the future.

It is now known that engine manufacturers have configured some engine maps so that injection timing may vary according to the engine operation. In such a case, emissions in the field, or on a chassis dynamometer, may no longer relate to engine certification values because the engine operation has changed. Although this practice will cease following a consent decree between the federal government and major manufacturers, many vehicles in service have the potential to yield bifurcations in plots of NO_X emissions versus power as a result of “off-cycle” behavior. Figure 5.7 shows the problem associated with predicting NO_X in these circumstances: no ready solution is evident.

Figure 5.7 Plot of bifurcation of NO_X emissions from chassis testing.



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 production. 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.

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.

Example using Power-based Prediction

The chassis data recorded by WVU includes instantaneous emissions, axle torque, and vehicle speed. The emissions can be correlated to the instantaneous axle power. Using this method, if the axle power required of the vehicle is known, a representative emissions rate can be determined from this plot. To determine a vehicle emissions factor in the units of g/mile, the axle power for the vehicle in question needs to be determined. This can be accomplished using the road load relation considering aerodynamic drag, tire rolling resistance, and grade as shown in Equation 5.2.

Equation 5.2 $$P = \frac{1}{2} r_a C_d A V^3 + mMgV + MgV \sin(q) + MaV$$

where P is the power required for a steady speed, r_a is the density of air, C_d is the aerodynamic drag coefficient of the vehicle, A is the frontal area of the vehicle, V is the speed at which the vehicle is traveling, m is the tire rolling resistance coefficient, M is the mass of the vehicle, g is the acceleration due to gravity, q is the angle of inclination of the road grade, and a is the acceleration of the vehicle. This road load equation can be used to determine the instantaneous power required while a vehicle is traveling, as long as the speed-time schedule is known. By applying the emissions versus power data derived from chassis testing, an emissions versus time trace can be determined. Then, by summing the emissions over the cycle and dividing by the distance traveled by the vehicle, the emissions factor in g/mile can be determined.

The following example is from testing performed with a bus from the Flint Mass Transit Authority in Flint, MI. This testing was performed by WVU as a part of a program funded by the U.S. Department of Energy, Office of Transportation Technologies. The bus was powered by a Detroit Diesel Series 50 engine coupled to a 5 speed automatic transmission. The engine was a four cylinder unit, having 8.5 liters of displacement rated at 275 brake horsepower (bhp) operating on D2 diesel. Figure 5.8 shows the NO_X emissions as a function of axle power. The equation of the best fit curve was used for calculating the emissions after the road load equation was used to determine the instantaneous power required by the vehicle.

Figure 5.8 Plot and best fit curve for low NO_X mode of the Flint bus driving the CBD Cycle (seq. # 921, run # 1)

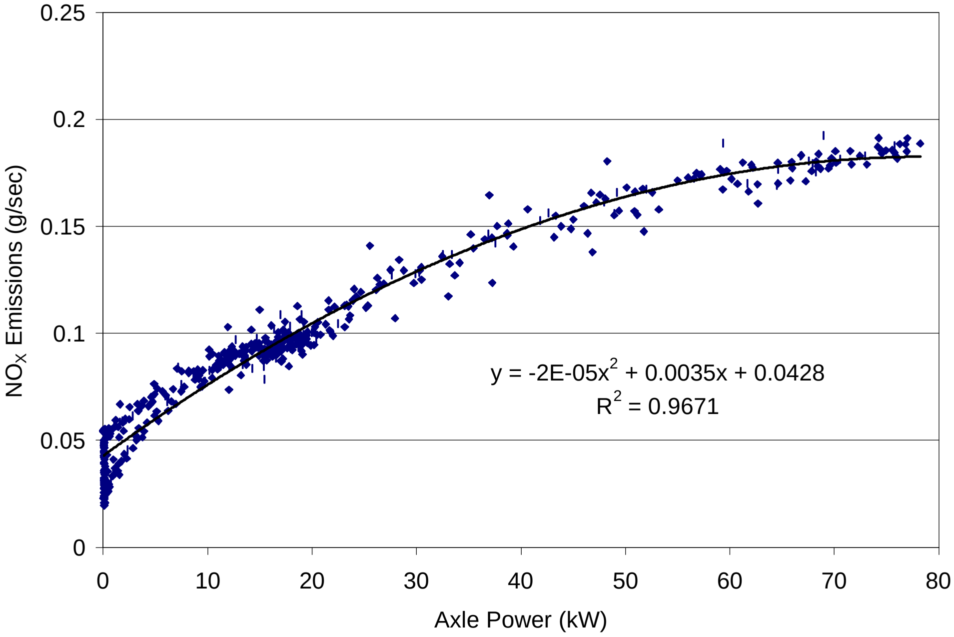


Table 5.1 Constants used in the road load equation for determining the instantaneous power demand.

Constant	Value	Source
ρ_a	1.2 kg/m^3	Marks Handbook
C_d	0.7	Marks Handbook
A	7 m^2	Marks Handbook
μ	0.00938	40 CFR Part 86 Subpart N
M	13000 kg	Flint bus test weight
g	9.807 m/s^2	Marks Handbook

Table 5.2 Results from the power-based emissions prediction.

Total distance of scheduled CBD cycle	2.0 miles
NO_X emissions predicted	52.07 g/cycle
NO_X emissions predicted	25.96 g/mile
Actual NO_X emissions measured from sequence # 921-01	28.7 g/mile
Difference of predicted and actual	9.5 %

The results show that the power-based prediction method for this example under-predicted the actual emissions produced by 9.5%. This is because the phenomenon of off-cycle emissions was present in this test, and the low NO_X portion of the test was used to determine the relationship of axle power and NO_X.

5.4 NO_X / CO_2 Ratios

NO_X and CO_2 values on a mass basis (grams) can easily be totaled from a database and applied to a particular region and 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 per gallon of fuel basis. Again, the database values are subject to the characteristics of the driving cycle followed on the chassis dynamometer.

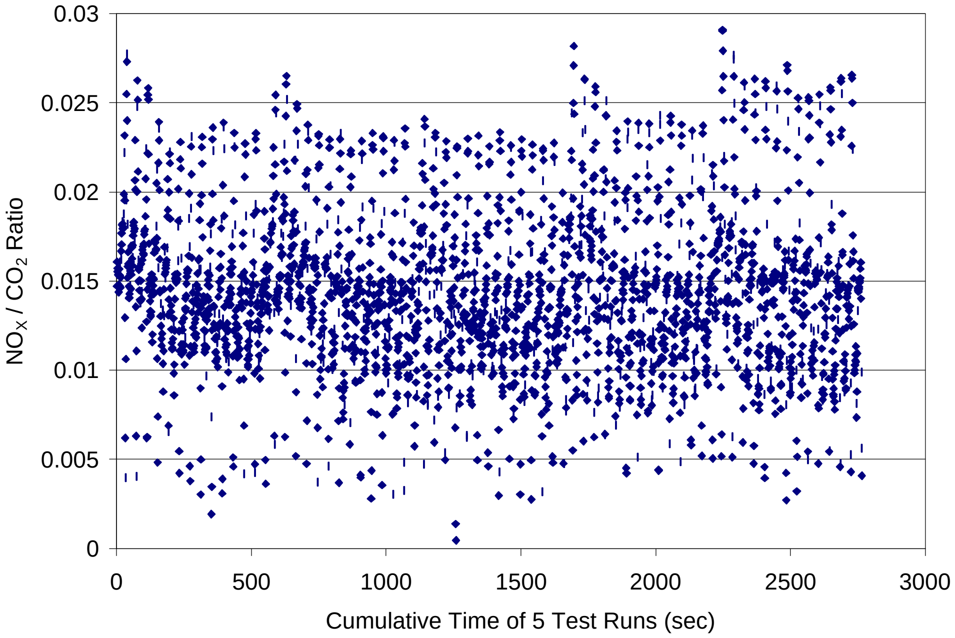
Example of NO_X / CO_2 Emissions Factors

To demonstrate this method, data from a 1996 transit bus powered by a Cummins M11 engine rated at 280 hp were used. Figure 5.9 shows the continuous data of NO_X divided by CO_2 for five consecutive test runs of the CBD cycle, the emissions data were time shifted to align with the axle power. 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 per mile, the fuel mileage of the vehicle, density of the fuel, and CO_2 production per amount of diesel need to be determined. The CO_2 production, or mass of CO_2 produced per mass of fuel used, can be obtained by using a carbon balance. This results in 44 grams of CO_2 produced for every 13.8 grams of diesel used. Assuming that the vehicle achieves 4 miles per gallon of diesel, and the specific gravity of diesel is 0.85, by using Equation 5.3 a value of emissions in grams per mile was obtained.

Equation 5.3
$$\frac{gNO_X}{mile} = \left(\frac{0.014 gNO_X}{gCO_2}\right)\left(\frac{44 gCO_2}{13.8 g\ diesel}\right)\left(\frac{gallon}{4\ miles}\right)\left(\frac{3217 g\ diesel}{gallon}\right)$$

Using the data from above, the NO_X production was determined to be 35.9 g/mile. The average NO_X emissions for the 5 tests from which the NO_X/CO_2 ratio was determined was 28.5 g/mile.

Figure 5.9 NO_X divided by CO_2 values for 5 consecutive test runs of the CBD cycle.



5.5 Speed-Acceleration Based

This approach is closely related to the modeling and modal approaches. 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 govern 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. Unfortunately, not all existing cycles cover the speed-acceleration envelope thoroughly. Figure 5.10 shows that the CBD cycle fails miserably in this regard, although the City-Suburban Heavy Vehicle Route (CSHVR) has better coverage, as shown in Figure 5.11.

Figure 5.10 Speed versus acceleration for transit bus being driven on the CBD cycle.

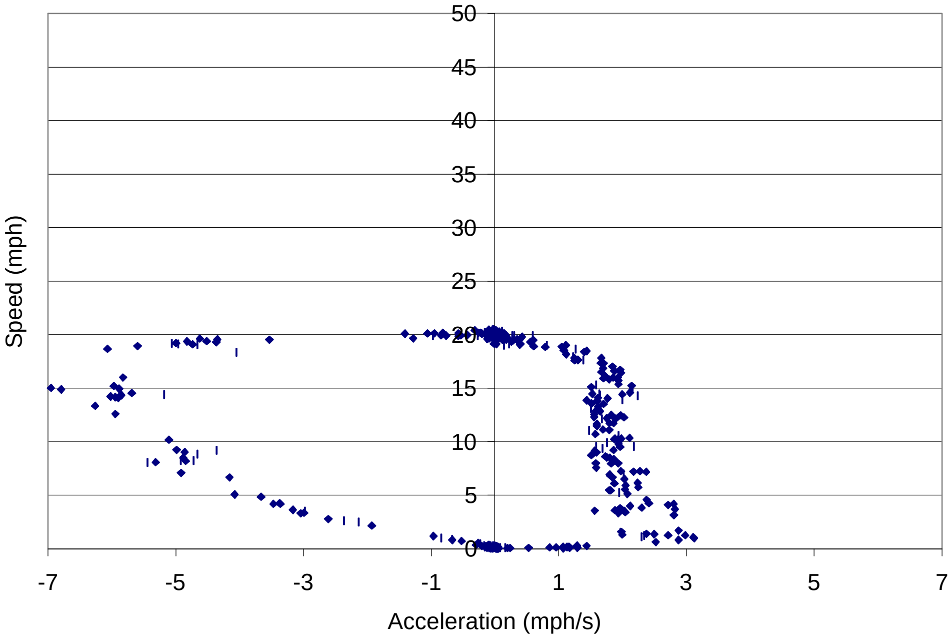
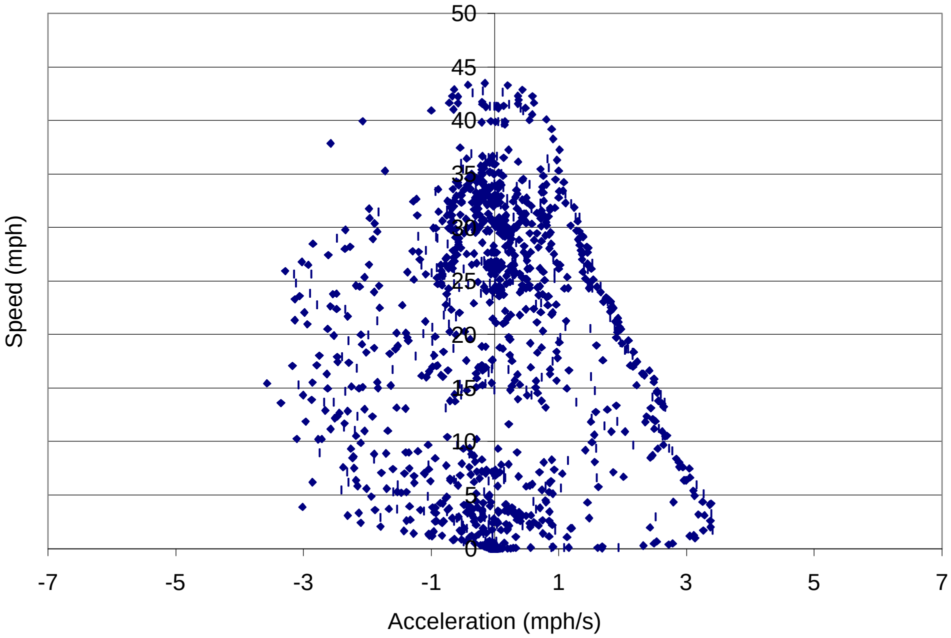


Figure 5.11 A transit bus fills a speed acceleration envelope thoroughly when exercised through the CSHVR.



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 acceleration rates are low in heavy-duty vehicles. Problems in using a speed-acceleration approach to 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 know because the test schedules used on a chassis dynamometer have no previsions for simulating hills. The WVU chassis dynamometers do not have the ability to motor the truck to simulate down hill 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 up-hill 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 is emissions data at full power.

This approach uses two variables of vehicle speed and vehicle acceleration for a multivariable analysis. The accuracy of this system relies on the bin size of each variable. To increase this accuracy, a continuous fit approach could be used that eliminates the process of putting the data into bins. One such approach would be to use a neural network. A neural network would provide a continuous, non-linear fit to the data in the speed-acceleration domain. The increased cost and complexity of this option was not desired for the accuracy needed from this basic analysis.

6. Methodology of Producing Speed – Acceleration Based Emissions Factors

The following is a description of the methodology used to convert the emissions data in WVU's database to the desired format of transit bus emissions factors. The WVU database consists 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. Each test sequence does not necessarily represent different vehicles because each vehicle may have been tested on multiple cycles (or routes) and also some vehicles were tested in multiple years.

6.1 Speed – Acceleration Profiles of Test Schedules and Creation of the Kern Cycle

The data in the WVU database were taken largely with the CBD cycle, which does not explore full power of the vehicle or require a multitude of cruising speeds. This limits the data in that not all of the speed-acceleration cells will have a value in them. Figures 6.1 through 6.4 show the speed-acceleration envelope of the common cycles used in the WVU database. Note that the CBD cycle (Figure 6.4) does not fill the range of speeds and accelerations that a typical heavy-duty vehicle can cover. A cycle was made in an ad-hoc fashion that explores multiple acceleration rates at various speeds up to a maximum speed of 50 mph. This speed was chosen as a practical limit for the WVU chassis laboratory. This cycle, termed the Kern Cycle, was used for testing on some vehicle that will be included in this analysis. Figure 6.5 shows the speed-acceleration envelope that the Kern Cycle requires from the vehicle and Figure 6.6 shows the scheduled speed versus time for the Kern Cycle. More recently, data from the CSHVR has been available and shows similar results as the Kern Cycle in that they both completely fill the speed-acceleration profile.

Figure 6.1 Plot of speed versus acceleration for a tractor truck driven on the WVU 5-Mile Route. The vehicle was powered by a 435 hp Cummins N14 using No. 2 diesel and was tested at a simulated weight of 46,400 lbs.

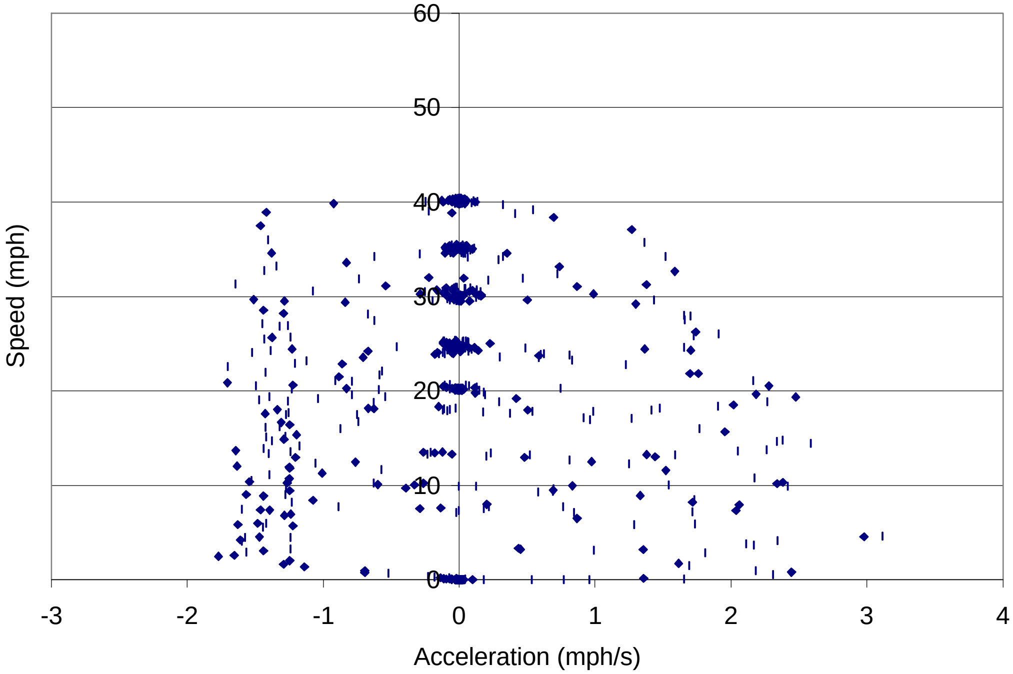


Figure 6.2 Plot of speed versus acceleration for a tractor truck driven on the City/Suburban Heavy Vehicle Route. The vehicle was powered by a 435 hp Cummins N14 using No. 2 and was tested at a simulated weight of 46,400 lbs.

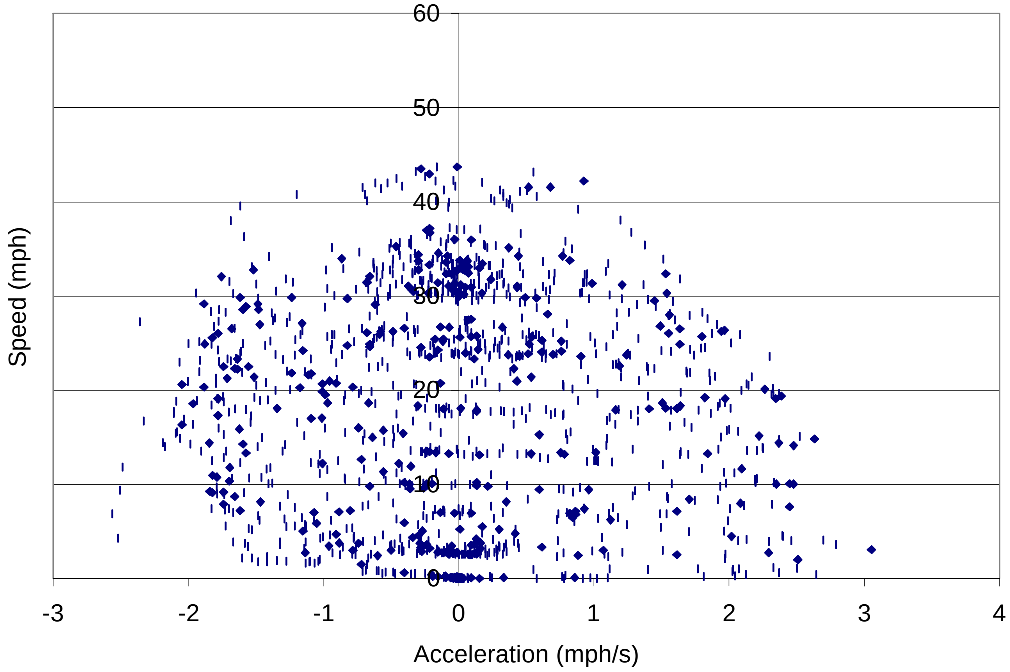


Figure 6.3 Plot of speed versus acceleration for a tractor truck driven on Test-D. The vehicle was powered by a 435 hp Cummins N14 using No. 2 diesel and was tested at a simulated weight of 46,400 lbs.

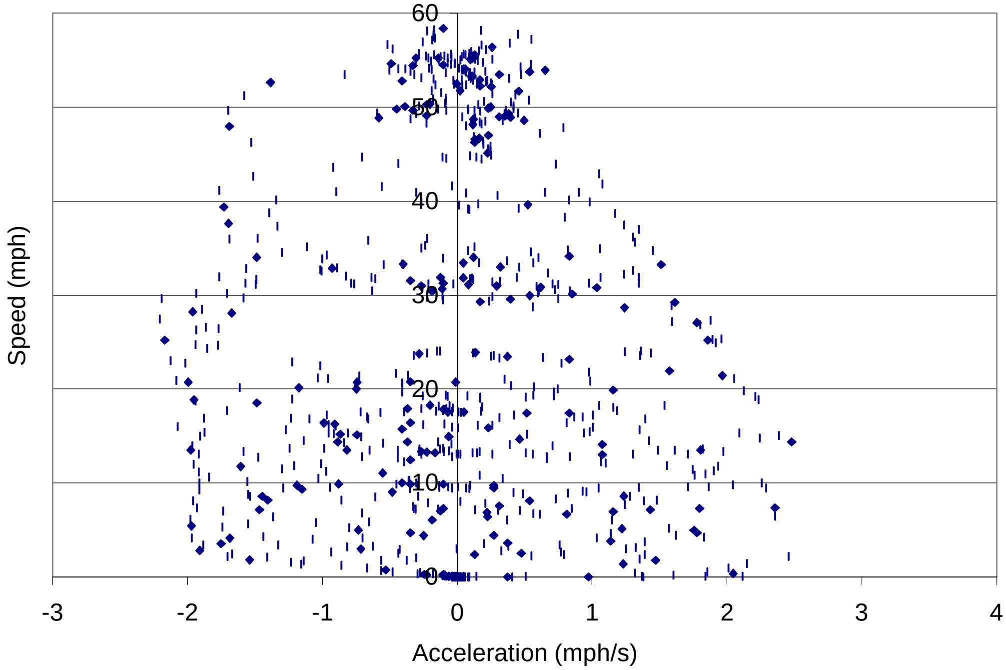


Figure 6.4 Speed versus acceleration for a transit bus driven on the CBD cycle. The vehicle was powered by a 275 hp DDC Series 50 using No. 2 diesel and was tested at a simulated weight of 33,000 lbs.

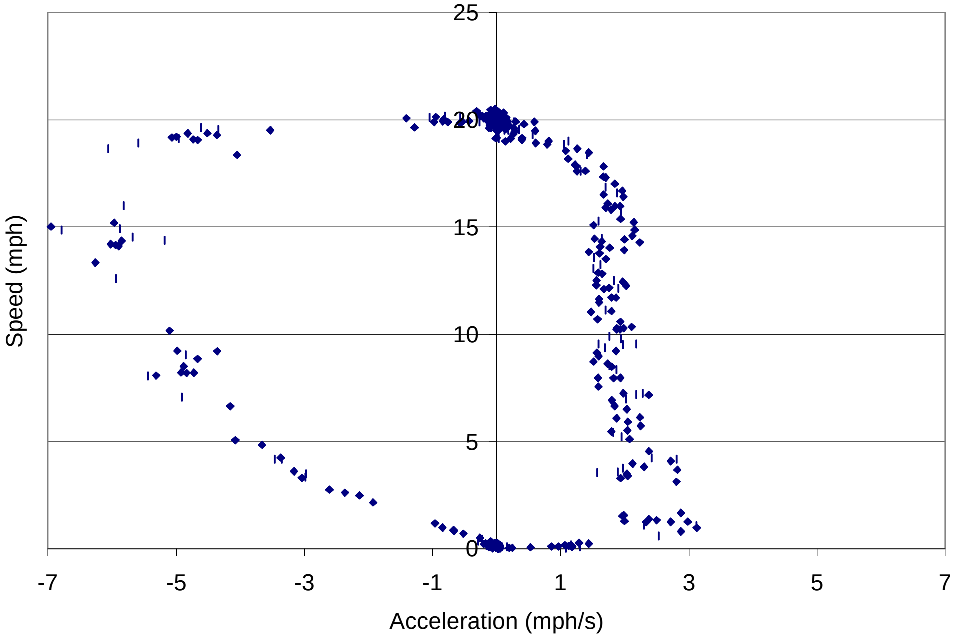


Figure 6.5 Speed versus acceleration for the Kern Cycle driven by a transit bus. The vehicle was powered by a 275 hp DDC Series 50 using No. 2 diesel and was tested at a simulated weight of 33,000 lbs.

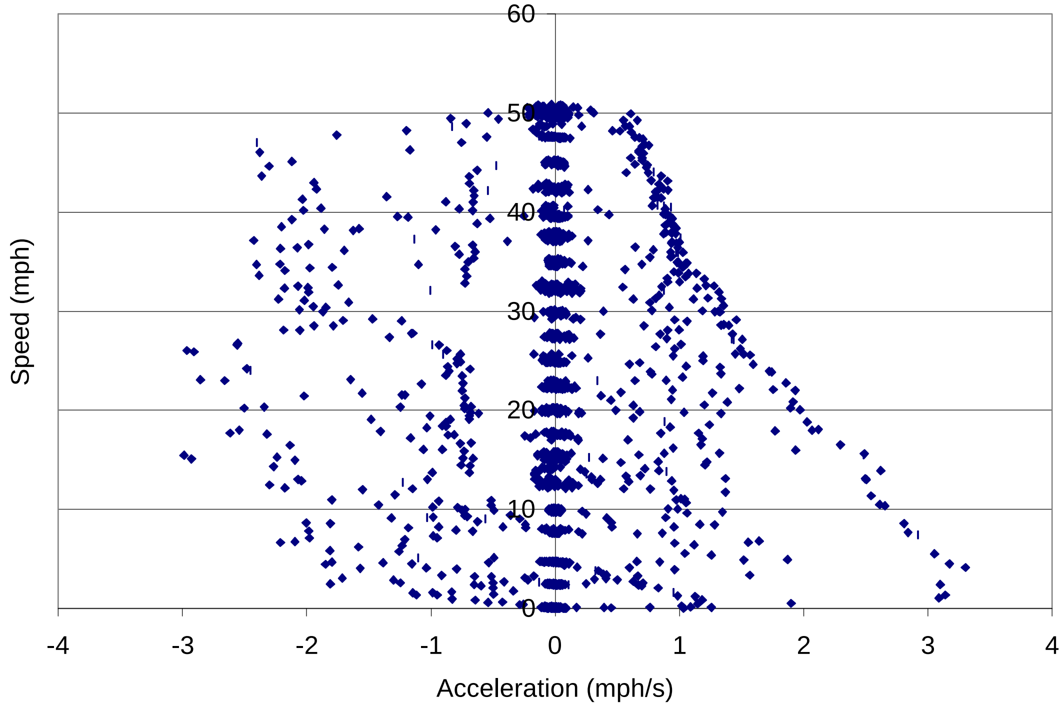
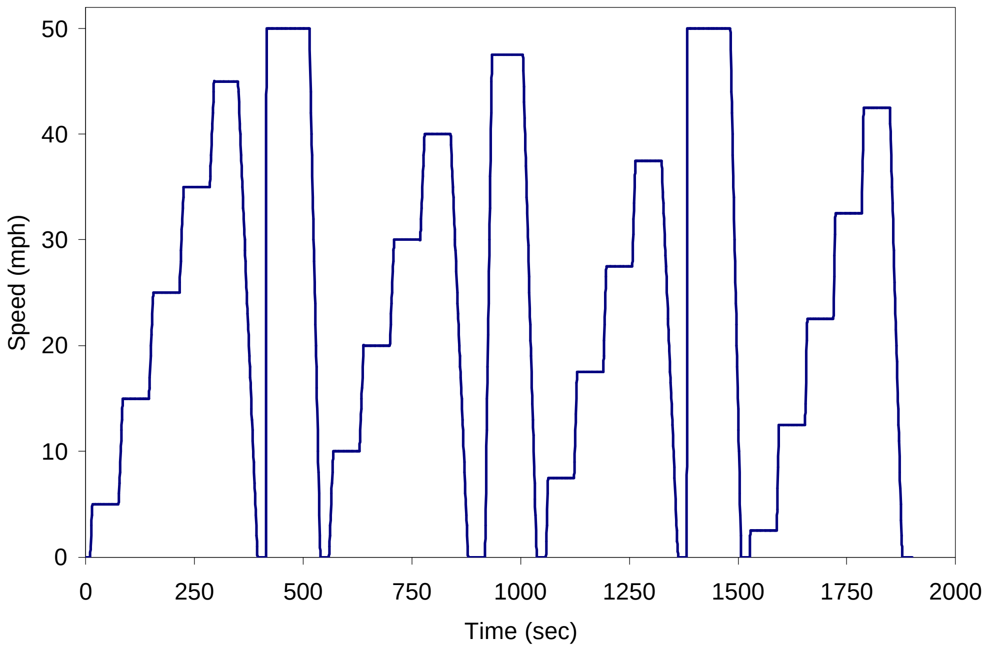


Figure 6.6 Scheduled speed versus time for the Kern cycle.



6.2 Vehicle Class and Model Year Divisions

The different vehicles tested in the WVU database can be seen in Table 6.1. This represents the No. 1 and No. 2 diesel fueled vehicles. The model year divisions are based on the certification standards. Significant changes in primarily NO_X and PM were used to determine the model year divisions for the groups presented below.

Table 6.1 Number of test sequences in WVU database based on weight class and model year.

	GVW Range (lbs.)	1985-1989	1990-1993	1994-1997	1998-current
Class 4-7 Trucks	14,001 to 33,000	8	18	19	0
Class 8 Straight Units	> 33,000	2	33	39	0
Combination Trucks	> 33,000	45	23	17	37
Transit Buses	All	83	152	92	23

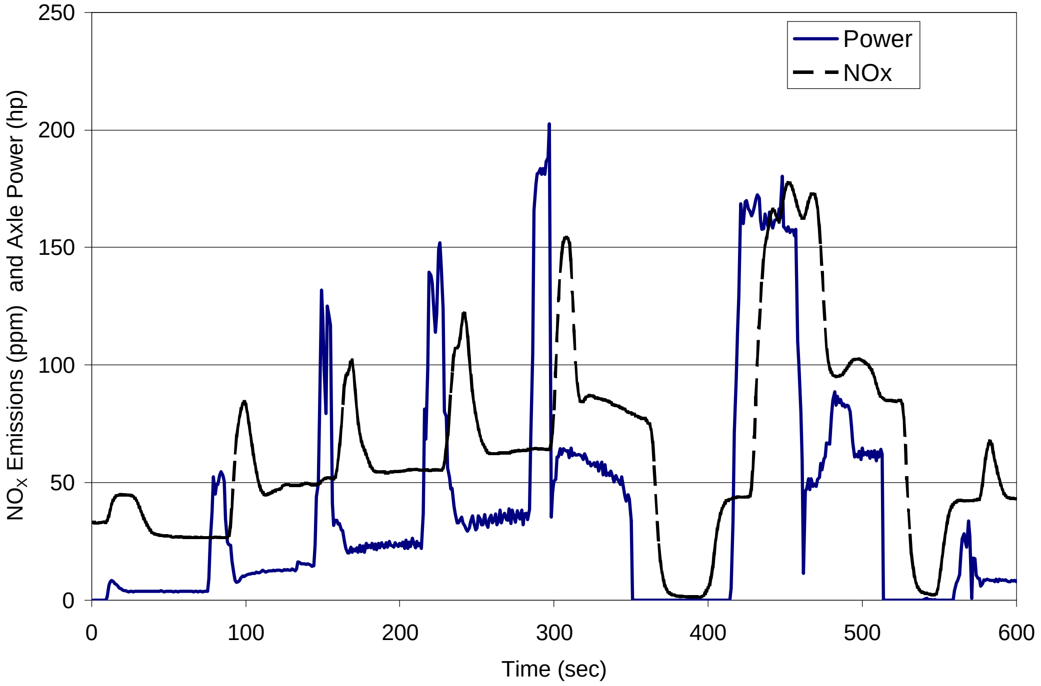
6.3 Time Alignment

The test runs contain emissions data on a second by second basis. 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 are measured. The vehicle speed and load are measured instantaneously at the axle, and there is 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 constant is 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. Figure 6.7 shows NO_X emissions and axle power versus time for the Kern cycle. 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 (Ramamurthy et al., 1998). This was accomplished using a cross-correlation method with Equation 6.1.

Equation 6.1 $$\Sigma\, d(load(t)) * d(NO_X(t+\Delta t))$$

Where the d( ) denotes the slope of the curve, and the terms "load" and "NO_X" represent the continuous curves of power (in units of horsepower) and NO_X emissions (in units of grams per second) recorded from the test. Different parameters were used for the load on the vehicle including axle power, axle torque and vehicle acceleration. The axle power was chosen for the correlation. The sum is calculated for different values of the time shift, Δt, and the time shift that produces the largest sum is used as the best correlation. This method is similar to the analysis used previously by Messer and Clark, (1995).

Figure 6.7 Continuous power and emissions versus time for a test run on the Kern Cycle showing emissions delay.



6.4 Converting data from ppm to grams per second

The continuous data measured by the laboratory was stored in units of parts per million (ppm). This data is converted to grams per second by using the following formula.

Emissions Rate (g/sec) = Emissions (ppm)/1,000,000 * Density (g/ft^3) * Flow Rate (ft^3/min)/60

The dilution factor is calculated using the formulas presented in the CFR 40 part 86.

6.5 Calculation of Axle Power

The database stores information other than the emissions data about the vehicle as a test is performed. Two of these are axle angular speed and axle torque. By using these two continuous curves, the vehicle speed in miles per hour and the axle power in horsepower were calculated.

6.6 Proportioning PM to CO

In the absence of continuously measured particulate matter in the WVU database, an alternate method was used. The PM is measured gravimetrically for each test run and is presented as a composite grams per mile for the test. The continuously measured emissions are summed for the test and also presented in grams per mile for the whole test. Taking the composite PM value and dividing by the composite CO value created a ratio of emissions. This ratio was then multiplied by the continuous CO data to make continuous PM data. This method has been explored in detail by Clark, Jarrett, and Atkinson (1999). Only recently has continuous PM data been available from the use of a Tapered Element Oscillating Microbalance (TEOM). However, the accuracy of this data and the small amount available minimize its usefulness and it has not been included in this project.

6.7 Speed – Acceleration Tables and Methods Used to Fill Empty Cells

The different speeds and accelerations that a heavy-duty vehicle experiences during travel must be divided into bins so that any operating point defined by a speed value and an acceleration value is represented by a specific bin. The emissions factor for that particular vehicle is then placed in the appropriate bin based on the corresponding speed and acceleration from the test data. The optimum range of values covered by each bin may vary depending on application and the bins presented here are for an example of this method. Table 6.2 shows NO_X emissions data for 1997 transit buses grouped according to three acceleration bins and 12 speed bins. The acceleration range (positive to negative) was divided into the three bins, which leaves many data points in each bin. By doing this, the confidence in each numerical value is greater than the data shown in Table 6.3 discussed next. The value of ±0.3 mph/s was chosen for the cruise bin range. This value was selected graphically and on advice from Nine and Daley (SAE 1999-01-1467), who developed the CSHVR.

Table 6.2 NO_X Emissions data grouped according to speed and three acceleration bins for 1997 transit buses. Emissions data are in grams per second.

		Acceleration	Cruise	Deceleration
Speed group	Range (mph)	> 0.3 mph/s	-0.3 to 0.3 mph/s	< -0.3 mph/s
0	< 2.5	0.0581	0.0322	0.0215
1	2.5-7.5	0.1041	0.0355	0.0204
2	7.5-12.5	0.1358	0.0734	0.0282
3	12.5-17.5	0.1507	0.0711	0.0339
4	17.5-22.5	0.1134	0.0834	0.0617
5	22.5-27.5	0.1498	0.1062	0.0359
6	27.5-32.5	0.1413	0.1206	0.0525
7	32.5-37.5	0.1556	0.1048	0.0704
8	37.5-42.5	0.1564	0.1120	0.0749
9	42.5-47.5	0.1621	0.1430	0.0643
10	47.5-52.5	0.1731	0.1495	0.0918
11	> 52.5	0.2339	0.2048	0.1617

A QBasic computer program was used to process the continuous emissions data recorded by the WVU THDVETL. This program is shown in Appendix A along with results for all emissions species.

The speed and acceleration bins used in the above example were modified to allow greater resolution of the accelerations. The acceleration range was divided into seven groups and the speed range was divided into 12 groups. Table 6.3 shows the speed and acceleration divisions and contains the NO_X emissions data from all of the 1997 transit buses in the WVU database. Each number represents the average of many points from all the tests included in the table. The number of points in a cell, maximum and minimum value in each, and the standard deviation of each cell were also calculated.

The cells that contain a zero represent operating points that the tested vehicles would not achieve and have been replaced with the term “No Data” (ND). Some tables have more cells without data than others, depending on which test cycles were used for testing. The cells with “No Data” in these tables can exist because of two reasons. The reasons are independent, and the first reason is that the vehicle could not achieve the performance represented by some cells (the vehicle was not powerful enough). The second reason was that the test cycle did not require the vehicle to operate at the performance level represented by some cells.

Table 6.3 NO$_X$ Emissions data grouped according to speed and multiple acceleration bins for 1997 transit buses. Emissions data are in grams per second. (ND = No Data)

		Heavy accel.	Medium accel.	Light accel.	Cruise	Light Decel.	Medium Decel.	Heavy Decel.
Speed bin	Range (mph)	> 2 mph/s	1 to 2 mph/s	0.3 to 1 mph/s	-0.3 to 0.3 mph/s	-0.3 to -1 mph/s	-1 to -2 mph/s	< -2 mph/s
0	< 2.5	0.0762	0.0533	0.0414	0.0322	0.0231	0.0199	0.0196
1	2.5-7.5	0.1088	0.1086	0.0518	0.0355	0.0282	0.0210	0.0187
2	7.5-12.5	0.1488	0.1361	0.1102	0.0734	0.0365	0.0190	0.0288
3	12.5-17.5	0.1779	0.1246	0.1016	0.0711	0.0415	0.0233	0.0346
4	17.5-22.5	0.1885	0.1454	0.1003	0.0834	0.0674	0.0571	0.0553
5	22.5-27.5	0.1979	0.1650	0.1272	0.1062	0.0552	0.0289	0.0160
6	27.5-32.5	0.1153	0.1634	0.1249	0.1206	0.0656	0.0382	0.0257
7	32.5-37.5	ND	0.1794	0.1471	0.1048	0.0799	0.0564	0.0284
8	37.5-42.5	ND	0.1557	0.1565	0.1120	0.0851	0.0563	0.0419
9	42.5-47.5	ND	0.1355	0.1664	0.1430	0.0675	0.0574	0.0014
10	47.5-52.5	ND	0.1627	0.1743	0.1495	0.0944	0.0726	0.1113
11	> 52.5	ND	0.1843	0.2366	0.2048	0.1552	0.2030	0.1689

The acceleration range was divided into seven groups and the speed range was divided into 16 groups for the next example. The extra speed bins were added so that the complete speed-acceleration envelope of the vehicle would be observed. By doing this, there are now cells without data in the higher speed ranges because the test cycle did not require the vehicle to operate at these speeds. Table 6.4 shows the speed and acceleration divisions and contains the NO_X data from all 1998 combination tractor trucks in the WVU database. Each number represents the average of many points from all the tests included in the table. The number of points in a cell, maximum and minimum value in each, and the standard deviation of each cell were also calculated.

Table 6.4 NO_X Emissions data grouped according to speed and acceleration of the vehicle for 1998 combination tractor trucks.

		Heavy accel.	Medium accel.	Light accel.	Cruise	Light Decel.	Medium Decel.	Heavy Decel.
Speed bin	Range (mph)	> 2 mph/s	1 to 2 mph/s	0.3 to 1 mph/s	-0.3 to 0.3 mph/s	-0.3 to -1 mph/s	-1 to -2 mph/s	< -2 mph/s
0	< 2.5	0.0530	0.0431	0.0358	0.0230	0.0288	0.0242	0.0195
1	2.5-7.5	0.1130	0.1014	0.0837	0.0505	0.0430	0.0249	0.0206
2	7.5-12.5	0.1410	0.1290	0.1191	0.1031	0.0575	0.0240	0.0176
3	12.5-17.5	0.1770	0.1597	0.1397	0.1240	0.0684	0.0213	0.0161
4	17.5-22.5	0.2279	0.1998	0.1538	0.1334	0.0691	0.0236	0.0211
5	22.5-27.5	0.2638	0.2409	0.1896	0.1371	0.0827	0.0315	0.0310
6	27.5-32.5	0.2444	0.2910	0.2290	0.1589	0.0854	0.0410	0.0312
7	32.5-37.5	0.2699	0.3362	0.2984	0.1421	0.0776	0.0445	0.0220
8	37.5-42.5	ND	0.3901	0.3402	0.2018	0.0721	0.0594	0.0581
9	42.5-47.5	ND	0.5440	0.4426	0.3000	0.0654	0.0686	ND
10	47.5-52.5	ND	0.5232	0.4508	0.3214	0.1144	0.0347	ND
11	52.5-57.5	ND	ND	0.5026	0.3403	0.0817	0.0597	ND
12	57.5-62.5	ND	ND	0.5489	0.4229	0.1735	0.0830	ND
13	62.5-67.5	ND	ND	ND	ND	ND	ND	ND
14	67.5-72.5	ND	ND	ND	ND	ND	ND	ND
15	> 72.5	ND	ND	ND	ND	ND	ND	ND

6.7.1 Linear Extrapolation

Two methods have been explored for filling in the cells that contain no data. For the first method, the cells containing no data in the table were filled in using linear extrapolation. A linear least-squares best fit line was created using the non-zero points, and then the equation for the line was evaluated at the appropriate speed to replace the empty cells.

6.7.2 Power-Based Extrapolation

The second method involved the use the instantaneous power required by the vehicle to maintain the speed-acceleration combination represented by each cell. A matrix based on speed and acceleration was created for each model year group and contains the instantaneous power required for the vehicle to operate at the speed and acceleration of each cell. From the measured emissions and the calculated power data, a linear least-squares line was fit to the data points that were available. The equation of this line was evaluated with the theoretical power calculated for the cells that were empty. The result was placed into the appropriate cell to complete emissions data in the speed-acceleration matrix.

For some acceleration bins, when the curve was evaluated at the higher speeds, a negative value was obtained. This occurred on the deceleration bins where the fuel is sometimes completely shut off during engine motoring, causing the middle speed bins to have very low emissions and the slower speed bins to have higher idle-like emissions. The higher speed cells in the matrix that, when interpolated were negative, were filled in using the same emissions rate as the previous cell of measured data. This causes the emissions for that acceleration column to be a horizontal line after the measured data.

6.8 Converting Emissions to Units of g/mile Using Speed-Acceleration Profiles

The project that funded this research included using the aforementioned data along with truck activity data to produce emissions factors (in units of grams per mile). The truck activity data was provided by Battelle Memorial Institute and was also in the form of a table with the same number of cells as those above. These tables were associated with a specific road type and average speed of vehicle operation on that road type, and also the vehicle class. The road types are specified by a number that corresponds to the following: 1) highway, 3) primary and secondary roads, 4) local roads. Road type 2 was merged with type 3 and was given the designation of type 3. The value in each cell of the activity tables was the percent operating time at that speed/acceleration combination, so that the sum of all cells equals 100% of the operation time. To produce one emissions factor for the particular road type, average speed, truck class, and vehicle model year, the activity table was multiplied cell by cell with the emissions table, and then summed over all cells. This produces one value in grams per second for each exhaust emissions species. The factors were then converted to units of grams per mile by dividing the factor in g/sec by the average speed of the speed class (accounting for the time units). Next, these values were placed in a table according to each of the parameters. The emissions factors are shown in Table 6.5.

Appendix B shows the QBasic computer code that was used to combine the emissions data with the activity data provided by Battelle. This computer program also performed the extrapolation procedures described above.

Figures 6.8 and 6.9 show the trend of the emissions factors across the average speed bins. Both figures show lower values in the center bins (speed bins 3, 4, and 5). The high emissions value in the units of g/mile in the low speed bins is due to the low amount of miles traveled as the vehicle is moving. The high emissions value at the higher speeds is due to the high amount of emissions produced because of high wind drag and rolling resistance loading the engine. The NO_X emissions factors for the 1990 and 1985 model year groups also show this same trend.

Figure 6.8 Plot of NO_X emissions factors for 1998 and current model year tractor trucks.

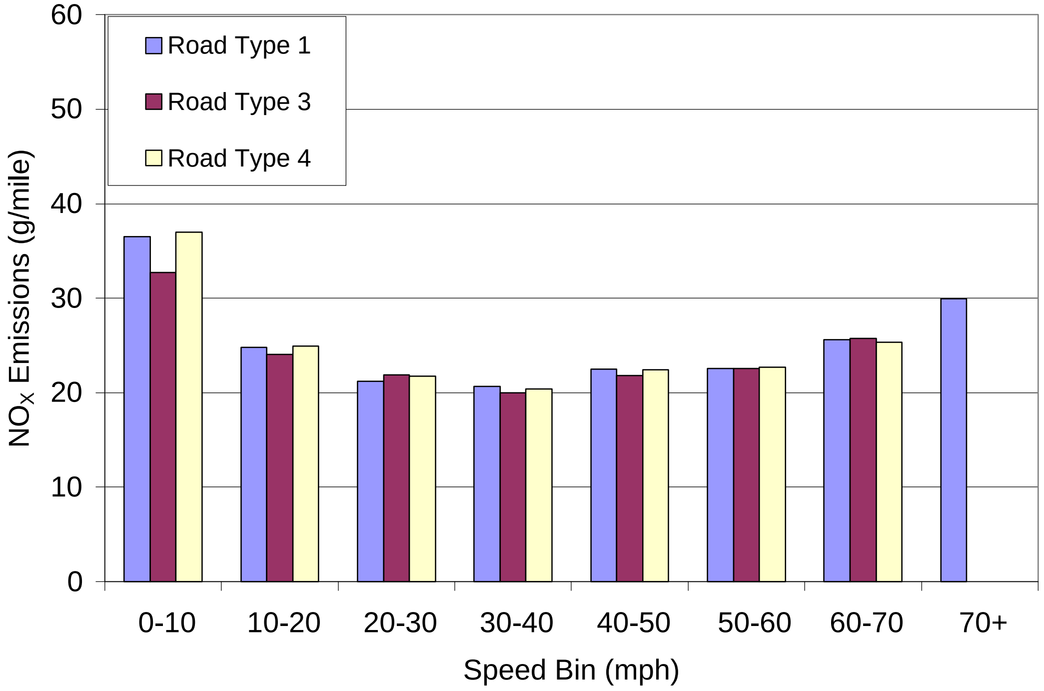


Figure 6.9 Plot of NO_X emissions factors for 1994 to 1997 model year tractor trucks.

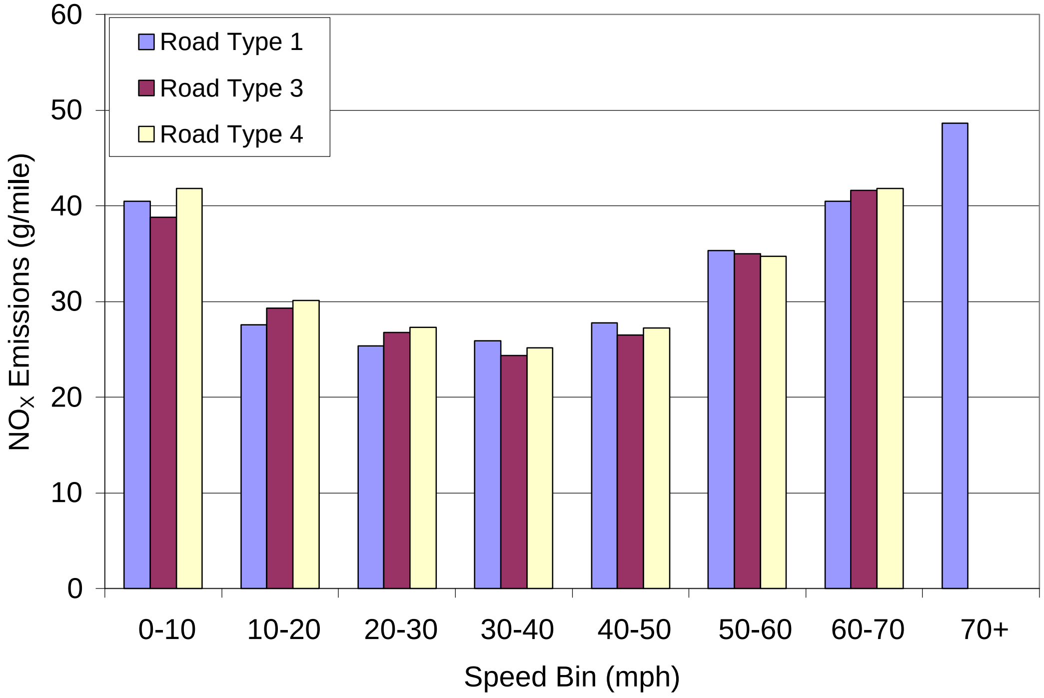


Table 6.5 Combination truck emissions factors (grams per mile).

Year Group	Emissions Type	Road Type	0-10 (mph)	10-20 (mph)	20-30 (mph)	30-40 (mph)	40-50 (mph)	50-60 (mph)	60-70 (mph)	70+ (mph)
85	NO_X	1	60.68	37.26	29.83	27.86	28.45	33.18	37.02	42.90
85	NO_X	3	52.10	35.31	31.01	26.96	27.45	32.93	37.83	-
85	NO_X	4	59.87	37.53	31.35	27.82	28.13	32.85	38.16	-
90	NO_X	1	40.84	24.32	20.04	19.08	19.22	22.31	25.08	29.25
90	NO_X	3	36.78	24.39	21.21	18.35	18.48	22.12	25.43	-
90	NO_X	4	41.09	25.42	21.59	19.12	19.03	22.09	25.57	-
94	NO_X	1	40.48	27.56	25.35	25.93	27.78	35.36	40.51	48.66
94	NO_X	3	38.81	29.31	26.80	24.38	26.49	35.03	41.64	-
94	NO_X	4	41.81	30.12	27.31	25.19	27.26	34.77	41.80	-
98	NO_X	1	36.52	24.81	21.21	20.63	22.50	22.54	25.63	29.92
98	NO_X	3	32.74	24.06	21.90	19.96	21.82	22.55	25.71	-
98	NO_X	4	36.97	24.96	21.71	20.41	22.43	22.67	25.32	-
85	CO	1	31.29	28.71	18.76	15.55	13.52	6.80	6.97	6.65
85	CO	3	26.69	26.47	21.59	15.74	13.18	7.11	5.12	-
85	CO	4	33.39	28.56	23.30	16.94	13.92	7.97	4.30	-
90	CO	1	17.16	11.80	6.85	5.20	4.11	2.35	2.46	2.62
90	CO	3	13.88	10.26	7.81	5.22	3.98	2.45	1.74	-
90	CO	4	17.07	11.24	8.57	5.77	4.16	2.80	1.51	-
94	CO	1	8.53	7.34	5.07	3.95	3.02	1.52	1.57	1.98
94	CO	3	7.85	7.46	6.03	4.00	2.95	1.55	0.92	-
94	CO	4	9.08	7.84	6.56	4.53	3.05	1.84	0.78	-
98	CO	1	9.82	6.48	3.92	2.63	1.90	1.53	1.12	1.00
98	CO	3	8.13	5.46	4.08	2.70	1.86	1.55	1.02	-
98	CO	4	10.20	6.23	4.33	2.83	1.93	1.58	1.01	-
85	HC	1	6.34	3.04	1.76	1.07	0.49	0.28	0.14	0.13
85	HC	3	5.14	2.47	1.76	1.16	0.50	0.27	0.10	-
85	HC	4	6.22	2.87	1.86	1.19	0.52	0.27	0.09	-
90	HC	1	4.85	1.79	0.99	0.66	0.48	0.30	0.22	0.13
90	HC	3	4.13	1.53	1.00	0.67	0.49	0.30	0.20	-
90	HC	4	4.74	1.73	1.05	0.69	0.50	0.31	0.20	-
94	HC	1	3.62	1.49	1.02	0.80	0.70	0.69	0.70	0.73
94	HC	3	3.10	1.30	1.00	0.79	0.69	0.69	0.70	-
94	HC	4	3.52	1.43	1.02	0.80	0.70	0.69	0.70	-
98	HC	1	4.80	1.82	1.21	0.88	0.69	0.58	0.57	0.52
98	HC	3	4.18	1.63	1.19	0.89	0.70	0.59	0.56	-
98	HC	4	4.71	1.80	1.22	0.91	0.71	0.59	0.56	-
85	PM	1	3.07	2.57	1.71	1.42	1.16	0.52	0.55	0.61
85	PM	3	2.57	2.35	1.93	1.43	1.14	0.57	0.33	-
85	PM	4	3.16	2.51	2.07	1.54	1.20	0.68	0.23	-
90	PM	1	2.08	1.38	0.83	0.65	0.47	0.23	0.25	0.28
90	PM	3	1.69	1.21	0.94	0.66	0.46	0.24	0.15	-
90	PM	4	2.06	1.32	1.03	0.72	0.48	0.29	0.11	-
94	PM	1	2.38	1.44	1.01	0.82	0.70	0.52	0.53	0.57
94	PM	3	1.99	1.31	1.09	0.82	0.68	0.54	0.46	-
94	PM	4	2.35	1.41	1.13	0.86	0.70	0.57	0.43	-
98	PM	1	1.26	0.91	0.58	0.38	0.27	0.27	0.21	0.18
98	PM	3	1.05	0.77	0.59	0.39	0.27	0.27	0.20	-
98	PM	4	1.33	0.88	0.62	0.41	0.28	0.27	0.21	-

7. Results of Emissions Prediction

7.1 Comparison of Results

The emissions data in the form of the speed-acceleration tables were used to predict the emissions from the CBD test schedule. This was accomplished by "driving" the CBD cycle and reading the instantaneous emissions value from the table that corresponds with the speed and acceleration at each point throughout the cycle. The computer program shown in Appendix C was used to perform this simulation. Next, the instantaneous emissions were summed throughout the cycle to produce a composite grams per mile emissions factor. This factor in units of grams per mile was then compared to the measured data. The speed-acceleration tables that were used for this prediction were derived from one test sequence, which contains data from only one test schedule. Three different test sequences were used for the source of the emissions data, and are the CBD Cycle, the Kern Cycle, and the CSHVR. Table 7.1 shows the results of predicting the CBD Cycle emissions from various test schedule data processed into the speed-acceleration tables. The prediction from the Kern Cycle data produced an error much higher than the predictions from the other cycle data. This is because the Kern Cycle has a smaller number of transients and the overall emissions produced from this cycle are lower than the other cycles.

Table 7.1 Predicted emissions using the speed-acceleration method from one test schedule.

	Emissions Factor	Difference
Bus emissions on CBD Cycle	30.0 g/mile	-
CBD emissions predicted from CBD Cycle emissions	31.6 g/mile	+ 5 %
CBD emissions predicted from Kern Cycle emissions	24.0 g/mile	- 20 %
CBD emissions predicted from CSHVR emissions	30.5 g/mile	+ 2 %

The speed-acceleration tables containing emissions data were also produced with all vehicles in a year group averaged together as shown in chapter 6. These tables represent data as if one vehicle drove multiple test schedules many times and all the data were placed into these tables. The above approach for predicting emissions was also completed with the composite data. Tables 7.2 and 7.3 show the results of using the emissions data for all 1998 tractor truck tests in the database to predict the emissions of the CSHVR and the WVU 5-Mile Route. Two tests were selected to compare the measured data to the predicted values. The results are shown in units of grams per mile for each test and the speed-acceleration prediction. The tables also show the derived emissions factor (in units of grams per mile) that was weighted by the Battelle activity data. The average speed of each test schedule was used to determine the emissions factor from Table 6.6.

Table 7.2 Predicted NO_X emissions using the speed-acceleration method from all 1998 tractor truck emissions using the CSHVR (average speed = 14.9 mph).

	Emissions Factor	Difference
Measured from seq. # 1149	24.6 g/mile	-
Predicted for seq. #1149	23.2 g/mile	- 5.7 %
Predicted from activity weighted table	24.8 g/mile	+ 0.8 %

Table 7.3 Predicted NO_X emissions using the speed-acceleration method from all 1998 tractor truck emissions using the 5-Mile Route (average speed = 20.1 mph).

	Emissions Factor	Difference
Measured from seq. # 1121	20.1 g/mile	-
Predicted for seq. # 1121	20.6 g/mile	+ 2.5 %
Predicted from activity weighted table	21.2 g/mile	+ 5.5 %

The two test sequences used in the above analyses are tests from a 1998 tractor truck. This one tractor truck was the only 1998 vehicle in the database at the time the speed-acceleration tables were made, and its emissions data was the only data that was used in creating the speed-acceleration tables.

The emissions data in the speed-acceleration table for 1994 to 1997 tractor trucks was also used for predicting the emissions of certain test sequences. These tables contain emissions data from a various number of vehicles, which make them more comprehensive in an inventory setting, but less accurate at predicting the emissions from one specific vehicle. Tables 7.4 and 7.5 show the results of using these tables for NO_X.

Table 7.4 Predicted NO_X emissions using the speed-acceleration method from all 1994 to 1997 tractor truck emissions using the 5-Mile Route (average speed = 19.9 mph).

	Emissions Factor	Difference
Measured from seq. # 0951 (1995 model year)	28.1 g/mile	-
Predicted for seq. # 0951	24.0 g/mile	- 15 %
Predicted from activity weighted table	27.6 g/mile	- 2 %

Table 7.5 Predicted NO_X emissions using the speed-acceleration method from all 1994 to 1997 tractor truck emissions using the 5-Mile Route (average speed = 16.1 mph).

	Emissions Factor	Difference
Measured from seq. # 0961 (1994 model year)	33.5 g/mile	-
Predicted for seq. # 0961	27.5 g/mile	- 18 %
Predicted from activity weighted table	27.6 g/mile	- 18 %

The comparison presented in Table 7.6 was conducted using a single vehicle. The tractor truck was a 1998 International Eagle powered by a Cummins N-14 engine rated at 435 hp. Simulated test weight was set to 46,400 lbs. The vehicle was originally operated through various cycles, including the CSHVR, while emissions were measured. Two speed-acceleration emissions matrices were produced. One (MATRIX A) was produced from a single CSHVR test on this vehicle alone. The second (MATRIX B) was produced using a far larger database incorporating all available chassis emissions test data from this vehicle operating on a variety of cycles.

The speed-time data from that specific CSHVR test were combined with the emissions values in each of the two matrices described above to yield overall emissions levels (in g/mile) for the whole CSHVR test. Table 7.6 shows these results of using the processed emissions data to predict the emissions of the CSHVR test schedule. Agreement between the actual data and the two predictions is good.

Table 7.6 Predicted NO_X emissions using the speed-acceleration method from all 1998 tractor truck emissions using the CSHVR (average speed = 14.9 mph).

CSHVR emissions data	Emissions Factor	Difference
Actual emissions from dynamometer test (seq. # 1149)	24.6 g/mile	-
Predicted using MATRIX A from the CSHVR test on the same vehicle.	25.8 g/mile	+ 4.9 %
Predicted using MATRIX B from several tests using various cycles.	23.2 g/mile	- 5.7 %

The next comparison detailed in Table 7.7 was conducted by comparing a number of actual individual vehicle emissions levels to a level predicted using the proposed model. The comparison was done using the WVU 5-Mile Route as a vehicle activity basis, because there was a wealth of data on this cycle. The predicted NO_X emissions, gained using an emissions matrix employing all emissions data from a variety of cycles, for 1994 to 1997 tractor trucks operated through the speed-acceleration behavior of the 5-Mile Route, sum to 24 g/mile for the whole 5-Mile Route. Table 7.7 presents the values of actual emissions for 1994 to 1997 tractor trucks driven over the 5-Mile Route for comparison with this number. Clearly emissions for each vehicle will not agree with this 24 g/mile number because vehicle-to-vehicle emissions variations are substantial. However, the average of the 5-Mile Route tests that contributed to the emissions matrix differs little from the predicted value for the 5-Mile Route.

Table 7.7 Predicted NO_X emissions using the speed-acceleration method from all 1994 to 1997 tractor truck emissions using the WVU 5-Mile Route (average speed = 19.9 mph).

	Emissions Factor
Predicted for 5-Mile Route	24.0 g/mile
Measured from seq. # 0476	14.7 g/mile
Measured from seq. # 0671	20.7 g/mile
Measured from seq. # 0951	28.1 g/mile
Measured from seq. # 0961	27.5 g/mile
Measured from seq. # 0962	28.8 g/mile
Measured from seq. # 0963	32.8 g/mile
Measured from seq. # 0964	33.8 g/mile
Measured from seq. # 0976	28.5 g/mile
Measured from seq. # 0977	31.9 g/mile
Measured from seq. # 0978	35.2 g/mile
Measured from seq. # 0979	33.5 g/mile
Measured from seq. # 1059	20.8 g/mile
Measured from seq. # 1060	20.9 g/mile
Measured from seq. # 1061	17.1 g/mile
Average from 5-Mile Route tests	26.7 g/mile
Difference from predicted value	10 %

7.2 Incorporation of Various Factors Effecting Emissions

7.2.1 Effect of Age/Mileage-Accumulation on Emissions

From the WVU emissions database, there are only eight different vehicles that have been tested three or more times throughout their usage. The highest mileage on a vehicle that was tested was 230,000 miles, and the largest span of mileage accumulation was approximately 133,000 miles. These extremes were encountered on two different vehicles. This data lacks both mileage span and a respectable number of vehicles for comparing the emissions as mileage accumulates on an in-use vehicle. The emissions data shows little or no increase in emissions as mileage accumulates. The two conclusions that can possibly be made from this data is either 1) this is not enough data to make a decision about age effects, or 2) there is no change in emissions as mileage accumulates over the range of mileage accumulation observed in the WVU database.

Table 7.8 presents data from one of the vehicles that were tested multiple times at various levels of mileage accumulation.

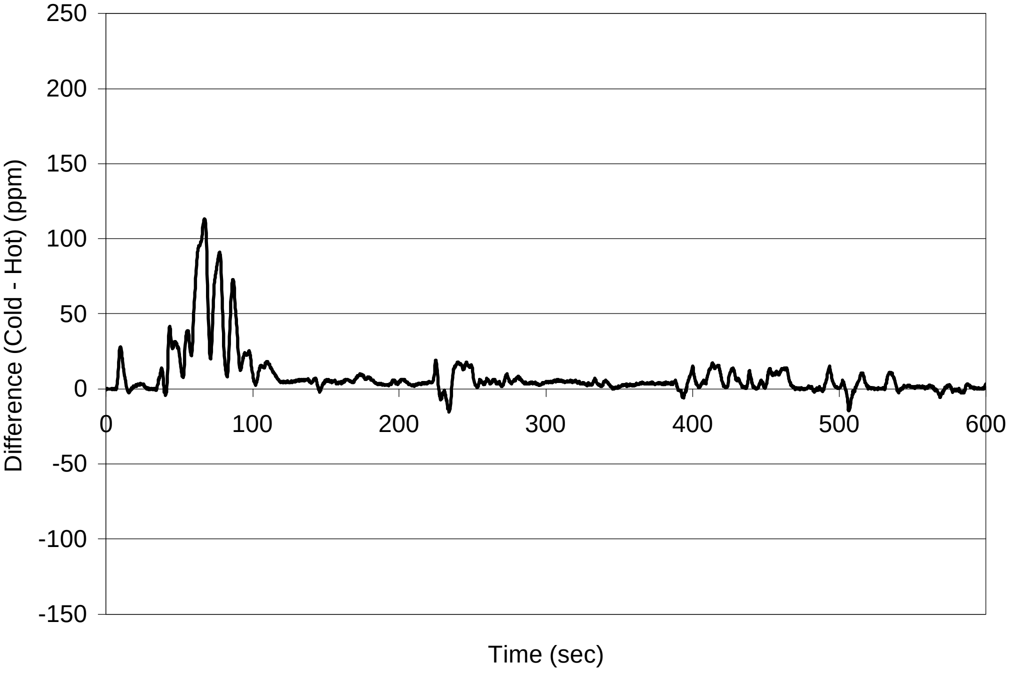
Table 7.8 Mileage accumulation data for a 1989 transit bus powered by a DDC 6V-92TA engine rated at 277 hp.

Test ID	Odometer (miles)	CO (g/mile)	NO_X (g/mile)	HC (g/mile)	PM (g/mile)	CO_2 (g/mile)	Fuel Economy (mpg)	Test Date
287	136,541	14.0	32.93	1.68	0.53	2552	3.93	6/7/1994
392	179,543	7.4	49.11	2.29	0.72	2668	3.79	3/20/1995
655	230,395	7.5	45.39	2.08	0.63	2730	3.70	4/17/1996

7.2.2 Cold Start Emissions

The only data reflecting the emissions for hot start and cold start operation available from the WVU database resides in stationary engine dynamometer data from Federal Test Procedure (FTP) certification tests. The NO_X emissions from one set of stationary tests were considered to demonstrate the possible analysis to develop an emissions factor of grams per cold start to be used with the number of cold starts from the activity data. Figure 7.1 shows a plot of the difference between the cold NO_X emissions and the hot NO_X emissions versus time for an FTP test. These two tests were run consecutively. The large positive and negative differences at the end of the test are most likely from a small time misalignment between the two tests.

Figure 7.1 Plot of the difference between cold and hot NO_X emissions for an FTP.



The two tests differ greatly for approximately the first two minutes of the test and then the difference becomes smaller. To compare the tests, a term referred to as the "penalty ratio" has been adopted. The penalty ratio is the ratio of sums of the cold start emissions over hot start emissions for a specified time. A penalty ratio of 1.00 would mean that the cold test produced the same emissions as the hot test. Table 7.9 gives the penalty ratio as the test progresses. The data should be read as "for an operating time of 60 seconds, the cold test produced 1.3 times the emissions of the hot test." Equation 7.1 shows the formula for converting the time that the emissions differs for a cold start and the penalty ratio to the desired factor with units of excess grams of emissions per cold start. The grams per second term is weighted by the activity data and is associated with a particular road type, average speed, model year, vehicle type, and emissions type. Assuming for this example that the emissions rate is 0.15 grams per second, the corresponding excess cold start emissions are shown in Table 7.9. The emissions rate for this example was chosen to be representative of tractor trucks and for the final analysis, the actual rate in grams per second will be used.

Equation 7.1 $$\frac{excess\ grams}{cold\ start} = \left(\frac{grams}{second}\right) * \left(\frac{seconds}{cold\ start}\right) * \left(penalty\ ratio - 1\right)$$

Table 7.9 Example of penalty ratio and NO_X emissions per cold start for different lengths of time considered for cold operation.

Cold Operation Time (sec)	Penalty Ratio	Excess Emissions per Cold Start (grams/cold start)
0	1.000	0.0
60	1.303	2.7
120	1.558	10.0
180	1.534	14.4
240	1.387	13.9
300	1.323	14.5
360	1.320	17.3
420	1.251	15.8
480	1.229	16.5

This factor can then be applied to the number of cold starts that is determined from the activity data.

7.2.3 Off-Cycle Operation

Off-cycle emissions arise when diesel fuel injection timing is varied, commonly to facilitate improved fuel economy, but also to improve cold start in some circumstances. The effect is that emissions of oxides of nitrogen (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.

Let us assume that the off-cycle ("highway") emissions and on-cycle ("urban") 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.

The existing WVU chassis dynamometer database shows incidences of high NOx emissions that may be ascribed to off-cycle fueling strategies. Figures 7.2 and 7.3 show data from over-the-road tractors operating over the WVU 5-Mile Route.

Figure 7.2 A class 8 tractor truck driving the WVU 5-Mile Route showing off-cycle emissions at the end of the 2nd, 4th, and 5th peaks. The vehicle was a 1994 White GMC powered by a Caterpillar 3176BG rated at 350 hp. The transmission was a 9-Speed manual and the fuel was No. 2 diesel. Test weight was 42,040 lbs.

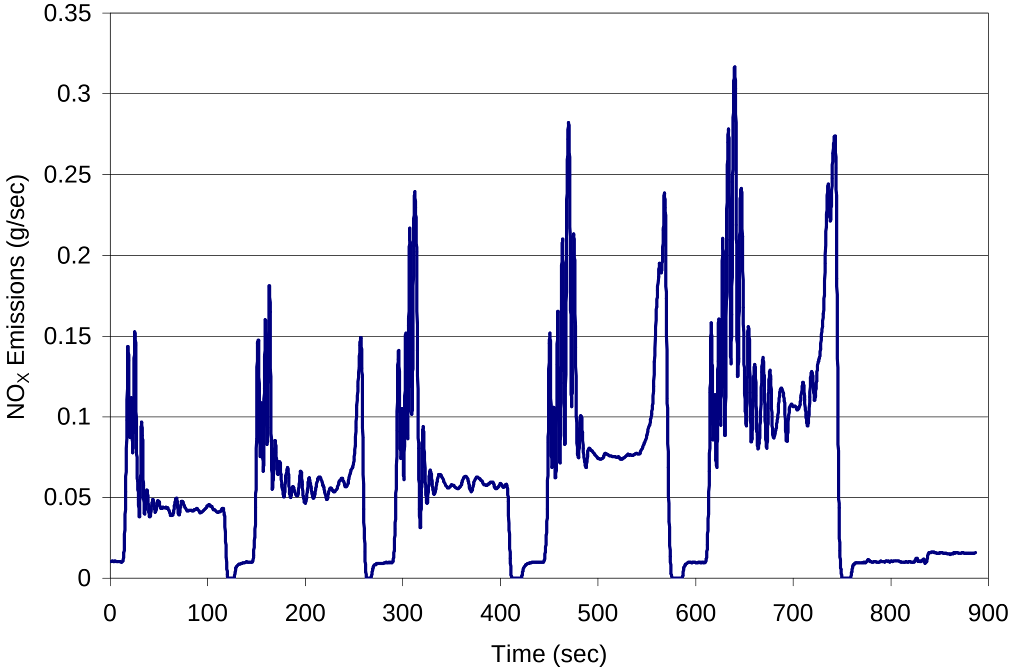


Figure7.3 A class 8 tractor truck driving the WVU 5-Mile Route showing possible off-cycle emissions at the end of the 2^{nd} and 3^{rd} peaks. Off-cycle operation is also evident in the high peaks while the vehicle is accelerating. The vehicle was a 1995 Kenworth powered by a Cummins M-11 rated at 330 hp. The transmission was a 10-Speed manual and the fuel was No. 2 diesel. Test weight was 42,040 lbs.

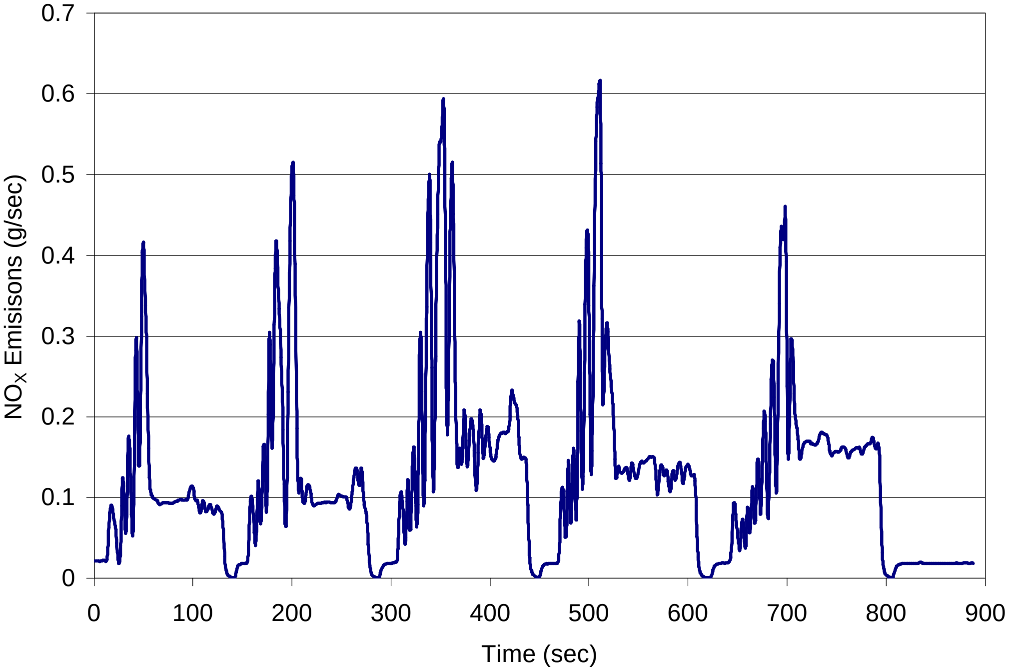
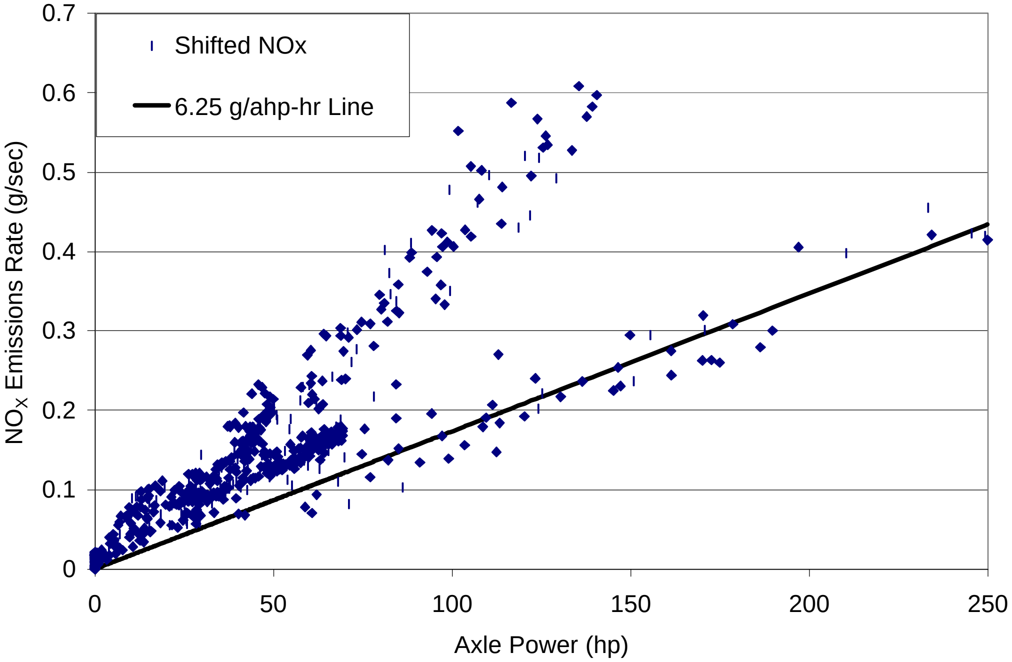


Figure 7.4 Plot of NO_X versus power, which displays the off-cycle operation.



It is evident toward the end of the higher steady-state road speed peaks that NO_X emissions undergo a step rise that would be associated with off-cycle emissions. In this case, it is likely that the high NO_X mode was provoked by prolonged cruise at speed. However, in some other cases, the cause for high NO_X emissions is less readily attributed to vehicle behavior. Ramamurthy & Clark (1999) published NO_X versus power plots for urban buses, as shown in Figure 7.5. Data were acquired using the CBD Cycle, which consists of 14 identical peaks. Occasional peaks showed high NO_X events, without obvious reason, as shown in Figure 7.6.

Figure 7.5 NO_X versus power for a vehicle driving the CBD cycle showing high and low NO_X operation. (Sequence #922)

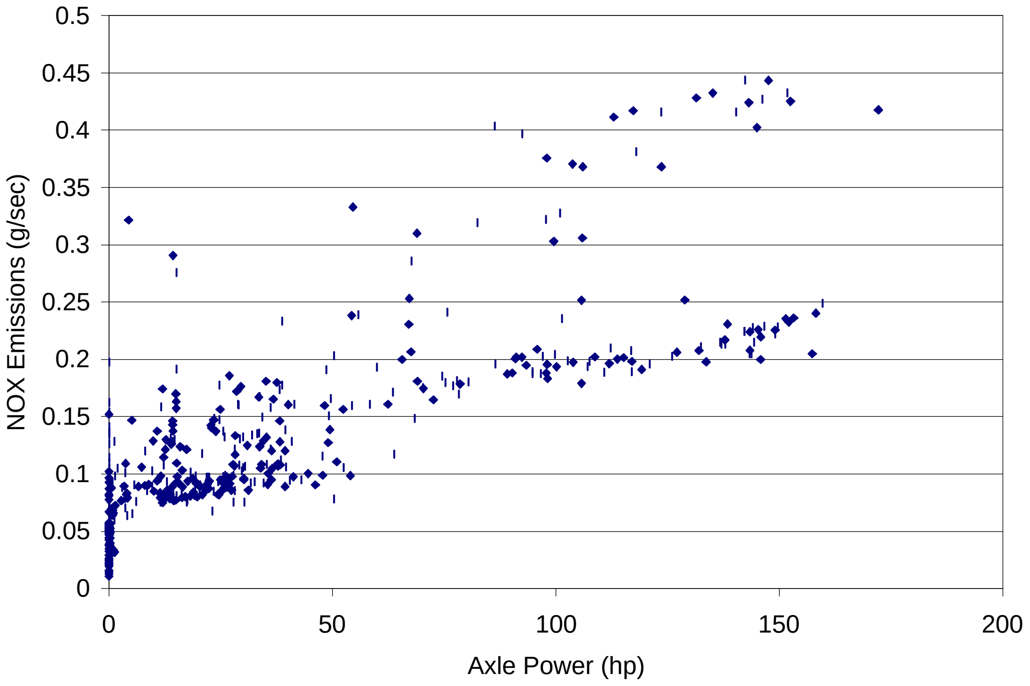
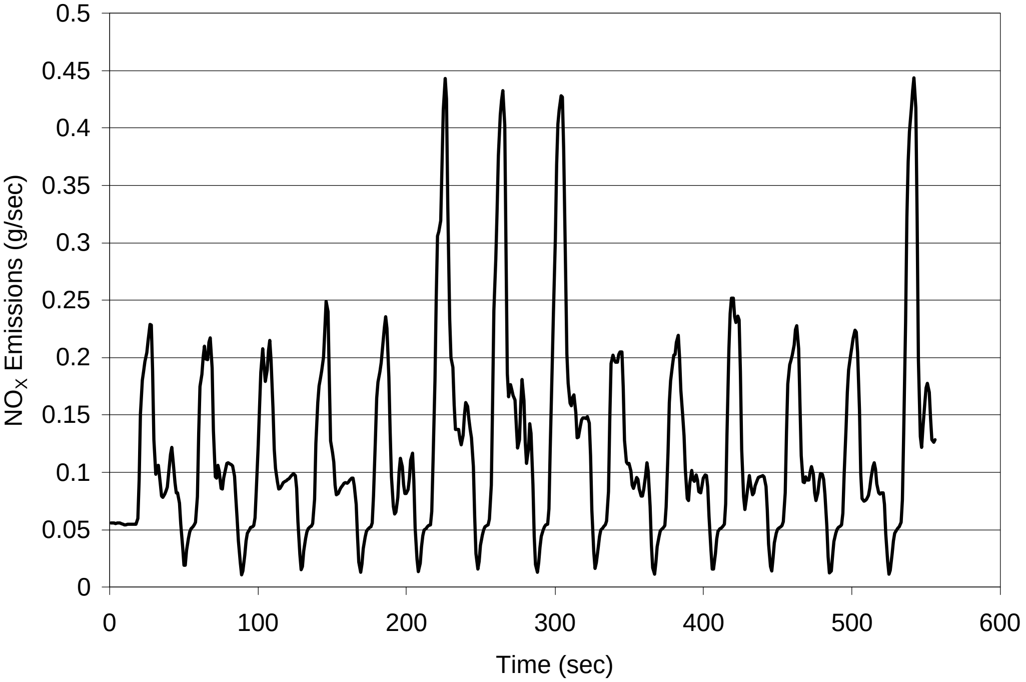


Figure 7.6 Continuous NO_X emissions for a vehicle driving the CBD cycle showing off-cycle operation on the 6th, 7th, 8th, and 14th peaks.



Recently, WVU participated in a team conducting research on mobile source emissions for National Renewable Energy Laboratory. This study, along with the data above, confirmed that the mass emissions rate in the high NO_X mode could be accessed readily, and that these rates were between 2 and 3 times the low NO_X emissions rate. Unfortunately, it is not possible to deduce from the WVU data the extent to which the high NO_X mode is induced in real life operation. If national vehicle miles traveled (VMT) are considered, then for class 8 trucks or combination vehciles, a preponderance of mileage is spent under cruise conditions, which are likely to provoke high NO_X emissions. The WVU database, however, has been derived using cycles that are transient and biased toward lower speed operation, so that it is likely that the overall average of WVU data is close to the low NO_X emissions level and includes little high NO_X operation. In other words, the WVU database may be taken as a reflection of low NO_X operation, rather than a representative composite for the nation.

7.3 Conclusions and Recommendations

The analyses in Chapter four give an indication of the relative effects of certain variables on the exhaust emissions of chassis-based testing. Section 4.9 gives a summary of the factors. These factors cause inaccuracies in the use of chassis emissions data for inventory and prediction.

Chapter five reviews different methods that can be used to develop emissions factors in grams per mile for inventory purposes. The current method used by the EPA and CARB uses emissions information from engine testing on FTP test cycle. The only influence of vehicle activity present in this method is through the fuel economy values used to convert the engine data to grams per mile of emissions. The fuel economy value is an average of fuel economies from various driving conditions and different vehicles. This cycle-dependency and lack of varying fuel economy limits the variability of the method. The method chosen for this analysis includes emissions information from many different chassis cycles, and some of these cycles have been developed from recent activity data and are meant to accurately represent the activity that in-use vehicles are experiencing. Also, the off-cycle emissions modes of modern electronically controlled engines are explored in the chassis testing and, by design do not occur on an FTP engine test.

The speed-acceleration method of predicting emissions presented in chapter six shows acceptable results when compared to measured chassis emissions in units of grams per mile. Comparisons of the predicted values were made in chapter seven both before and after the weighting by the activity data. The error of the predicted values was less than 20 % when compared to measured data.

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. It is suggested that further research will be needed to shed light on the incidence of high NO_X operation, in the following way. Representative vehicles with electronic engine management should be procured and exercised on a chassis dynamometer for long periods of time, using target speed-time traces selected statistically from in-use truck activity. Emissions measured from the vehicles would provide not only composite emissions factors representative of real use with low and high NO_X operation, but would also provide information on the fraction of time spent in a high NO_X mode. This can be assessed by monitoring real-time NO_X/power and NO_X/CO_2 ratios for the subject vehicles. These ratios will readily reveal the binary strategy. Also, runs of this kind would richen the overall database for an inventory study and would provide an opportunity to log real-time particulate matter (PM) emissions using a Tapered Element Oscillating Microbalance (TEOM). There has been little discussion of the effects of elimination of advanced timing strategies on PM production, and no comprehensive data exist to date to quantify the effect.

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Appendices

Appendix A Program for developing tables of emissions based on speed-acceleration

```
' Los-Alamos and NCHRP Program
' 5-7-1999
' and 7-20-99

DECLARE SUB binconv (A())
DECLARE SUB shiftemis (A())
DECLARE SUB flowcon (A())

'dimension arrays for storage

COMMON SHARED emistable(), powertable(), datapath$, count, flowtable(), seqnum, flownum, coback,
co2back, noxback, hcback, deltatnox, deltatco, deltatco2, deltathc
DIM noxmat(0 TO 120, 1 TO 7, 1 TO 7)   ' speed, accel bins, type of data
DIM comat(0 TO 120, 1 TO 7, 1 TO 7)   ' speed, accel bins, type of data
DIM co2mat(0 TO 120, 1 TO 7, 1 TO 7)   ' speed, accel bins, type of data
DIM hcmat(0 TO 120, 1 TO 7, 1 TO 7)   ' speed, accel bins, type of data
DIM pmmat(0 TO 120, 1 TO 7, 1 TO 7)  ' speed, accel bins, type of data
DIM emistable(1 TO 1900, 1 TO 7)         ' speed, accel, nox, co, co2, hc, pm
DIM powertable(1 TO 1900, 1 TO 2)       ' ahp, hub torque
DIM flowtable(1 TO 1900, 1 TO 3)        ' temp, pres, flowrate
DIM df(1 TO 1900)

'
'read file of usable sequence numbers
'

'******************************************************************
DO
CLS
' clear values out of arrays here!!
 FOR x = 0 TO 120
    FOR y = 1 TO 7
       FOR z = 1 TO 7
          noxmat(x, y, z) = 0
          comat(x, y, z) = 0
          co2mat(x, y, z) = 0
          hcmat(x, y, z) = 0
       NEXT z
    NEXT y
 NEXT x

INPUT " Enter sequence number (zero to quit) 4 digits > ", seqnum$
'seqnum$ = "3159"

seqnum = VAL(seqnum$)
IF seqnum = 0 THEN STOP

maxsp = 0
datapoints = 0
ON ERROR RESUME NEXT

outpath$ = "d:/results2/res" + seqnum$ + "/"
'outpath$ = "j:/results2/res" + seqnum$ + "/"
outdir$ = "d:\results2\res" + seqnum$
'outdir$ = "j:\results2\res" + seqnum$
'makepath$ = "mkdir " + outdir$
'SHELL makepath$

' set minimums to a large value
FOR y = 0 TO 120
   FOR z = 1 TO 6
      noxmat(y, z, 4) = 1
      comat(y, z, 4) = 1
      co2mat(y, z, 4) = 50
      hcmat(y, z, 4) = .1
   NEXT z
NEXT y
```

```
OPEN outpath$ + "noxco2.txt" FOR OUTPUT AS #6
CLOSE #6
' output for nox/co2 example analysis
OPEN outpath$ + "noxco2.txt" FOR APPEND AS #6
PRINT #6, year$
PRINT #6, "run number , acceleration (mph/s) , nox (g/s) , co2 (g/s) , nox/co2"

' Begining of main loop!!!
FOR runnum = 1 TO 10
   runnum$ = STR$(runnum)
   IF runnum < 10 THEN MID$(runnum$, 1, 1) = "0"
   runnum$ = LTRIM$(runnum$)

   'INPUT " Enter desired run number (two digits) ", runnum$

datapath$ = "d:/data/" + seqnum$ + "/" + runnum$ + "/"
'datapath$ = "j:/data/" + seqnum$ + "/" + runnum$ + "/"
PRINT datapath$

OPEN outpath$ + "maindata.txt" FOR OUTPUT AS #5
PRINT #5, datapath$;

' open first run number and get model year, tire diameter,
' tunnel flow rate, and total PM
OPEN datapath$ + "vstat.dat" FOR INPUT AS #1

IF ERR = 76 THEN PRINT #5, "": GOTO 20
PRINT #5, " Good data."

FOR i = 1 TO 13
    LINE INPUT #1, year$
NEXT i
FOR i = 1 TO 17
    LINE INPUT #1, tirediameter$
NEXT i
tirediameter = VAL(tirediameter$)
PRINT " Tire diameter "; tirediameter; " inches"
PRINT " Vehicle model year: "; year$
CLOSE #1

' read in flow number thingy
OPEN datapath$ + "test_cx.dat" FOR INPUT AS #1
FOR i = 1 TO 4
    INPUT #1, flownum
NEXT i
FOR i = 1 TO 6
    LINE INPUT #1, test$
NEXT i
PRINT " The test cycle is "; test$; "."
CLOSE #1

flownum = flownum * 1000

' read in background values
OPEN datapath$ + "bak_gnd.dat" FOR INPUT AS #1
INPUT #1, junk, coback
INPUT #1, junk, junk
INPUT #1, junk, co2back
INPUT #1, junk, noxback
INPUT #1, junk, hcback
CLOSE #1

' call binary to ascii conversion sub, also converts background
' values from adc code to ppm
PRINT
binconv emistable()
PRINT

' calculate ahp from axle torque and hub speed
FOR i = 1 TO count
   powertable(i, 1) = emistable(i, 1) * powertable(i, 2) / 5252
```

```
   ' keep power positive by assigning zeros to negative powers
   IF powertable(i, 1) < 0 THEN powertable(i, 1) = 0
NEXT i


' convert hub speed to mph
FOR i = 1 TO count
   emistable(i, 1) = emistable(i, 1) * tirediameter / 336.135
NEXT i

' calculate acceleration from mph
' decrease count because of acceleration
count = count - 1
FOR i = 1 TO count
   emistable(i, 2) = emistable(i + 1, 1) - emistable(i, 1)
NEXT i

' call sub to shift emissions data
shiftemis emistable()

' take background into consideration
PRINT
PRINT " background values (ppm)"
PRINT " co", " co2", " nox", " hc"
PRINT coback, co2back, noxback, hcback
PRINT

' calculate dillution factor, and subtract background
FOR i = 1 TO count
   df(i) = 13.4 * 1000000 / (emistable(i, 4) + emistable(i, 5) + emistable(i, 6))
   emistable(i, 3) = emistable(i, 3) - noxback * (1 - 1 / df(i))
   emistable(i, 4) = emistable(i, 4) - coback * (1 - 1 / df(i))
   emistable(i, 5) = emistable(i, 5) - co2back * (1 - 1 / df(i))
   emistable(i, 6) = emistable(i, 6) - hcback * (1 - 1 / df(i))
NEXT i

' calculate temp, press, flowrate
flowcon flowtable()

' calculate g/s emissions data from ppm
FOR i = 1 TO count
   emistable(i, 3) = emistable(i, 3) / 1000000 * 54.16 * flowtable(i, 3) / 60
   IF emistable(i, 3) < 0 THEN emistable(i, 3) = 0
   emistable(i, 4) = emistable(i, 4) / 1000000 * 32.97 * flowtable(i, 3) / 60
   IF emistable(i, 4) < 0 THEN emistable(i, 4) = 0
   emistable(i, 5) = emistable(i, 5) / 1000000 * 51.81 * flowtable(i, 3) / 60
   IF emistable(i, 5) < 0 THEN emistable(i, 5) = 0
   emistable(i, 6) = emistable(i, 6) / 1000000 * 16.27 * flowtable(i, 3) / 60
   IF emistable(i, 6) < 0 THEN emistable(i, 6) = 0
NEXT i

' put in big matrix and calculate statiscs
FOR i = 1 TO count
   speed = INT(emistable(i, 1) * 2)
   IF speed < 0 THEN speed = 0
   IF speed > maxsp THEN maxsp = speed

   IF emistable(i, 2) > 2 THEN
      accel = 6 ' heavy acceleration
   ELSEIF emistable(i, 2) > 1 THEN
      accel = 5 ' medium acceleration
   ELSEIF emistable(i, 2) > .3 THEN
      accel = 4 ' light acceleration
   ELSEIF emistable(i, 2) < -1.5 THEN
      accel = 1 ' heavy deceleration
   ELSEIF emistable(i, 2) < -.3 THEN
      accel = 2 ' light deceleration
   ELSE
      accel = 3 ' cruise
      END IF
```

```
   noxmat(speed, accel, 1) = (emistable(i, 3) + noxmat(speed, accel, 2) * noxmat(speed, accel,
1)) / (noxmat(speed, accel, 2) + 1)
   noxmat(speed, accel, 2) = noxmat(speed, accel, 2) + 1
   IF emistable(i, 3) > noxmat(speed, accel, 3) THEN noxmat(speed, accel, 3) = emistable(i, 3)
   IF emistable(i, 3) < noxmat(speed, accel, 4) THEN noxmat(speed, accel, 4) = emistable(i, 3)
   noxmat(speed, accel, 5) = noxmat(speed, accel, 5) + emistable(i, 3)
   noxmat(speed, accel, 6) = noxmat(speed, accel, 6) + emistable(i, 3) ^ 2
   noxmat(speed, accel, 7) = SQR((noxmat(speed, accel, 2) * noxmat(speed, accel, 6) -
noxmat(speed, accel, 5) ^ 2) / noxmat(speed, accel, 2) ^ 2)

   comat(speed, accel, 1) = (emistable(i, 4) + comat(speed, accel, 2) * comat(speed, accel, 1)) /
(comat(speed, accel, 2) + 1)
   comat(speed, accel, 2) = comat(speed, accel, 2) + 1
   IF emistable(i, 4) > comat(speed, accel, 3) THEN comat(speed, accel, 3) = emistable(i, 4)
   IF emistable(i, 4) < comat(speed, accel, 4) THEN comat(speed, accel, 4) = emistable(i, 4)
   comat(speed, accel, 5) = comat(speed, accel, 5) + emistable(i, 4)
   comat(speed, accel, 6) = comat(speed, accel, 6) + emistable(i, 4) ^ 2
   comat(speed, accel, 7) = SQR((comat(speed, accel, 2) * comat(speed, accel, 6) - comat(speed,
accel, 5) ^ 2) / comat(speed, accel, 2) ^ 2)

   co2mat(speed, accel, 1) = (emistable(i, 5) + co2mat(speed, accel, 2) * co2mat(speed, accel,
1)) / (co2mat(speed, accel, 2) + 1)
   co2mat(speed, accel, 2) = co2mat(speed, accel, 2) + 1
   IF emistable(i, 5) > co2mat(speed, accel, 3) THEN co2mat(speed, accel, 3) = emistable(i, 5)
   IF emistable(i, 5) < co2mat(speed, accel, 4) THEN co2mat(speed, accel, 4) = emistable(i, 5)
   co2mat(speed, accel, 5) = co2mat(speed, accel, 5) + emistable(i, 5)
   co2mat(speed, accel, 6) = co2mat(speed, accel, 6) + emistable(i, 5) ^ 2
   co2mat(speed, accel, 7) = SQR((co2mat(speed, accel, 2) * co2mat(speed, accel, 6) -
co2mat(speed, accel, 5) ^ 2) / co2mat(speed, accel, 2) ^ 2)

   hcmat(speed, accel, 1) = (emistable(i, 6) + hcmat(speed, accel, 2) * hcmat(speed, accel, 1)) /
(hcmat(speed, accel, 2) + 1)
   hcmat(speed, accel, 2) = hcmat(speed, accel, 2) + 1
   IF emistable(i, 6) > hcmat(speed, accel, 3) THEN hcmat(speed, accel, 3) = emistable(i, 6)
   IF emistable(i, 6) < hcmat(speed, accel, 4) THEN hcmat(speed, accel, 4) = emistable(i, 6)
   hcmat(speed, accel, 5) = hcmat(speed, accel, 5) + emistable(i, 6)
   hcmat(speed, accel, 6) = hcmat(speed, accel, 6) + emistable(i, 6) ^ 2
   hcmat(speed, accel, 7) = SQR((hcmat(speed, accel, 2) * hcmat(speed, accel, 6) - hcmat(speed,
accel, 5) ^ 2) / hcmat(speed, accel, 2) ^ 2)
NEXT i

' read in PM/CO data
OPEN "d:/data/PMdata.txt" FOR INPUT AS #8
LINE INPUT #8, junk$
DO
INPUT #8, readseqnum, pmoverco
LOOP UNTIL readseqnum = seqnum
CLOSE #8
PRINT "PM / CO =", pmoverco
PRINT

' proportion PM matrix to CO
' two nested loops for pmmat, no need for statistics.

' nox/co2
FOR q = 1 TO count
   PRINT #6, runnum$; ","; emistable(q, 2); ","; emistable(q, 3); ","; emistable(q, 5); ",";
(emistable(q, 3) / emistable(q, 5))
NEXT q

datapoints = datapoints + count

' main data file
PRINT #5, " sequence number "; seqnum$
PRINT #5, " Tire diameter "; tirediameter; " inches"
PRINT #5, " Vehicle model year: "; year$
PRINT #5, " The test cycle is "; test$; "."
PRINT #5, "  "
PRINT #5, " NOx ,"; deltatnox; ", second time shift."
PRINT #5, " CO  ,"; deltatco; " ,second time shift."
```

```
PRINT #5, " CO2 ,"; deltatco2; ", second time shift."
PRINT #5, " HC  ,"; deltathc; " ,second time shift."
PRINT #5, "  "
PRINT #5, " background values (ppm)"
PRINT #5, " co , co2 , nox , hc "
PRINT #5, coback; ","; co2back; ","; noxback; ","; hcback
PRINT #5, "count (time) , speed(mph) , acceleration(mph/s) , nox (g/s) , co (g/s) , co2 (g/s) ,
hc (g/s) , axle horsepower (hp) , hub torque (ft-lb) , temperature (C or F) , pressure (psf) ,
flowrate (CFM) , dill factor "
FOR q = 1 TO count
   PRINT #5, q; ","; emistable(q, 1); ","; emistable(q, 2); ","; emistable(q, 3); ",";
emistable(q, 4); ","; emistable(q, 5); ","; emistable(q, 6); ","; powertable(q, 1); ",";
powertable(q, 2); ","; flowtable(q, 1); ","; flowtable(q, 2); ",";  _
flowtable(q, 3); ","; df(q)
NEXT q


20 NEXT runnum
' End of main loop!!!

CLOSE #6
CLOSE #5

OPEN outpath$ + "noxres.txt" FOR OUTPUT AS #4
PRINT #4, year$
PRINT #4, seqnum$, test$
PRINT #4, " nox (g/s) "
PRINT #4, "Speed (mph) ,Heavy Acceleration ,Medium Acceleration ,Light Acceleration ,Cruise
,Light Deceleration ,Heavy Deceleration "
FOR q = 0 TO maxsp
   PRINT #4, q / 2; ","; noxmat(q, 6, 1); ","; noxmat(q, 5, 1); ","; noxmat(q, 4, 1); ",";
noxmat(q, 3, 1); ","; noxmat(q, 2, 1); ","; noxmat(q, 1, 1)
NEXT q
CLOSE #4
OPEN outpath$ + "noxpop.txt" FOR OUTPUT AS #4
PRINT #4, " number of occurances in each cell "
PRINT #4, " total data points for all run numbers = "; datapoints
PRINT #4, "Speed (mph) ,Heavy Acceleration ,Medium Acceleration ,Light Acceleration ,Cruise
,Light Deceleration ,Heavy Deceleration "
FOR q = 0 TO maxsp
   PRINT #4, q / 2; ","; noxmat(q, 6, 2); ","; noxmat(q, 5, 2); ","; noxmat(q, 4, 2); ",";
noxmat(q, 3, 2); ","; noxmat(q, 2, 2); ","; noxmat(q, 1, 2)
NEXT q
CLOSE #4
OPEN outpath$ + "noxmax.txt" FOR OUTPUT AS #4
PRINT #4, " maximum value in each cell "
PRINT #4, "Speed (mph) ,Heavy Acceleration ,Medium Acceleration  ,Light Acceleration ,Cruise
,Light Deceleration ,Heavy Deceleration "
FOR q = 0 TO maxsp
   PRINT #4, q / 2; ","; noxmat(q, 6, 3); ","; noxmat(q, 5, 3); ","; noxmat(q, 4, 3); ",";
noxmat(q, 3, 3); ","; noxmat(q, 2, 3); ","; noxmat(q, 1, 3)
NEXT q
CLOSE #4
OPEN outpath$ + "noxmin.txt" FOR OUTPUT AS #4
PRINT #4, " minimum value in each cell "
PRINT #4, "Speed (mph) ,Heavy Acceleration ,Medium Acceleration ,Light Acceleration  ,Cruise
,Light Deceleration ,Heavy Deceleration "
FOR q = 0 TO maxsp
   PRINT #4, q / 2; ","; noxmat(q, 6, 4); ","; noxmat(q, 5, 4); ","; noxmat(q, 4, 4); ",";
noxmat(q, 3, 4); ","; noxmat(q, 2, 4); ","; noxmat(q, 1, 4)
NEXT q
CLOSE #4
OPEN outpath$ + "noxstd.txt" FOR OUTPUT AS #4
PRINT #4, " standard deviation in each cell "
PRINT #4, "Speed (mph) ,Heavy Acceleration ,Medium Acceleration ,Light Acceleration ,Cruise
,Light Deceleration ,Heavy Deceleration "
FOR q = 0 TO maxsp
   PRINT #4, q / 2; ","; noxmat(q, 6, 7); ","; noxmat(q, 5, 7); ","; noxmat(q, 4, 7); ",";
noxmat(q, 3, 7); ","; noxmat(q, 2, 7); ","; noxmat(q, 1, 7)
NEXT q
CLOSE #4
```

```
OPEN outpath$ + "cores.txt" FOR OUTPUT AS #4
PRINT #4, year$
PRINT #4, seqnum$, test$
PRINT #4, " co (g/s) "
PRINT #4, "Speed (mph) ,Heavy Acceleration ,Medium Acceleration ,Light Acceleration ,Cruise
,Light Deceleration ,Heavy Deceleration "
FOR q = 0 TO maxsp
   PRINT #4, q / 2; ","; comat(q, 6, 1); ","; comat(q, 5, 1); ","; comat(q, 4, 1); ","; comat(q,
3, 1); ","; comat(q, 2, 1); ","; comat(q, 1, 1)
NEXT q
CLOSE #4
OPEN outpath$ + "copop.txt" FOR OUTPUT AS #4
PRINT #4, " number of occurances in each cell "
PRINT #4, " total data points for all run numbers = "; datapoints
PRINT #4, "Speed (mph) ,Heavy Acceleration ,Medium Acceleration ,Light Acceleration ,Cruise
,Light Deceleration ,Heavy Deceleration "
FOR q = 0 TO maxsp
   PRINT #4, q / 2; ","; comat(q, 6, 2); ","; comat(q, 5, 2); ","; comat(q, 4, 2); ","; comat(q,
3, 2); ","; comat(q, 2, 2); ","; comat(q, 1, 2)
NEXT q
CLOSE #4
OPEN outpath$ + "comax.txt" FOR OUTPUT AS #4
PRINT #4, " maximum value in each cell "
PRINT #4, "Speed (mph) ,Heavy Acceleration ,Medium Acceleration ,Light Acceleration ,Cruise
,Light Deceleration ,Heavy Deceleration "
FOR q = 0 TO maxsp
   PRINT #4, q / 2; ","; comat(q, 6, 3); ","; comat(q, 5, 3); ","; comat(q, 4, 3); ","; comat(q,
3, 3); ","; comat(q, 2, 3); ","; comat(q, 1, 3)
NEXT q
CLOSE #4
OPEN outpath$ + "comin.txt" FOR OUTPUT AS #4
PRINT #4, " minimum value in each cell "
PRINT #4, "Speed (mph) ,Heavy Acceleration ,Medium Acceleration ,Light Acceleration ,Cruise
,Light Deceleration ,Heavy Deceleration "
FOR q = 0 TO maxsp
   PRINT #4, q / 2; ","; comat(q, 6, 4); ","; comat(q, 5, 4); ","; comat(q, 4, 4); ","; comat(q,
3, 4); ","; comat(q, 2, 4); ","; comat(q, 1, 4)
NEXT q
CLOSE #4
OPEN outpath$ + "costd.txt" FOR OUTPUT AS #4
PRINT #4, " standard deviation in each cell "
PRINT #4, "Speed (mph) ,Heavy Acceleration ,Medium Acceleration ,Light Acceleration ,Cruise
,Light Deceleration ,Heavy Deceleration "
FOR q = 0 TO maxsp
   PRINT #4, q / 2; ","; comat(q, 6, 7); ","; comat(q, 5, 7); ","; comat(q, 4, 7); ","; comat(q,
3, 7); ","; comat(q, 2, 7); ","; comat(q, 1, 7)
NEXT q
CLOSE #4


OPEN outpath$ + "hcres.txt" FOR OUTPUT AS #4
PRINT #4, year$
PRINT #4, seqnum$, test$
PRINT #4, " hc (g/s) "
PRINT #4, "Speed (mph) ,Heavy Acceleration ,Medium Acceleration ,Light Acceleration ,Cruise
,Light Deceleration ,Heavy Deceleration "
FOR q = 0 TO maxsp
   PRINT #4, q / 2; ","; hcmat(q, 6, 1); ","; hcmat(q, 5, 1); ","; hcmat(q, 4, 1); ","; hcmat(q,
3, 1); ","; hcmat(q, 2, 1); ","; hcmat(q, 1, 1)
NEXT q
CLOSE #4
OPEN outpath$ + "hcpop.txt" FOR OUTPUT AS #4
PRINT #4, " number of occurances in each cell "
PRINT #4, " total data points for all run numbers = "; datapoints
PRINT #4, "Speed (mph) ,Heavy Acceleration ,Medium Acceleration ,Light Acceleration ,Cruise
,Light Deceleration ,Heavy Deceleration "
FOR q = 0 TO maxsp
   PRINT #4, q / 2; ","; hcmat(q, 6, 2); ","; hcmat(q, 5, 2); ","; hcmat(q, 4, 2); ","; hcmat(q,
3, 2); ","; hcmat(q, 2, 2); ","; hcmat(q, 1, 2)
```

```
NEXT q
CLOSE #4
OPEN outpath$ + "hcmax.txt" FOR OUTPUT AS #4
PRINT #4, " maximum value in each cell "
PRINT #4, "Speed (mph) ,Heavy Acceleration ,Medium Acceleration ,Light Acceleration ,Cruise
,Light Deceleration ,Heavy Deceleration "
FOR q = 0 TO maxsp
   PRINT #4, q / 2; ","; hcmat(q, 6, 3); ","; hcmat(q, 5, 3); ","; hcmat(q, 4, 3); ","; hcmat(q,
3, 3); ","; hcmat(q, 2, 3); ","; hcmat(q, 1, 3)
NEXT q
CLOSE #4
OPEN outpath$ + "hcmin.txt" FOR OUTPUT AS #4
PRINT #4, " minimum value in each cell "
PRINT #4, "Speed (mph) ,Heavy Acceleration ,Medium Acceleration ,Light Acceleration ,Cruise
,Light Deceleration ,Heavy Deceleration "
FOR q = 0 TO maxsp
   PRINT #4, q / 2; ","; hcmat(q, 6, 4); ","; hcmat(q, 5, 4); ","; hcmat(q, 4, 4); ","; hcmat(q,
3, 4); ","; hcmat(q, 2, 4); ","; hcmat(q, 1, 4)
NEXT q
CLOSE #4
OPEN outpath$ + "hcstd.txt" FOR OUTPUT AS #4
PRINT #4, " standard deviation in each cell "
PRINT #4, "Speed (mph) ,Heavy Acceleration ,Medium Acceleration ,Light Acceleration ,Cruise
,Light Deceleration ,Heavy Deceleration "
FOR q = 0 TO maxsp
   PRINT #4, q / 2; ","; hcmat(q, 6, 7); ","; hcmat(q, 5, 7); ","; hcmat(q, 4, 7); ","; hcmat(q,
3, 7); ","; hcmat(q, 2, 7); ","; hcmat(q, 1, 7)
NEXT q
CLOSE #4


OPEN outpath$ + "co2res.txt" FOR OUTPUT AS #4
PRINT #4, year$
PRINT #4, seqnum$, test$
PRINT #4, " co2 (g/s) "
PRINT #4, "Speed (mph) ,Heavy Acceleration ,Medium Acceleration ,Light Acceleration ,Cruise
,Light Deceleration ,Heavy Deceleration "
FOR q = 0 TO maxsp
   PRINT #4, q / 2; ","; co2mat(q, 6, 1); ","; co2mat(q, 5, 1); ","; co2mat(q, 4, 1); ",";
co2mat(q, 3, 1); ","; co2mat(q, 2, 1); ","; co2mat(q, 1, 1)
NEXT q
CLOSE #4
OPEN outpath$ + "co2pop.txt" FOR OUTPUT AS #4
PRINT #4, " number of occurances in each cell "
PRINT #4, " total data points for all run numbers = "; datapoints
PRINT #4, "Speed (mph) ,Heavy Acceleration ,Medium Acceleration ,Light Acceleration ,Cruise
,Light Deceleration ,Heavy Deceleration "
FOR q = 0 TO maxsp
   PRINT #4, q / 2; ","; co2mat(q, 6, 2); ","; co2mat(q, 5, 2); ","; co2mat(q, 4, 2); ",";
co2mat(q, 3, 2); ","; co2mat(q, 2, 2); ","; co2mat(q, 1, 2)
NEXT q
CLOSE #4
OPEN outpath$ + "co2max.txt" FOR OUTPUT AS #4
PRINT #4, " maximum value in each cell "
PRINT #4, "Speed (mph) ,Heavy Acceleration ,Medium Acceleration ,Light Acceleration ,Cruise
,Light Deceleration ,Heavy Deceleration "
FOR q = 0 TO maxsp
   PRINT #4, q / 2; ","; co2mat(q, 6, 3); ","; co2mat(q, 5, 3); ","; co2mat(q, 4, 3); ",";
co2mat(q, 3, 3); ","; co2mat(q, 2, 3); ","; co2mat(q, 1, 3)
NEXT q
CLOSE #4
OPEN outpath$ + "co2min.txt" FOR OUTPUT AS #4
PRINT #4, " minimum value in each cell "
PRINT #4, "Speed (mph) ,Heavy Acceleration ,Medium Acceleration ,Light Acceleration ,Cruise
,Light Deceleration ,Heavy Deceleration "
FOR q = 0 TO maxsp
   PRINT #4, q / 2; ","; co2mat(q, 6, 4); ","; co2mat(q, 5, 4); ","; co2mat(q, 4, 4); ",";
co2mat(q, 3, 4); ","; co2mat(q, 2, 4); ","; co2mat(q, 1, 4)
NEXT q
CLOSE #4
OPEN outpath$ + "co2std.txt" FOR OUTPUT AS #4
```

```
PRINT #4, " standard deviation in each cell "
PRINT #4, "Speed (mph) ,Heavy Acceleration ,Medium Acceleration ,Light Acceleration ,Cruise
,Light Deceleration ,Heavy Deceleration "
FOR q = 0 TO maxsp
   PRINT #4, q / 2; ","; co2mat(q, 6, 7); ","; co2mat(q, 5, 7); ","; co2mat(q, 4, 7); ",";
co2mat(q, 3, 7); ","; co2mat(q, 2, 7); ","; co2mat(q, 1, 7)
NEXT q
CLOSE #4



' read next sequence number

PRINT
PRINT " Number of data points available for use= "; datapoints
PRINT


PRINT " ** Hit the any key. ** "
DO
LOOP WHILE INKEY$ = ""


LOOP
'****************************************************************

' The
END

SUB binconv (A())

'****************************************************************
' Display curve in engineering unit
'
' CalData and CurveData Passed in
'
' modified for use in the los alamos program... by justin
'****************************************************************
DIM bytelocation AS LONG
DIM Loco AS LONG
DIM adccode AS INTEGER
DIM RealValue AS SINGLE
DIM j AS INTEGER
DIM i AS INTEGER
DIM k AS INTEGER

DIM RealValueSum AS DOUBLE
DIM AscFileName AS STRING
DIM CO(1 TO 4)
DIM CO2(1 TO 4)
DIM HC(1 TO 4)
DIM nox(1 TO 4)
DIM TQ1(1 TO 2)
DIM TQ2(1 TO 2)
DIM HS(1 TO 2)


PRINT " Reading binary file, please wait..."


IF seqnum >= 633 THEN
   totchan = 64
ELSE
   totchan = 32
END IF

'
' open a file for store ASCII data
'
'datapath$ = "c:\data\1045\01\"
'OPEN datapath$ + "emisdata.asc" FOR OUTPUT AS #11
```

```
'read calibration data
OPEN datapath$ + "lco.cal" FOR INPUT AS #12
LINE INPUT #12, junk$
LINE INPUT #12, junk$
FOR i = 1 TO 4
        INPUT #12, CO(i)
NEXT i
CLOSE #12

OPEN datapath$ + "co2.cal" FOR INPUT AS #12
LINE INPUT #12, junk$
LINE INPUT #12, junk$
FOR i = 1 TO 4
        INPUT #12, CO2(i)
NEXT i
CLOSE #12

OPEN datapath$ + "hc.cal" FOR INPUT AS #12
LINE INPUT #12, junk$
LINE INPUT #12, junk$
FOR i = 1 TO 2
        INPUT #12, HC(i)
NEXT i
CLOSE #12

OPEN datapath$ + "nox.cal" FOR INPUT AS #12
LINE INPUT #12, junk$
LINE INPUT #12, junk$
FOR i = 1 TO 4
        INPUT #12, nox(i)
NEXT i
CLOSE #12

OPEN datapath$ + "hs1.cal" FOR INPUT AS #12
LINE INPUT #12, junk$
LINE INPUT #12, junk$
FOR i = 1 TO 2
        INPUT #12, HS(i)
NEXT i
CLOSE #12

OPEN datapath$ + "tq1.cal" FOR INPUT AS #12
LINE INPUT #12, junk$
LINE INPUT #12, junk$
FOR i = 1 TO 2
        INPUT #12, TQ1(i)
NEXT i
CLOSE #12

OPEN datapath$ + "tq2.cal" FOR INPUT AS #12
LINE INPUT #12, junk$
LINE INPUT #12, junk$
FOR i = 1 TO 2
        INPUT #12, TQ2(i)
NEXT i
CLOSE #12

' convert background adc code to ppm
hcback = HC(1) + HC(2) * hcback
coback = CO(1) + CO(2) * coback + CO(3) * coback ^ 2 + CO(4) * coback ^ 3
co2back = CO2(1) + CO2(2) * co2back + CO2(3) * co2back ^ 2 + CO2(4) * co2back ^ 3
noxback = nox(1) + nox(2) * noxback + nox(3) * noxback ^ 2 + nox(4) * noxback ^ 3


OPEN datapath$ + "cyc_bin.dat" FOR BINARY AS #1

numofscan = LOF(1) / totchan / 2

'
' find the first data in the data file
```

```
'
   '
   ' Get Engine Data from Binary File
   '
   Loco = 0
   count = 0
'   PRINT numofscan
   FOR j = 1 TO numofscan

       Loco = Loco + totchan * 2

       'Hub Speed (rpm)
       Channel = 24
       bytelocation = ((Channel + 1) * 2 - 1) + (Loco): GET #1, bytelocation, adccode
       RealValueAS = adccode * HS(2) + HS(1)

       'Actual Torque (for one side of truck)
       Channel = 22
       bytelocation = ((Channel + 1) * 2 - 1) + (Loco): GET #1, bytelocation, adccode
       RealValueAT = adccode * TQ1(2) + TQ1(1)

       'Actual Torque (for the other side of truck)
       Channel = 23
       bytelocation = ((Channel + 1) * 2 - 1) + (Loco): GET #1, bytelocation, adccode
       RealValueAT2 = adccode * TQ2(2) + TQ2(1)

       'HC
       Channel = 12
       bytelocation = ((Channel + 1) * 2 - 1) + (Loco): GET #1, bytelocation, adccode
       RealValueHC = HC(1) + HC(2) * adccode


       'CO
       Channel = 8
       bytelocation = ((Channel + 1) * 2 - 1) + (Loco): GET #1, bytelocation, adccode
       RealValueCO = CO(1) + CO(2) * adccode + CO(3) * adccode ^ 2 + CO(4) * adccode ^ 3

       'CO2
       Channel = 10
       bytelocation = ((Channel + 1) * 2 - 1) + (Loco): GET #1, bytelocation, adccode
       RealValueCO2 = CO2(1) + CO2(2) * adccode + CO2(3) * adccode ^ 2 + CO2(4) * adccode ^ 3

       'NOX
       Channel = 11
       bytelocation = ((Channel + 1) * 2 - 1) + (Loco): GET #1, bytelocation, adccode
       RealValueNOX = nox(1) + nox(2) * adccode + nox(3) * adccode ^ 2 + nox(4) * adccode ^ 3

       'blower temp
       Channel = 13
       bytelocation = ((Channel + 1) * 2 - 1) + (Loco): GET #1, bytelocation, adccode
       RealValueTMP = adccode

       'blower press
       Channel = 14
       bytelocation = ((Channel + 1) * 2 - 1) + (Loco): GET #1, bytelocation, adccode
       RealValuePRS = adccode

       '
       ' average data in one second
       '
       RealValueASSum = RealValueASSum + RealValueAS / 10
       RealValueATSum = RealValueATSum + RealValueAT / 10
       RealValueAT2Sum = RealValueAT2Sum + RealValueAT2 / 10
       RealValueHCSum = RealValueHCSum + RealValueHC / 10
       RealValueCOSum = RealValueCOSum + RealValueCO / 10
       RealValueCO2Sum = RealValueCO2Sum + RealValueCO2 / 10
       RealValueNOXSum = RealValueNOXSum + RealValueNOX / 10
       RealValueTMPSum = RealValueTMPSum + RealValueTMP / 10
       RealValuePRSSum = RealValuePRSSum + RealValuePRS / 10

       IF j MOD 10 = 0 THEN
```

```
          'put data into the array here
          k = j / 10
          emistable(k, 1) = RealValueASSum
          powertable(k, 2) = RealValueATSum + RealValueAT2Sum
          emistable(k, 3) = RealValueNOXSum
          emistable(k, 4) = RealValueCOSum
          emistable(k, 5) = RealValueCO2Sum
          emistable(k, 6) = RealValueHCSum
          flowtable(k, 1) = RealValueTMPSum
          flowtable(k, 2) = RealValuePRSSum

          count = count + 1
          'PRINT #11, count, ",", RealValueASSum, ",", RealValueATSum + RealValueAT2Sum, ",",
RealValueHCSum, ",", RealValueCOSum, ",", RealValueCO2Sum, ",", RealValueNOXSum
          RealValueASSum = 0
          RealValueATSum = 0
          RealValueAT2Sum = 0
          RealValueHCSum = 0
          RealValueCOSum = 0
          RealValueCO2Sum = 0
          RealValueNOXSum = 0
          RealValueTMPSum = 0
          RealValuePRSSum = 0
       END IF

   NEXT j

CLOSE #1

END SUB

SUB flowcon (A())
' this subroutine calculates the temperature and pressure
' from the adc code, then calculates the flowrate.
' using look up tables for the constants needed.

' get temp conversion number
SELECT CASE seqnum
CASE 1 TO 331, 340 TO 365, 487 TO 544, 587 TO 591, 845 TO 888, 1088 TO 1159, 3001 TO 3999
   tempnum = .29297
CASE 332 TO 339, 366 TO 486, 545 TO 586, 592 TO 628, 635 TO 843, 889 TO 1087, 1160 TO 2000
   tempnum = .10025
END SELECT

' get press conversion number
SELECT CASE seqnum
CASE 1 TO 262
   presnum = 1.05488
CASE 263 TO 544, 587 TO 3999, 5001 TO 5999
   presnum = 1.44
CASE 545 TO 586
   presnum = 1.4232
END SELECT

' convert temp and press
'PRINT
'PRINT " tempnum= "; tempnum
'PRINT " presnum= "; presnum

FOR i = 1 TO count
   flowtable(i, 1) = (flowtable(i, 1) * tempnum + 273.15) * 1.8
   flowtable(i, 2) = flowtable(i, 2) * presnum
NEXT i

' get venturi constant k
IF flownum = 1000 THEN
   SELECT CASE seqnum
   CASE 1 TO 104
      k = 10.791
   CASE 105 TO 331, 340 TO 365, 487 TO 544, 587 TO 591, 630 TO 632
      k = 10.416
```

```
   CASE 805 TO 824, 845 TO 888, 1088 TO 1159, 3001 TO 3999
      k = 10.281
   CASE 332 TO 339, 366 TO 486, 545 TO 586, 592 TO 629, 635 TO 756
      k = 11.1
   CASE 757 TO 804, 825 TO 843, 889 TO 1087, 1160 TO 2000
      k = 10.766
   END SELECT
END IF

IF flownum = 1500 THEN
   SELECT CASE seqnum
   CASE 105 TO 331, 340 TO 365, 487 TO 544, 587 TO 591, 630 TO 632
      k = 15.165
   CASE 332 TO 339, 366 TO 486, 545 TO 586, 592 TO 629, 635 TO 756
      k = 16.502
   CASE 805 TO 824, 845 TO 888, 1088 TO 1159, 3001 TO 3999
      k = 14.746
   CASE 757 TO 804, 825 TO 843, 889 TO 1087, 1160 TO 2000
      k = 16.27
   END SELECT
END IF

IF flownum = 2000 THEN
   SELECT CASE seqnum
   CASE 1 TO 104
      k = 21.633
   CASE 105 TO 331, 340 TO 365, 487 TO 544, 587 TO 591, 630 TO 632
      k = 19.138
   CASE 805 TO 824, 845 TO 888, 1088 TO 1159, 3001 TO 3999
      k = 19.205
   CASE 332 TO 339, 366 TO 486, 545 TO 586, 592 TO 629, 635 TO 756
      k = 22.026
   CASE 757 TO 804, 825 TO 843, 889 TO 1087, 1160 TO 2000
      k = 21.768
   END SELECT
END IF

IF flownum = 2500 THEN
   SELECT CASE seqnum
   CASE 105 TO 331, 340 TO 365, 487 TO 544, 587 TO 591, 630 TO 632, 805 TO 824, 845 TO 888, 1088
TO 1159, 3001 TO 3999
      k = 23.797
   CASE 332 TO 339, 366 TO 486, 545 TO 586, 592 TO 629, 635 TO 756, 757 TO 804, 825 TO 843, 889
TO 1087, 1160 TO 2000
      k = 27.567
   END SELECT
END IF

IF flownum = 3000 THEN
   SELECT CASE seqnum
   CASE 1 TO 104
      k = 32.585
   CASE 105 TO 331, 340 TO 365, 487 TO 544, 587 TO 591, 630 TO 632, 805 TO 824, 845 TO 888, 1088
TO 1159, 3001 TO 3999
      k = 0
   END SELECT
END IF

' calculate flowrate
'PRINT
'PRINT k
FOR i = 1 TO count
   flowtable(i, 3) = k * flowtable(i, 2) / SQR(flowtable(i, 1))
NEXT i

END SUB

SUB shiftemis (A())

' this subroutine uses cross corelation to shift the emissions data
' to account for sampling delay time
```

```
PRINT " Correlating to power..."


'OPEN "e:\noxshift.txt" FOR OUTPUT AS #4
'PRINT #4, "time shift , ccr nox"


'  NOx
ccrmax = 0
deltatnox = 0
FOR deltat = 1 TO 20
   ccrsum = 0
   FOR t = 1 TO count - 1 - deltat
      dload = powertable(t + 1, 1) - powertable(t, 1) '1 is for ahp correlations
      dnox = emistable(t + deltat + 1, 3) - emistable(t + deltat, 3)
      ccrsum = ccrsum + dload * dnox
   NEXT t
   'PRINT #4, deltat; ","; ccrsum
   'PRINT ccrsum
   'save the time max occurs max
   IF ccrsum > ccrmax THEN
      ccrmax = ccrsum
      deltatnox = deltat
   END IF
NEXT deltat
'now shift nox
FOR t = 1 TO count
   emistable(t, 3) = emistable(t + deltatnox, 3)
NEXT t
'CLOSE #4


'OPEN "e:\coshift.txt" FOR OUTPUT AS #4
'PRINT #4, "time shift , ccr co"

'  CO
ccrmax = 0
deltatco = 0
FOR deltat = 1 TO 22
   ccrsum = 0
   FOR t = 1 TO count - 1 - deltat
      dload = powertable(t + 1, 1) - powertable(t, 1) '1 is for ahp correlations
      dco = emistable(t + deltat + 1, 4) - emistable(t + deltat, 4)
      ccrsum = ccrsum + dload * dco
      'IF dco > 0 THEN ccrsum = ccrsum + dload * dco
   NEXT t
   'PRINT #4, deltat; ","; ccrsum
   'save the time max occurs max
   IF ccrsum > ccrmax THEN
      ccrmax = ccrsum
      deltatco = deltat
   END IF
NEXT deltat
'now shift co
FOR t = 1 TO count
   emistable(t, 4) = emistable(t + deltatco, 4)
NEXT t
'CLOSE #4

'OPEN "e:\co2shift.txt" FOR OUTPUT AS #4
'PRINT #4, "time shift , ccr co2"


'  CO2
ccrmax = 0
deltatco2 = 0
FOR deltat = 1 TO 20
   ccrsum = 0
   FOR t = 1 TO count - 1 - deltat
      dload = powertable(t + 1, 1) - powertable(t, 1) '1 is for ahp correlations
      dco2 = emistable(t + deltat + 1, 5) - emistable(t + deltat, 5)
```

```
      ccrsum = ccrsum + dload * dco2
   NEXT t
   'PRINT #4, deltat; ","; ccrsum
   'save the time max occurs max
   IF ccrsum > ccrmax THEN
      ccrmax = ccrsum
      deltatco2 = deltat
   END IF
NEXT deltat
'now shift co2
FOR t = 1 TO count
   emistable(t, 5) = emistable(t + deltatco2, 5)
NEXT t
'CLOSE #4

'OPEN "e:\hcshift.txt" FOR OUTPUT AS #4
'PRINT #4, "time shift , ccr hc"


'  HC
ccrmax = 0
deltathc = 0
FOR deltat = 1 TO 20
   ccrsum = 0
   FOR t = 1 TO count - 1 - deltat
      dload = powertable(t + 1, 1) - powertable(t, 1) '1 is for ahp correlations
      dhc = emistable(t + deltat + 1, 6) - emistable(t + deltat, 6)
      ccrsum = ccrsum + dload * dhc
   NEXT t
   'PRINT #4, deltat; ","; ccrsum
   'PRINT ccrsum
   'save the time max occurs max
   IF ccrsum > ccrmax THEN
      ccrmax = ccrsum
      deltathc = deltat
   END IF
NEXT deltat
'now shift hc
FOR t = 1 TO count
   emistable(t, 6) = emistable(t + deltathc, 6)
NEXT t
'CLOSE #4

' new count is lower by the maximum time shift
deltatmax = 0
IF deltatnox > deltatmax THEN deltatmax = deltatnox
IF deltatco > deltatmax THEN deltatmax = deltatco
IF deltatco2 > deltatmax THEN deltatmax = deltatco2
IF deltathc > deltatmax THEN deltatmax = deltathc
count = count - deltatmax

PRINT
PRINT " The time shift for NOx is "; deltatnox; " seconds."
PRINT " The time shift for CO  is "; deltatco; " seconds."
PRINT " The time shift for CO2 is "; deltatco2; " seconds."
PRINT " The time shift for HC  is "; deltathc; " seconds."

END SUB
```

Appendix B Program for combining SAP's and emissions to get emissions factors in grams/mile

```
' This program combines the file from Battelle containing the
' speed acceleration profiles with the emissions data file
'
' 7-27-1999
'
' 8-4-1999  changed for power proportion
' 8-31-1999 still waiting for new saps and added cold/hot stuff
' 9-7-1999 finished new speed bins and power extrapolation

DECLARE SUB powerfill (a())

COMMON SHARED emisdata(), inter(), hil3data(), year$, emis$
DIM sapdata(0 TO 15, 1 TO 7)           ' speed bin, acceleration bin
DIM emisdata(0 TO 15, 1 TO 7)          ' speed bin, acceleration bin
DIM hil3data(0 TO 15, 1 TO 7)          ' speed bin, acceleration bin for 3% hill
DIM sum(1 TO 8)                        ' average speed bins
DIM sum3(1 TO 8)                       ' used for the cold/hot stuff
DIM inter(1 TO 7, 1 TO 7)              ' for the linear extrapolation
DIM rowspeed(0 TO 15)                  ' for determining the actual average speed of the speed
bin

CLS
PRINT "Processing combination trucks..."
OPEN "d:\combos\combos.txt" FOR OUTPUT AS #3
OPEN "d:\combos\combtbl.txt" FOR OUTPUT AS #5
OPEN "d:\combos\secdata.txt" FOR OUTPUT AS #7
OPEN "d:\combos\cmbtbhl3.txt" FOR OUTPUT AS #12
PRINT #3, "year group, road type, avg speed, emissions type, factor, units"
PRINT #5, "year group, emissions type, ,road type, 0-10, 10-20, 20-30, 30-40, 40-50,  50-60, 60-
70, 70+, units"
PRINT #7, "year group, emissions type, ,road type, 0-10, 10-20, 20-30, 30-40, 40-50,  50-60, 60-
70, 70+, units"
PRINT #12, "year group, emissions type, ,road type, 0-10, 10-20, 20-30, 30-40, 40-50,  50-60, 60-
70, 70+, units"
PRINT "year group, road type, avg speed, emissions type, factors ,units"


' increment emissions type
FOR emission = 1 TO 5
   IF emission = 1 THEN emis$ = "nox"
   IF emission = 2 THEN emis$ = "co"
   IF emission = 3 THEN emis$ = "co2"
   IF emission = 4 THEN emis$ = "hc"
   IF emission = 5 THEN emis$ = "pm"

   FOR i = 1 TO 4
      IF i = 1 THEN year$ = "85"
      IF i = 2 THEN year$ = "90"
      IF i = 3 THEN year$ = "94"
      IF i = 4 THEN year$ = "98"
      emisfile$ = "d:\combos\" + year$ + "\" + emis$ + "res.txt"

      ' open and read emissions results file
      OPEN emisfile$ FOR INPUT AS #4
      LINE INPUT #4, junk$
      LINE INPUT #4, junk$
      LINE INPUT #4, junk$
      FOR speed = 0 TO 15
         INPUT #4, junk$, emisdata(speed, 1), emisdata(speed, 2), emisdata(speed, 3),
emisdata(speed, 4), emisdata(speed, 5), emisdata(speed, 6), emisdata(speed, 7)
      NEXT speed
      CLOSE #4

      ' fill in zeros by power extrapolation
      ' proportion to power
      powerfill emisdata()
```

```
      ' open and read dan's file
      FOR road = 1 TO 3
         'if road=4 then road$="local"
         IF road = 1 THEN road$ = "1"
         IF road = 2 THEN road$ = "3"
         IF road = 3 THEN road$ = "4"


         FOR avgspeed = 1 TO 8
            IF avgspeed = 1 THEN avgs$ = "a01"
            IF avgspeed = 2 THEN avgs$ = "a12"
            IF avgspeed = 3 THEN avgs$ = "a23"
            IF avgspeed = 4 THEN avgs$ = "a34"
            IF avgspeed = 5 THEN avgs$ = "a45"
            IF avgspeed = 6 THEN avgs$ = "a56"
            IF avgspeed = 7 THEN avgs$ = "a67"
            IF avgspeed = 8 THEN avgs$ = "a7p"

            sapfile$ = "d:\combos\ccr" + road$ + avgs$ + ".txt"
            'PRINT sapfile$


            OPEN sapfile$ FOR INPUT AS #4
            LINE INPUT #4, junk$
            FOR speed = 0 TO 15
               IF speed = 0 THEN group = 1.25
               IF speed = 1 THEN group = 5
               IF speed = 2 THEN group = 10
               IF speed = 3 THEN group = 15
               IF speed = 4 THEN group = 20
               IF speed = 5 THEN group = 25
               IF speed = 6 THEN group = 30
               IF speed = 7 THEN group = 35
               IF speed = 8 THEN group = 40
               IF speed = 9 THEN group = 45
               IF speed = 10 THEN group = 50
               IF speed = 11 THEN group = 55
               IF speed = 12 THEN group = 60
               IF speed = 13 THEN group = 65
               IF speed = 14 THEN group = 70
               IF speed = 15 THEN group = 75

               INPUT #4, junk$, sapdata(speed, 1), sapdata(speed, 2), sapdata(speed, 3),
sapdata(speed, 4), sapdata(speed, 5), sapdata(speed, 6), sapdata(speed, 7)

               ' calculate AverageSpeed
               rowspeed(speed) = group * (sapdata(speed, 1) + sapdata(speed, 2) + sapdata(speed,
3) + sapdata(speed, 4) + sapdata(speed, 5) + sapdata(speed, 6) + sapdata(speed, 7))

            NEXT speed
            CLOSE #4

            sum2 = 0
            FOR r = 0 TO 15
               sum2 = sum2 + rowspeed(r)
            NEXT r
            AverageSpeed = sum2
            IF AverageSpeed = 0 THEN AverageSpeed = 1

            ' multiply files together and sum
            sum(avgspeed) = 0
            sum3(avgspeed) = 0
            FOR a = 1 TO 7
               FOR s = 0 TO 15
                  sum(avgspeed) = sum(avgspeed) + sapdata(s, a) * emisdata(s, a) / AverageSpeed *
3600
                  sum3(avgspeed) = sum3(avgspeed) + sapdata(s, a) * emisdata(s, a)
               ' stuff here for hill
               NEXT s
            NEXT a
```

```
            ' PRINT AverageSpeed
            PRINT #3, AverageSpeed
            PRINT #3, year$; ","; road$; ","; avgs$; ","; emis$; ","; sum(avgspeed); ",";
"grams/mile"
            PRINT year$; " "; road$; " "; avgs$; " "; emis$, sum(avgspeed), "grams/mile"
         NEXT avgspeed
         PRINT #5, year$; ","; emis$; ", ,"; road$; ","; sum(1); ","; sum(2); ","; sum(3); ",";
sum(4); ","; sum(5); ","; sum(6); ","; sum(7); ","; sum(8); ","; "grams/mile"
         PRINT #7, year$; ","; emis$; ", ,"; road$; ","; sum3(1); ","; sum3(2); ","; sum3(3);
","; sum3(4); ","; sum3(5); ","; sum3(6); ","; sum3(7); ","; sum3(8); ","; "grams/second"
         ' print hill file
      NEXT road
   NEXT i
NEXT emission


CLOSE
PRINT " Done."
END

SUB powerfill (a())

DIM powerdata(0 TO 15, 1 TO 7)
DIM hill3(0 TO 15, 1 TO 7)

halfrhocda = 5
mu = .00938
gravity = 9.807

M = 19100            ' kilograms for the average of the combination trucks

OPEN "d:\combos\" + year$ + "\powerfil.txt" FOR OUTPUT AS #6
PRINT #6, "speed bin, h accel, m accel, l accel, cruise, l decel, m decel, h decel"
OPEN "d:\combos\" + year$ + "\hill3pw.txt" FOR OUTPUT AS #11
PRINT #11, "speed bin, h accel, m accel, l accel, cruise, l decel, m decel, h decel"
'OPEN "d:\combos\" + year$ + "\ahpres.txt" FOR INPUT AS #8
OPEN "d:\combos\" + year$ + "\" + emis$ + "fil.txt" FOR OUTPUT AS #9
OPEN "d:\combos\" + year$ + "\" + emis$ + "hl3.txt" FOR OUTPUT AS #10
PRINT #10, "speed bin, h accel, m accel, l accel, cruise, l decel, m decel, h decel"
PRINT #9, "speed bin, h accel, m accel, l accel, cruise, l decel, m decel, h decel"

' read in power
'LINE INPUT #8, junk$
'LINE INPUT #8, junk$
'LINE INPUT #8, junk$
'FOR q = 0 TO 15
'   INPUT #8, stuff, powerdata(q, 1), powerdata(q, 2), powerdata(q, 3), powerdata(q, 4),
powerdata(q, 5), powerdata(q, 6), powerdata(q, 7)
'NEXT q

' fill in power

FOR i = 0 TO 15
   IF i = 0 THEN speed = .559     ' values in meters/second
   IF i = 1 THEN speed = 2.235
   IF i = 2 THEN speed = 4.47
   IF i = 3 THEN speed = 6.705
   IF i = 4 THEN speed = 8.94
   IF i = 5 THEN speed = 11.18
   IF i = 6 THEN speed = 13.41
   IF i = 7 THEN speed = 15.65
   IF i = 8 THEN speed = 17.88
   IF i = 9 THEN speed = 20.12
   IF i = 10 THEN speed = 22.35
   IF i = 11 THEN speed = 24.59
   IF i = 12 THEN speed = 26.82
   IF i = 13 THEN speed = 29.06
   IF i = 14 THEN speed = 31.29
   IF i = 15 THEN speed = 33.53

   FOR j = 1 TO 7
```

```
      IF j = 1 THEN accel = .9     ' values in meters/second^2
      IF j = 2 THEN accel = .66
      IF j = 3 THEN accel = .29
      IF j = 4 THEN accel = 0
      IF j = 5 THEN accel = -.29
      IF j = 6 THEN accel = -.66
      IF j = 7 THEN accel = -.9
      powerdata(i, j) = (halfrhocda * speed ^ 3 + M * accel * speed + mu * M * g * speed) / 745.7
      hill3(i, j) = (halfrhocda * speed ^ 3 + M * accel * speed + mu * M * g * speed + M * g *
speed * .03) / 745.7
   NEXT j
   PRINT #6, speed; ","; powerdata(i, 1); ","; powerdata(i, 2); ","; powerdata(i, 3); ",";
powerdata(i, 4); ","; powerdata(i, 5); ","; powerdata(i, 6); ","; powerdata(i, 7)
   PRINT #11, speed; ","; hill3(i, 1); ","; hill3(i, 2); ","; hill3(i, 3); ","; hill3(i, 4); ",";
hill3(i, 5); ","; hill3(i, 6); ","; hill3(i, 7)
NEXT i
CLOSE #6
CLOSE #11

' fit curves to power/emissions data

      ' fill interp with zeros
      FOR x = 1 TO 7
         FOR y = 1 TO 7
            inter(x, y) = 0!
         NEXT y
      NEXT x

      ' calculate sums

      FOR accel = 1 TO 7
         FOR speed = 0 TO 15

            IF emisdata(speed, accel) <> 0 THEN
               inter(1, accel) = inter(1, accel) + emisdata(speed, accel)   ' sum of y
               inter(2, accel) = inter(2, accel) + emisdata(speed, accel) * powerdata(speed,
accel)  'sum of xy
               inter(5, accel) = inter(5, accel) + powerdata(speed, accel)      ' sum of x
               inter(6, accel) = inter(6, accel) + powerdata(speed, accel) ^ 2  ' sum of x
squared
               inter(7, accel) = inter(7, accel) + 1  ' n
            END IF
         NEXT speed
      ' PRINT
      ' PRINT emis$, year$, inter(7, accel), inter(5, accel), inter(6, accel)
      ' PRINT inter(1, accel), inter(2, accel)
      NEXT accel

      ' calculate m and b
      FOR accel = 1 TO 7
         inter(3, accel) = (inter(7, accel) * inter(2, accel) - inter(5, accel) * inter(1,
accel)) / (inter(7, accel) * inter(6, accel) - inter(5, accel) ^ 2)
         inter(4, accel) = (inter(1, accel) - inter(3, accel) * inter(5, accel)) / inter(7,
accel)
      NEXT accel

' evaluate curves to fill in emissions data
' use y=mx+b to fill in zeros

      FOR speed = 0 TO 15

         FOR accel = 1 TO 7
            IF emisdata(speed, accel) = 0 THEN
               emisdata(speed, accel) = inter(3, accel) * powerdata(speed, accel) + inter(4,
accel)
               IF emisdata(speed, accel) < 0 THEN emisdata(speed, accel) = emisdata(speed - 1,
accel)
            END IF
            hil3data(speed, accel) = inter(3, accel) * powerdata(speed, accel) + inter(4, accel)
         NEXT accel
```

```
         PRINT #9, speed; ","; emisdata(speed, 1); ","; emisdata(speed, 2); ","; emisdata(speed,
3); ","; emisdata(speed, 4); ","; emisdata(speed, 5); ","; emisdata(speed, 6); ",";
emisdata(speed, 7)
         PRINT #10, speed; ","; hil3data(speed, 1); ","; hil3data(speed, 2); ","; hil3data(speed,
3); ","; hil3data(speed, 4); ","; hil3data(speed, 5); ","; hil3data(speed, 6); ",";
hil3data(speed, 7)
      NEXT speed


CLOSE #9
CLOSE #10

END SUB
```

Appendix C Program for predicting emissions using the grams/second emissions factors

```
' program to predict the emissions from current nchrp tables.
' source emissions from 1994 to 1997 tractor trucks
' speed time from 0961 5-Mile Route
' made to work with new bins as of 5-17-99

DIM nox(0 TO 15, 1 TO 8)
DIM cycle(0 TO 1700, 1 TO 4)   ' speed, acceleration, actual nox, predicted nox

' read in emission data
CLS

OPEN "d:\combos\94\noxfil.txt" FOR INPUT AS #2
'LINE INPUT #2, junk$
FOR i = 0 TO 15
   '          speed      heavy      medium     light      cruise     ldecel     mdecel     hdecel
   INPUT #2, nox(i, 1), nox(i, 2), nox(i, 3), nox(i, 4), nox(i, 5), nox(i, 6), nox(i, 7), nox(i,
8)
NEXT i
CLOSE #2


' read in speed and accleration data


OPEN "d:\combos\mph0961.csv" FOR INPUT AS #3
LINE INPUT #3, junk$
FOR t = 1 TO 900
   '         time    speed      accel
   INPUT #3, count, cycle(t, 1), cycle(t, 2)
   IF cycle(t, 1) < 0 THEN cycle(t, 1) = 0
NEXT t
CLOSE #3

' predict emissions and write output file


OPEN "d:\combos\predict.txt" FOR OUTPUT AS #4
PRINT #4, " time(sec) , speed(mph) , accel (mph/s) , act nox (g/s) , predicted nox (g/s)"

FOR t = 1 TO 900

   IF cycle(t, 1) < 2.5 THEN
      speed = 0
   ELSEIF cycle(t, 1) < 7.5 THEN
      speed = 1
   ELSEIF cycle(t, 1) < 12.5 THEN
      speed = 2
   ELSEIF cycle(t, 1) < 17.5 THEN
      speed = 3
   ELSEIF cycle(t, 1) < 22.5 THEN
      speed = 4
   ELSEIF cycle(t, 1) < 27.5 THEN
      speed = 5
   ELSEIF cycle(t, 1) < 32.5 THEN
      speed = 6
   ELSEIF cycle(t, 1) < 37.5 THEN
      speed = 7
   ELSEIF cycle(t, 1) < 42.5 THEN
      speed = 8
   ELSEIF cycle(t, 1) < 47.5 THEN
      speed = 9
   ELSEIF cycle(t, 1) < 52.5 THEN
      speed = 10
   ELSEIF cycle(t, 1) < 57.5 THEN
      speed = 11
   ELSEIF cycle(t, 1) < 62.5 THEN
      speed = 12
   ELSEIF cycle(t, 1) < 67.5 THEN
```

```
      speed = 13
   ELSEIF cycle(t, 1) < 72.5 THEN
      speed = 14
   ELSEIF cycle(t, 1) >= 72.5 THEN
      speed = 15
   END IF


   IF cycle(t, 2) > 2 THEN
      accel = 2 ' heavy acceleration
   ELSEIF cycle(t, 2) > 1 THEN
      accel = 3 ' medium acceleration
   ELSEIF cycle(t, 2) > .3 THEN
      accel = 4 ' light acceleration
   ELSEIF cycle(t, 2) < -2 THEN
      accel = 8 ' heavy deceleration
   ELSEIF cycle(t, 2) < -1 THEN
      accel = 7 ' medium deceleration
   ELSEIF cycle(t, 2) < -.3 THEN
      accel = 6 ' light deceleration
   ELSE
      accel = 5 ' cruise
   END IF

   cycle(t, 4) = nox(speed, accel)
   'PRINT #4, " time(sec) , speed(mph) , accel (mph/s) , act nox (g/s) , predicted nox (g/s)"
   PRINT #4, t; ","; cycle(t, 1); ","; cycle(t, 2); ","; cycle(t, 3); ","; cycle(t, 4)

NEXT t
CLOSE #4

END
```