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Evaluation of Heavy-Duty Diesel Vehicle Emissions During Cold-Start and Steady-State Idling Conditions and Reduction of Emissions from a Truck-Stop Electrification Program

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To the Graduate Council:

I am submitting herewith a dissertation written by James A. Calcagno entitled "Evaluation of Heavy-Duty Diesel Vehicle Emissions During Cold-Start and Steady-State Idling Conditions and Reduction of Emissions from a Truck-Stop Electrification Program." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Civil Engineering.

Wayne T. Davis, Major Professor

We have read this dissertation and recommend its acceptance:

Terry L. Miller, R. Bruce Robinson, David R. Irick

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Acceptance for the Council:
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Vice Chancellor and Dean of
Graduate Studies

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Evaluation of Heavy-Duty Diesel Vehicle Emissions during Cold-Start and Steady-State Idling Conditions and Reduction of Emissions from a Truck-Stop Electrification Program

A Dissertation Presented for the Doctor of Philosophy Degree
The University of Tennessee, Knoxville

James A. Calcagno, III
December 2005

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ABSTRACT

Cold-start and extended-idling emissions of carbon monoxide (CO), oxides of nitrogen (NOx) and particulate matter (PM) were measured from 24, class-8B, heavy-duty diesel vehicles (HDDV8B) using portable emission monitoring equipment. The ratio of nitrogen dioxide (NO_2) to NOx and the ratio of $PM_{2.5}$ to total PM were reported. Truck model years ranged from 1992 to 2004. All vehicles were tested in the field during summer and fall months under ambient environmental conditions at low (600-800 rpm) and high (1000 rpm) engine idling speeds with the truck cab air-conditioner operating at “on” and “off” modes. Sampling data thus obtained were used to generate typical average cold-start and extended-idling emission factors and were used to estimate potential emission reductions associated from using Truck Stop Electrification (TSE) Itechnology.

Results indicated that cold-start emission rates, which were determined from the first 5-minutes of the cold-start period, were higher than the extended-idling emission rates by factors of 2.5 for CO, 1.5 for NOx and 1.7 for $PM_{2.5}$. Overall, the extended-idling emission factors of the present study compared favorable to both the U.S Environmental Protection Agency (EPA) values that are recommended for State Implementation Plans (SIP) and average emission factors that were established from a previous review of the literature. In summary, the NOx emission rates were greater than those reported for EPA-SIP purposes and from the literature review by 23.5% and 17.4%, respectively. The $PM_{2.5}$ emission rates observed in this study were less than those reported for EPA-SIP purposes by 3.8% and were greater than those reported in the literature by 6.3%, respectively. The average extended-idling emission factors for CO, NOx and PM2.5 were 64.5 g/hr, 167 g/hr and 3.51 g/hr, respectively.

Electricity utilization and related emissions from TSE were calculated for a coal-fired power plant equipped with Selective Catalytic Reduction (SCR) technology for NOx removal and that meets New Source Performance Standards (NSPS) for NOx and $PM_{2.5}$ emissions. In general, it was found that the cold-start emissions and the emissions from electricity were moderately small in comparison with the extended-idling emissions. Conversely, it was determined that the actual emission savings that could be associated with the TSE technology were 62.4 g/hr for CO, 158 g/hr for NOx and 3.19 g/hr for $PM_{2.5}$. Finally, the corrected or actual emission reductions for CO, NOx and $PM_{2.5}$ using a cold-start period for 5-minutes were approximately 3.2%, 5.0% and 10% less than the extended-idling emission rate, respectively.

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NOMENCLATURE

AC	Air Conditioner
ACT	Actual
acm	Actual Cubic Feet per Minute (ACM)
AERR	Actual Emission Reduction Rate
Al	Aluminum
ANOVA	Analysis of Variance
AP	Air Pollution
Ave	Average
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
C	Carbon, Centigrade or Concentration
CAA	Clean Air Acts
CAL	Calibration
CEM	Continuous Emission Monitoring
CEMS	Continuous Emission Monitoring System
CFM	Cubic Feet per Minute
C_G	Gravimetric concentration
CH_n	Carbon-Hydrogen atoms
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CSEF	Cold-Start Emission Factor
CS-n	Cold-Start (at 5, 10 or 15 minutes)
CSER	Cold-Start Emission Rate
CS-SS	Cold-Start Steady-State
delta p, Δp	Pressure drop
DOT	Department of Transportation
e	Power-plant thermal efficiency
EAC	Early Action Compact

EC	Elemental Carbon
ECES	Electric Consumption Emission Standard
ECM	Electronic Control Module
EDS	Energy-Dispersive Spectrometry
EF	Emission Factors
EIER	Extended-Idling Emission Rate
EPA	Environmental Protection Agency
EUER	Electricity-Use Emission Rate
Exp	Experimental
F	Fahrenheit
FID	Flame Ionization Detection
FMCSA	Federal Motor Carrier Safety Administration
g	Gram
gal	Gallon
GVWR	Gross Vehicle Weight Rating
H	Hydrogen
HC	Hydrocarbon
HEPA	High Efficiency Particulate
HDDV	Heavy Duty Diesel Vehicle
HOS	Hours-of-Service
hp	Horsepower (HP)
hr	Hour
HVAC	Heating, Vitalization and Air-Conditioning
ID	Identification
IR	Idle Reduction
J	Joule
K	Kelvin
keV	Kilo-electron volt
L	Liter or Load
lb	Pound

LitRev	Literature Review
lpm	Liters per minute
m	Mass or meters
mg	Milligram
μg	Microgram
min	Minute
μm	Micron (micrometer)
MOBILE	Mobile Source Emission Factor
mph	Miles per hour (MPH)
MW	Molecular Weight
n	Sample size or number
N^*	Crankshaft rotational speed per number of power stroke revolutions
NA	Not Available
NAAQS	National Ambient Air Quality Standards
NDIR	Non-dispersive Infrared
nm	Nanometer
NO	Nitrogen Oxide
NO_2	Nitrogen Dioxide
NOx	Oxides of Nitrogen ($NO + NO_2$) or Nitrogen Oxides
NSPS	New Source Performance Standards
η_V	Volumetric efficiency
O_2	Oxygen
O_3	Ozone
OBS	Observed
OC	Organic Carbon
P	Absolute Pressure
Pa	Pascal
PAH	Polycyclic Aromatic Hydrocarbons
Pb	Lead

PCV	Positive Crankcase Ventilation
PEMS	Portable Emission Monitoring System
phi, ϕ	Equivalence ratio
PM	Particulate Matter (10 or 2.5 mm aerodynamic diameter)
ppb	Parts-per-billion
ppm	Parts-per-million
p-value	Probability value
Q	Volumetric flow rate
R	Universal gas constant or Rankin
R^2	R-square value
rho, ρ	Density
ROVER	Realtime On-road Vehicle Emissions Reporter
rpm	Revolutions per minute (RPM)
RSD	Relative Standard Deviation
scfm	Standard cubic feet per minute (SCFM)
S	Sulfur
SCR	Selective Catalytic Reduction
SD	Standard Deviation
Si	Silica
SIP	State Implementation Plan
SO_2	Sulfur Dioxide
SOF	Soluble Organic Fraction
STD	Standard
Stdev	Standard deviation
T	Temperature (absolute)
t_A	Extended-idling rest period (or TSE time)
t_B	Idling time during cold-start period
Temp	Temperature
TEOM	Tapered Element Oscillating Microbalance
THC	Total Hydrocarbons

TSE	Truck Stop Electrification
T_R	Run time
TRB	Transportation Research Board
TVA	Tennessee Valley Authority
TWA	Time-Weighted Average
US	United States
V	Volume
VIUS	Vehicle Inventory and Use Survey
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compound
VOF	Volatile Organic Fraction
WP	Power utilization by HVAC
$\overline{X}$	Mean

1 INTRODUCTION

Commercial trucking has displaced the railroad to become the dominant form of transportation for hauling most freight in this country. The propulsion system of choice for long-haul freight trucks are usually diesel engines because they are more efficient per unit of work and are far more durable than gasoline engines. Out of necessity, long-haul truck drivers generally idle their diesel engines while parked at travel centers during federally mandated driver rest periods. Idling the engine provides power for heat or air conditioning and helps maintain adequate battery voltage while the driver uses electrical appliances in the sleeping berth, such as, microwave, refrigerator or television. Idling also keeps the fuel and lubricating oil more fluid, and so precludes difficult engine start-up during cold days. Furthermore, some heavy-duty diesel trucks have refrigerated trailers that are cooled by an independent, diesel-driven unit that must be kept running while the driver is resting.

Care must be taken when relating vehicle types across different data sources because different classification systems are used for reporting local vehicle registration information and Vehicle Miles Traveled (VMT) data. The United States Environmental Protection Agency (EPA) Mobile Source Emission Factor (MOBILE6) model categorizes heavy-duty diesel vehicles (HDDV) according to the gross vehicle weight rating (GVWR) of the vehicle. HDDV is any diesel-powered vehicle greater than 8,500 pounds (lbs) GVWR. Other examples are HDDV7 - diesel vehicles between 26,001 and 33,000 lbs GVWR, HDDV8A - diesel vehicles between 33,001 and 60,000 lbs GVWR and HDDV8B -diesel vehicles greater than 60,000 lbs GVWR.[1]

The Vehicle Inventory and Use Survey (VIUS) is conducted every five years by the United States (US) Census Bureau to provide information on the physical and operational characteristics of the nation's truck population. VIUS uses the following categories to define heavy-duty diesel trucks: (1) heavy-heavy, trucks with an average vehicle weight over 26,000 lbs, (2) trucks using diesel as fuel and (3) truck-trailer combinations having five-axles or more. With respect to GVWR, the heavy-heavy designation includes both MOBILE6 categories: HDDV7 and HDDV8. Truck and trailer configurations are further divided into categories of truck with one trailer, truck tractor with semi-trailer and truck tractor with two or more trailing units.[2,3] The main focus of this paper will be the long-haul HDDV8 category that includes a sleeping berth for the driver in the truck cab. Long-haul is defined as commercial freight hauling on long distance trips over 500 miles per day.

1.1 Hours-of-Service Regulations

The basic Hours-of-Service (HOS) regulations for interstate motor carriers and drivers have been in effect for over 60 years since Congress first became concerned about the effects of fatigue as a contributing factor in commercial motor vehicle accidents. The Federal Motor Carrier Safety Administration (FMCSA) has recently modified the HOS rules with compliance to occur January 4, 2004. Under these new regulations, drivers may drive 11 hours, following 10 hours off-duty but are limited to just 14 hours on-duty. The 14-hour duty period may not be extended with off-duty time for meal and fuel stops, etc., and only the use of a sleeper berth can extend the 14-hour duty period. Each duty period must begin with at least 10 hours off-duty. The weekly on-duty limits are 60 hours in any seven consecutive days or 70 hours in any eight consecutive days, and drivers can only restart the 7- or 8-day period by taking at least 34 consecutive hours off-duty. Finally, drivers may split on-duty time by using sleeper berth periods, but they still must be incompliance with all other HOS rules.[4,5]

1.2 Air Quality Trends

The EPA has established National Ambient Air Quality Standards (NAAQS) for the following criteria pollutants: carbon monoxide (CO), nitrogen dioxide (NO_2), particulate matter (PM), ground-level ozone (O_3), sulfur dioxide (SO_2) and lead (Pb). The NAAQS were created to protect public health and prevent the continued environmental degradation of regional air quality. Total emissions for the six criteria air pollutants have generally declined 48% in the US between 1970 and 2002. During this same time-period, gross national product increased 164 %, VMT increased 155%, energy consumption increased 42% and population increased 38%. In the face of increasing population and economic growth, reductions in criteria air pollution concentrations have occurred, and they are attributable to the Clean Air Act (CAA) regulations beginning in 1970 and continuing to the present. However in spite of great progresses made in air quality improvements, approximately 146 million people nationwide (during 2002) still lived in counties with pollution levels above the NAAQS. Out of the 230 non-attainment areas identified during the 1990 Clean Air Act Amendments designation process, 124 areas remain non-attainment areas.[6]

Of the six criteria pollutants, fine PM and ground-level O_3 continue to be problems in many regions. Primary concern is reserved for airborne PM less than or equal to 2.5 microns (µm) because it is in this range that PM is small enough to penetrate deep into the lungs. Smaller particles, less than 0.1 µm, are easily inhaled and trapped in the alveoli of the lungs, which can cause numerous health problems and aggravate respiratory conditions, such as asthma and bronchitis. Some PM can adsorb polycyclic aromatic hydrocarbons (PAH) from the diesel exhaust. PAH are known to be mutagenic and, in some cases, carcinogenic in character. The fine PM also impacts the environment by affecting the transmission of light and reducing visibility.[7]

Of all emissions from diesel engine, PM is probably the most problematic. Emission standards on diesel engines have led to dramatic reductions in particle mass emitted. Some studies show however, that low-emission diesel engines emit much higher concentrations of nanoparticles than older designs and other low-emission designs. Nanoparticles (or ultra-fine particles) are defined as particles less than 100 nanometers (nm). Many recent studies suggest that at similar mass concentrations, nanometer size particles are actually more dangerous to human health than the micron size particles.[8,9]

Diesel engines emit gaseous pollutants that are photo-chemically reactive, resulting in the formation of ground-level O_3. The main constituent of smog is ground-level O_3. Short-term exposure to O_3 (1 to 3 hours) can result in shortness of breath, coughing, chest tightness or irritation of the nose and throat. Children, the elderly and people with pre-existing respiratory illnesses are particularly susceptible. Long-term exposure (6 to 8 hours) or repeated exposure to O_3 will make people more vulnerable to respiratory infection and lung inflammation and can aggravate preexisting respiratory diseases, such as asthma. High concentrations of O_3 also cause detrimental effects to vegetation, which include reduced growth and decreased survivability to disease, pests and other environmental stresses. While national levels of O_3 improved in the last 10 years, 1-hour O_3 levels in selected regions increased, and the 8-hour levels in rural areas increased.[10]

On July 18, 1997, the EPA revised the national standard for ground-level O_3 from 120 parts-per-billion (ppb) 1-hour peak standard to 80 ppb 8-hour average standard. Under the new federal regulations, each state was required to submit a list of counties expected to exceed the federal O_3 standard. In addition to the counties that do not meet the standard, the list included counties that have been determined to be contributing to high O_3 levels in other counties.[6] The EPA conducted an independent review of the list of each state and made its final determination of non-attainment areas April 19, 2004.

Some counties and states have joined the EPA in agreements called Early Action Compacts (EAC), which commit them to taking early action to meet the revised O_3 standard by 2007. In return for this early action, EPA will defer their non-attainment designation, thereby avoiding certain economic and transportation restrictions that non-attainment would involve, in exchange for an earlier compliance schedule.

On October 27, 1998, the EPA issued a new regulation requiring 22 states and the District of Columbia to submit State Implementation Plans (SIP) to diminish the regional transport of ground-level O_3 through reductions in nitrogen oxide (NOx) emissions.[11] This regulation is commonly known as the NOx-SIP call. By reducing NOx emissions, the rule was targeted at diminishing the transport of ground-level O_3 across state boundaries.

1.3 Compression-Ignition Engines

Air is compressed to a higher pressure in the diesel engine than it is compressed in the spark-ignition gasoline engine. The higher compression ratio is needed to increase temperature and pressure of the air in the piston cylinder. So when fuel is injected into the cylinder just before the end of the compression stroke - the fuel mixes with the heated air, the fuel evaporates and spontaneous ignition occurs. In the gasoline engine, this ignition process occurs from an electric discharge through the aid of a spark plug.

The un-throttled operation and high compression ratio of the diesel engine contribute to the higher efficiency of the diesel engine relative to the gasoline engine.[12] Throttling is the process of regulating the amount of air pulled into the engine before it is mixed with the fuel and enters the cylinders. The spark-ignition engine primarily uses the throttling process to control torque. The spark-ignition engine is also designed to operate near the stoichiometric ratio. The key feature of the diesel engine is that the torque it generates is governed, not by throttling the air supply, but by simply varying the amount of fuel that is injected into the engine.[13]

The downside of the high compression ratio of the diesel is that it generates higher temperatures inside the engine. Unfortunately, this increases the production of nitric oxides (NO) in the hotter regions of the cylinder. The formation of NO and other oxides of nitrogen increase rapidly with flame temperature. In the engine, the amount of time spent in the combustion cycle is too short for the NO to be oxidized to NO_2, even though NO_2 is thermodynamically favored at lower temperature. Lower engine speeds generally produce a higher concentration of NOx for a given power due to the longer time available for the reactions to occur.[13] The term NOx refers to the sum of the two compounds: NO and NO_2. Additionally, since the air and diesel fuel are rarely mixed completely before auto-ignition takes place, the potential exists for some of the unburned fuel in the cooler regions of the cylinder to form soot during certain combinations of load and engine speeds.

The compression ratio is just one of several factors that influence emissions from diesel engines. Other factors that have a strong influence on emissions are engine injection timing and rate of fuel injection, equivalence ratio and engine speed. The equivalence ratio (ϕ) is defined as the fuel/air ratio normalized with respect to the stoichiometric fuel/air ratio, where $\phi > 1$ is fuel-rich, $\phi < 1$ is fuel-lean and $\phi = 1$ at the stoichiometric condition.

Injection timing is the most influential parameter with regard to emissions. For example, if a mixture burns early during the combustion process, it is compressed to a higher temperature, thus enhancing the formation of NO. Unfortunately, injection timing retardation is in conflict with good fuel economy and low PM emissions.[12] The combustion flame speed also influences the NOx formation. Lean mixtures have lower flame speeds, which gives more time for the NOx to form plus greater oxygen (O_2) availability. The equivalence ratio is essentially dictated by engine load requirements. Piston and cylinder designs that improve the mixing of fuel and air, and other secondary devices (such as, superchargers or turbochargers) that force more air into the combustion chamber can also influence emissions.[13]

The diesel engine characteristically operates fuel-lean (i.e., $\phi < 1$). All motor vehicle combustion engines are designed to ignite the air-fuel mixture at the optimum instant to maximize power output and to minimize fuel consumption and exhaust emissions. This creates special problems because the equivalence ratios are different for optimizing the operation of the engine to meet these three objectives simultaneously. For example, efforts to improve the fuel economy or engine performance may aggravate the emission problem. The following discussion demonstrates the impracticality to optimize a diesel engine so as to reduce both the NOx and the soot formation simultaneously.

Figure 1.1 shows the influence of the equivalence ratio on light-duty diesel engine performance and emissions. (Note: all tables and figures are located in the appendices.) This figure is used because a similar figure could not be located for HDDV8 engines, but it illustrates quite sufficiently the overall effects of the equivalence ratio. The terms BSFC and BMEP in Figure 1.1, part (a), refer to brake-specific fuel consumption and brake-mean effective pressure, respectively. The former term is the mass of fuel consumed per unit net energy output. The latter term refers to the net power output per engine cycle. It can be thought of as the work done per displacement volume. The units of the term are power per cycle volume, which actually cancel to give units of pressure.[14]

From Figure 1.1, part (a), the following conclusions can be reached about variations in engine performance and fuel consumption with change in the equivalence ratio (ϕ) between 0.2 and 1.0:

- The BMEP increases with equivalence ratio. Higher BMEP and equivalence ratios correspond to higher engine power output or load.
- The exhaust gas temperature increases with equivalence ratio.
- Fuel consumption (i.e., BSFC) is high at low equivalence ratio but decreases sharply when equivalence ratio increases. As equivalence ratio approaches unity, fuel consumption increases slightly above a minimum value at about $\phi = 0.5$.

The emission levels in Figure 1.1, part (b), are reported in terms of mass emissions per unit net power output. The reason for this convention is that the species concentrations in the exhaust gas are somewhat misleading. At low equivalence ratios, the pollutants are significantly diluted with excess air, as well as during normal engine operation, while the equivalence ratio is always changing because of varying demand on the engine. Accounting for this dilution effect and to facilitate comparison with other engines, the emission levels in the figure are usually reported in mass per unit energy.[14]

From Figure 1.1, part (b), the following conclusions can be reached about variations of emissions with change in the equivalence ratio (ϕ) between 0.2 and 1.0:

- All emissions are high at low equivalence ratios for which engine output is low.
- CO and PM emissions drop sharply with increasing equivalence ratio and pass through a minimum value at about $\phi = 0.5$ where fuel consumption is also a minimum. They then rise sharply as the equivalence ratio approaches unity.
- HC and NO emissions drop sharply with increasing equivalence ratio above about $\phi = 0.2$. They reach relatively low levels at about $\phi = 0.4$ and then change only slightly thereafter. It should be noted, that while brake specific emissions of these

pollutants decrease with increasing load, absolute emission rates might increase at high power output. The NO emissions can be influenced by injection parameters for a given equivalence ratio.

In summary, diesel engines have a higher maximum efficiency than gasoline engines because in diesel engines: (1) the compression ratio is higher; (2) throttling is not used to generate power; (3) during the initial part of compression, only air is present; and (4) the fuel/air mixture is always lean of stoichiometric, which gives a higher fuel conversion efficiency. However, those unique features that make the diesel engine more efficient than the gasoline engine also become trade-offs in terms of the relative magnitudes of emitted pollutants that occur between these types of engines.

1.3.1 Cold-Starting

Combustion instability and soot emissions are known problems during cold-starting the diesel engine. The factors that affect the diesel engine during cold-start are (1) fuel properties, (2) intake air temperature and pressure, (3) compression ratio, (4) leakage or blow-by, (5) cranking speed, (6) fuel injection and (7) combustion chamber design.[15] The effect of ambient temperature is probably the most critical factor because auto-ignition in the diesel engine relies on both high temperature and high pressure. In turbocharged diesel engines, the compression ratio is often reduced to restrict peak cylinder pressure. This obviously has a detrimental effect on engine starting performance. The actual compression ratio is usually determined by the cold-starting requirements and is often higher than optimum for either fuel economy or power. Under marginal starting conditions, it is also possible that some of the cylinders misfire until the engine reaches idling speed or the engine coolant has sufficiently warmed.[16] Such behavior is characterized by the emission of unburned fuel.

1.3.2 Vehicle Age

There are two factors of vehicle age that may affect the emissions production: normal engine wear and technology change. It is believed that as the vehicle ages and accumulates higher mileage, the engine will slowly wear and produce higher emissions. However, diesel engine deterioration is thought to be slow relative to most gasoline engines. Changes in technology, implies that the engines produced today are different from the older ones and must meet more stringent emissions standards. There is some documentation on vehicle deterioration for heavy-duty vehicles: generally, diesel engines have been reported to deteriorate little over the first 290, 000 miles, and newer engines can last between 500,000 and 1,000,000 miles before a rebuild.[17]

1.4 Heavy-Duty Diesel Vehicles

Little quantitative data exists on the amount of emissions that are emitted by HDDV8 engines during idling. Almost no published data exist for the engine during the cold-starting period. In general, diesel engines emit less CO and hydrocarbons (HC) when compared to gasoline engines since fuel-lean mixtures (i.e., conditions of excess air) tend to reduce CO and HC emissions. However, diesel engines emit more PM and NOx per unit of fuel burned in comparison to gasoline engines. NOx emitted from diesel engines and other combustion sources, serve as precursors in the formation of ground-level O_3. For diesel engines, the NOx portion of the exhaust gas is approximately 95%

NO and 5% NO_2.[14] Basically, incomplete combustion causes the formation of CO and PM emissions.

Volatile organic compounds (VOC) are the other important class of precursors in the formation of ground-level O_3. The VOC classification in the MOBILE6 model includes HC emissions as measured by flame ionization detection (FID) and aldehydes. The total HC (THC) classification includes HC as measured by FID, methane and ethane.

The 5-axles or more truck fleet in 1997 was approximately 1.4 million units, which was about 20.9% of the total national truck fleet. Of the 5-axles or more fleet, approximately 86.9% was comprised of tractor semi-trailer combinations. It is estimated that about 33% of the 5-axles or more truck fleet, or approximately 400,000 heavy-heavy diesel trucks have sleeper compartments.[2,3] Total annual interstate VMT for HDDV in the contiguous US for 1997 was over 100 billion miles. Annual rural interstate VMT for HDDV was approximately 40 billion miles.[18]

According to a recent freight analysis forecast published by the Department of Transportation (DOT), total domestic freight volume (i.e., air, highway, rail and water freight combined) is expected to grow by more than 65 percent, increasing from 13.5 billion tons in 1998 to 22.5 billion tons in 2020. Freight trucks moved 77 percent of the total tonnage in 1998, and they are expected to move at least 75 percent of the total tonnage in 2020.[19] Thus, the number of commercial freight trucks will increase to meet this need to transport the additional freight tonnage. Accordingly, when assessing the effects of these factors on vehicle idling emission control scenarios, primary effort must focus on reducing emissions in those categories that can be reduced in an effort to decrease overall emissions and meet air quality standards. Since long-haul trucks have the potential to contribute relatively high amounts of NOx and PM into the emission inventory, many environmental planning agencies and commercial interests are now investigating various strategies to reduce diesel truck emissions, including the emissions from trucks that are idling for long-periods of time.

1.5 Significance of the Study

The HDDV8 are excellent candidates for idle reduction (IR) technologies because of the large number of vehicles that idle for substantial periods of time. The term IR refers to technologies that allow drivers to refrain from long-duration idling of the truck engine by using an alternative technology. The main purposes of IR technologies are to reduce emissions and save fuel when compared to long-duration engine idling. Two examples of IR devices are auxiliary power units and fuel-fired heaters. Auxiliary power units provide electrical power and heating, ventilation and air-conditioning to the cab. They are usually driven by smaller diesel engines. Fuel-fired heaters are used to provide warm air to the cab during the cold winter months, and they normally rely on a secondary fuel for energy (e.g., natural gas). Limited experimental data have demonstrated that auxiliary power units are less polluting and more fuel-efficient than long-duration idling of the truck.

Most important among the IR technologies is truck stop electrification (TSE) because it has the greatest potential to reduce idling emissions and fuel usage. One company that provides advance TSE systems is IdleAire Technologies, Inc. with corporate offices located in Knoxville, Tennessee. Their product is a stationary structure that is installed at the rest area, which provides each parking space with an external thermostatically controlled, high capacity heating, ventilation and air-conditioning (HVAC) unit. Another approach is to just provide electrical connections to each parking space, whereby the truck must have an on-board HVAC unit.

The IdleAire TSE units are shown in Figure 1.2. A flexible duct from the main HVAC unit connects to the truck via a window-mounted service module, which also provides internal 110-volt outlets for in-cab appliances. Outside on the module, separate electric receptacles provide external 110-volt service to power refrigeration units. Other amenities, such as telephone, television and Internet access are also provided to the cab via the mounted service module. The in-cab air supply and service module are shown in Figure 1.3. Thus, by using electricity from the local utility company's power grid, substantial reductions in truck idling emissions can be achieved because electricity generating-power plants produce electricity more efficiently than diesel driven truck engines, and power plants already have embedded technology for pollution control of PM and, in most cases NOx, as well.

Previous emission reduction estimates that have been attributable to TSE have generally only included those idling emission savings that are associated with the driver simply shutting-off the engine and using TSE during required rest periods. A more thorough and realistic emission mass balance between idling and TSE should include an estimation of the increased emissions associated with the consumption of electricity from the power grid. However more importantly, since combustion inefficiency and the emissions generated during the engine cold-start are known problems for internal combustion engines, any increased emissions due to the cold-start should also be counted in the mass balance equations since the engine must be restarted after using TSE technology.

1.6 Purpose of the Study

The TSE concept has the potential to significantly reduce HDDV8 long-duration idling emissions. Currently, major TSE projects are in various stages of development in the states of California, Georgia, New York, Tennessee and Texas. The intent of the developers of TSE technology is to apply TSE nationwide along the interstate highway system in commercial areas that provide diesel fuel and other services to the trucking industry. Therefore, it is of great interest to quantify the total emission reductions that can be expected with TSE to support future administrative decisions from standpoints of environmental planning, human health and economic cost. To aid in this end, it will be necessary to examine (1) the complete emissions mass balance associated with the production of electricity that is needed to provide TSE, (2) the diesel engine long-duration idling emissions and (3) the engine cold-starting emissions.

The later cold-start emissions would be associated with a vehicle that participated at a TSE facility by not idling, followed by a relatively cold-start when the vehicle was restarted. Thus, the objective of the present study was to provide estimates of the approximate magnitude of exhaust emissions that occur immediately after a cold engine-start and during the extended-idling periods. The variation of emissions due to engine idling speeds and cycling of the air- conditioning load on the magnitude of emissions were characterized. The overall emission mass balance between truck idling and emissions produced from the electricity consumed in lieu of truck idling was also investigated. Electricity utilization and related emissions from TSE were calculated for a coal-fired power plant equipped with Selective Catalytic Reduction (SCR) technology for NOx removal and that meets the New Source Performance Standards (NSPS) for NOx and PM emissions.[20]

2 LITERATURE REVIEW

Numerous studies have been conducted of emissions using chassis dynamometers on heavy-duty diesel engines where the vehicle or the engine is driven through speed-time transient tests. However, only limited historic field data exists concerning HDDV8 idling emissions. Interest in HDDV8 idling emissions has been steadily increasing as regional planning agencies search for additional emission reductions strategies. Recently, a few independent research groups in conjunction with government and commercial interests have started to quantify the effects of engine speed, accessory load and other background environmental conditions, such as ambient air temperature, on idling emissions and fuel consumption rates. Moreover, emissions from various IR devices have also been evaluated with respect to the potential benefits that these devices may provide toward a decrease in overall vehicle emissions and fuel usage. The following sections summarize the methodologies and results from these research papers. The approach and purpose of each study will be summarized first, followed by a summary of the emissions testing results at the end of the discussion.

2.1 Major Idling Research Activities

McCormick, et.al.[21] measured idling emissions rates for total HC, CO, NOx and PM from 10 heavy-duty diesel trucks at roughly 1-mile above sea level using a full exhaust-flow dilution tunnel. The truck model years were between 1990 and 1998. The engine displacements and horsepower ranges were 11.1-12.7 liters (L) and 330-450 horsepower (hp), respectively. Each truck was tested while the engine was hot, within 20 minutes of completing a dynamometer driving cycle. All trucks were idled under the standard factory-specified idling speed. However, engine revolutions per minute (rpm) and the use of cab accessories were not quantified in the paper. For proposes of summarizing the results, the factory-specified idling speed was assumed to be between 600 and 800 rpm, which in the present paper is defined as low-idling speeds. High idling speed is defined here as engine idling at greater than 1000 rpm. The analytical methods that were used to measure the emissions were: FID for HC, non-dispersive infrared (NDIR) for CO, chemiluminescence for NOx and gravimetry for PM.

Brodrick, et.al.[22] measured idling emissions rates for HC, CO, carbon dioxide (CO_2) and NOx and fuel consumption rates from a single 1999 class-eight diesel truck using an emission measurement trailer that was on loan to the research group from EPA. The analytical methods used in the EPA measurement trailer were not mentioned in the paper. The engine horsepower for the vehicle was 450 hp. The idling test conditions were as follows: (1) standard idle (600 rpm) after cruising 55 miles per hour (mph) for 10-minutes (min); (2) standard idle after running a 10-min transient cycle; (3) standard idle with the air-conditioner (AC) running after performing a 10-min transient cycle; (4) high idle (1050 rpm) with the AC running after performing a 10-min transient cycle; (5) high idle with AC running for 5-hours (hrs). The transient cycle consists of driving the vehicle through a wide variety of different speeds and loads to simulate typical light and heavy traffic conditions with frequent stops and starts with acceleration and deceleration phases.

Lim[23] conducted two idling studies on nine, class-eight diesel vehicles and two auxiliary IR devices. One IR was a diesel direct-fired heater, and the other was a diesel auxiliary power unit, which is used to supply electric power to the refrigeration unit of the trailer. Emissions were compared between the trucks and the IR devices to determine if a net emission saving could be achieve from the use of IR. The first study was a short introductory study; the testing occurred on four trucks. The second idling study was performed with five trucks. The second study was also done in collaboration with researchers from the Storey group (see below). Idling emissions rates for HC, CO, CO_2 and NOx and fuel consumption were measured using the EPA Realtime On-road Vehicle Emissions Reporter (ROVER). However, only idling emissions for CO_2 and NOx and the fuel consumption rates were reported in the paper. The truck model years for the combined studies were between 1985 and 2001. The engine displacements and horsepower ranges were 12.7-14.6 L and 370-500 hp, respectively. All trucks were tested in a climate-controlled chamber at low idle (between 600 and 800 rpm) and/or at high idle (between 1,000 and 1,200 rpm) in the following environments: (1) 90-degrees Fahrenheit (F) with the AC running, (2) 0 F with the heater running and (3) 65 F with no accessory load applied. For the AC and heater conditions, the truck cab was maintained at 70 F. The analytical detection method used by ROVER to measure HC, CO and CO_2 was NDIR. An electrochemical sensor was used to measure NOx.

Storey, et.al.[24] conducted tests on five of the nine, class-eight vehicles from the Lim study (see above). Idling emissions rates for HC, CO, CO_2, NOx, and PM and fuel consumption rates were measured using the EPA ROVER. Aldehyde idling emission measurements were also conducted but are not reported in this paper. Two methods were used to quantify the PM: Tapered Element Oscillating Microbalance (TEOM) and conventional filter collection. The truck model years were between 1992 and 2001. The engine displacements and horsepower ranges were 12.7-14.6 L and 370-500 hp, respectively. All trucks were tested in the same climate-controlled chamber and under identical engine load and rpm conditions as in the Lim study.

2.2 Minor Idling Research Activities

Tang, et.al.[25] conducted dynamometer emissions tests on 35 heavy-duty diesel trucks using two test-driving cycles. Eight of the trucks were HDDV8. The truck model years were between 1988 and 1999. Engine displacements and horsepower were not reported in the paper. Periodically during the dynamometer test-driving cycle, the engine was idled for 100 seconds in duration. Emissions were measured with bench-top instruments from a sampling port located downstream of a constant volume sampling dilution tunnel. Emissions from HC, CO, CO_2, NOx and PM were measured. Idling emissions were calculated from the 100-second idling periods that were extracted from the continuous sampling data. Idling emissions and comparisons between the idling emissions and the dynamometer test-driving emissions were reported in the paper.

Lambert, et.al.[26] measured the emissions from 40 heavy-duty diesel trucks at a roadside intersection rest area using portable emission measurement instruments. The truck model years were between 1993 and 2001. Engine displacements and horsepower were not reported in the paper. Emissions for CO, CO_2, NOx and PM, and fuel consumption were measured under different configurations of stationary idling, engine accessory load and on-road driving conditions. The stationary test matrix included low and high idling (i.e., engine default and 1000 rpm, respectively) with on and off modes for AC usage. Following the curb idling test, drivers were asked to volunteer for the experimental on-road test, which consisted of a pre-trip idle, acceleration, cruise, deceleration and post-trip idle. Time durations for the idle tests were between one and five minutes. Since this was a preliminary paper, only idling NOx emissions and relative fuel consumption rates that occurred during idle testing were discussed in the paper.

2.3 Summary of Historic Field-Testing Data

The results from the McCormick, et.al.[21], Brodrick, et.al.[22], Lim[23] and Storey, et.al.[24] studies are summarized in Table 2.1. (Note: all tables and figures are located in the appendices.) These results were grouped together because it is believed that the vehicle testing programs of the studies were characteristic of the long-duration idling periods, which are common to roadside rest areas. The reported units for emissions are gram per hour (g/hr), and the units for fuel consumption are gallons per hour (gal/hr). Percent RSD is expressed as

$$\mathrm{RSD} = \frac{\mathrm{SD}}{\overline{\mathrm{X}}} \cdot 100 \tag{2.1}$$

where, SD = Standard deviation of values and

$\overline{\mathrm{X}}$ = Mean of the values.

The results shown in the table for each research group were calculated from tabular data that were available in the publications. It should be noted that some of the vehicle emission data from those papers were not used to calculate the descriptive statistical values listed in Table 2.1 because those vehicles did not fall within the HDDV8 category. For example, of the two vehicles that were tested and reported as average results in the McCormick study, one was a minor weight-rated rental truck (GVWR 25,900 lbs), and the other was a school bus. The overall averages, percent RSD and minimum/maximum values were also calculated from the original data. In summary, the approximate overall averages are HC = 34 g/hr, CO = 75 g/hr, CO_2 = 8,640 g/hr, NOx = 142 g/hr, PM = 3.3 g/hr and fuel consumption = 0.9 gal/hr.

Raw data that were used to generate the summaries in Table 2.1 were also plotted as a function of the engine load and rpm conditions. These plots are shown in Figure 2.1 for HC, CO, CO_2, NOx and PM emissions and for the fuel consumption rate. Six categories are represented along the x-axis in the individual plots: air-conditioner running at high and low engine rpm (A-H and A-L, respectively); heater running at high and low engine rpm (H-H and H-L, respectively); no-load condition at high and low engine rpm (N-H and N-L, respectively). The horizontal lines in the mid region of the six plots indicate the overall means for the 2x3 matrix of engine idling speed and accessory load conditions. These overall means are also the literature review averages that were summarized in Table 2.1.

Mean diamonds were used in the plots as an aid to visualize the data (i.e., one diamond per category or group). The x-axis is also divided proportionally by the group sample size (n). Hence, diamonds that are elongated in the x-direction are those groups with larger relative sample sizes. The centerline that divides the large diamond is the group mean for that category. The two smaller diamonds that lie within the larger diamond represent the 95% confidence interval for the group mean. These confidence intervals (i.e., the smaller diamonds) can be used to compare group means. Overlap of smaller diamonds between groups indicates that those two groups are not different at the 95% confidence level. For example referring to the NOx plot in Figure 2.1, the A-H group mean is not significantly different from the H-H and N-H group means. Conversely, the A-H group mean is significantly different from the group means of A-L, H-L and N-L.

Closer inspections of the plots reveal that the magnitudes of the idling emissions are generally larger for the high rpm conditions. This effect would be expected since a positive correlation exists between emissions and fuel consumption, and fuel consumption is higher at high rpm and higher engine loads (i.e., heating and AC). It is also obvious from inspection of the graphs in Figure 2.1 that broad ranges of emissions are possible during idling tests. Referring again to the NOx plot for example, the range of values for the A-H group was between 70 and 350 g/hr. The idling emissions that are shown in Figure 2.1 are also summarized in Table 2.2. So, comparisons of the minimum, maximum and average values can be examined for the engine load and rpm conditions.

The results from the Tang, et.al.[25] and Lambert, et.al.[26] papers are discussed together because the idling emission rates from these studies may be more characteristics of short time idling emissions from stop-and-go traffic. It should be noted that the testing results from these studies could not be grouped together into a single table because the raw data from the Lambert paper were not included in the summary of results. The summary from the Tang study is shown in Table 2.3. The approximate average idling emission rates are HC = 11 g/hr, CO = 26 g/hr, CO_2 = 7,530 g/hr and NOx = 96 g/hr. In contrast with the overall summary results listed in Table 2.1, the average emissions from long-duration idling were larger than the average results from the Tang study by factors of 3.1 for HC, 2.9 for CO, 1.1 for CO_2 and 1.5 for NOx. The maximum emissions were larger by factors of 2.9 for HC, 4.9 for CO, 1.4 for CO_2 and 1.9 for NOx. On the other hand, the minimum values from long-duration idling were generally lower than the minimum results from the Tang study. Discrepancies between these studies may be due to differences in the test vehicles and testing conditions. It is also possible that the recent operating history of the engine or the length of idling time over which emissions measurements were made may have affected the emission levels.

The preliminary results from the Lambert study for NOx idling emission are shown in Table 2.4. The minimum and maximum ranges are listed for high and low engine idling speed for the AC modes of operation (i.e., AC running and AC not running). The values listed in the table are at best only approximations that are derived from graphical results because the raw data were not divulged in the paper. Nevertheless, close inspection of Table 2.4 reveals once again that the high idling engine condition with the AC running generated the highest NOx emission rate and that wide ranges of emissions are likely during idle testing.

To demonstrate that average emissions levels may not provide a complete picture of idling emissions, the test results from the Brodrick study, which was discussed earlier, are presented in greater detail in Table 2.5. It must be noted that two cruising tests conducted at 55 mph are also included in this table for comparison purposes between engine idling and actual driving emissions. As shown in the table, the observed differences in emissions between engine test conditions 1 and 2 indicate that the conditions prior to idling may affect the idling emission behavior of the vehicle.[27] When the engine idling speed was increased from 600 to 1050 rpm with the air-conditioner running (i.e., condition 3 to 4), emissions of NOx and CO increased by factors of 1.53 and 5.62, respectively. A large increase in CO emissions also occurred between the high engine speed and long idling situations (i.e., between conditions 4 and 5). The emission produced while cruising at 55 mph (condition 7) were approximately 3.5 times greater than the NOx emissions that were produces during long-term idling at high rpm (condition 5).

In conclusion, the historic truck testing data indicated that there is large variability between individual vehicles tested at different engine idling speeds and accessory in-cab loading conditions. There may be differences in emission patterns and emission levels between short-term and long-term idling. Limited evidence suggests that emissions at idling may be affected by the idling duration period and the operating conditions of the vehicle prior to idling. The average emissions levels may provide an incomplete picture of idling emissions.

2.4 MOBILE6 Emission Factors

If certain assumptions are made, the US EPA MOBILE6 model can be used to estimate idling emissions.[28] Several of the researchers, which were discussed in the previous section (e.g., McCormick, et.al.[21], Brodrick, et.al.[22], Tang, et.al.[25] and Brodrick, et,al.[27]) also had compared the idling emission rates gathered from their field-testing studies to the idling emissions obtained from an algorithm in the MOBILE5b model. What these researchers essentially found was that the emissions generated from MOBILE5b model always underestimated idling emissions.

For purposes of this literature review and study, MOBILE6 was used to predict HDDV idling emissions rates for the calendar year 2000 fleet by applying the default parameters that are built into the program.

The other parameters used in the model are as follows:

- Evaluation month - January
- Minimum and maximum temperatures 66 and 90 F, respectively
- Pollutants - HC, CO, CO_2, NOx and PM
- Cut-off sizes for PM: 10 and 2.5 μm
- Diesel sulfur concentration - 500 parts-per-million (ppm)
- Average vehicle speed - 2.5 mph for the arterial roadway category.

The minimum speed allowed by MOBILE6 is 2.5 mph. In actuality, truck idling occurs at zero mph. Lacking more specific data, the usual modeling convention is to assume that idling emissions are equivalent to driving at 2.5 mph. Since the model reports emissions factors in units of g/mile, the conversion of emission factors to units of g/hr was achieved by multiplying the MOBILE6 emission values in g/mile by 2.5 mph.[23]

The MOBILE6 idling emission factors for the calendar year 2000 fleet are shown in Table 2.6 for HDDV, HDDV7, HDDV8A, HDDV8B and HDDV8 for the 2.5 mph average speed arterial roadway. The HDDV8 category was compiled from the VMT distribution mix from HDDV8A and HDDV8B for the year 2000. As an illustration, the emission factors for HDDV8 are THC = 7.8 g/hr, CO = 63 g/hr, CO_2 = 4,131 g/hr, NOx = 84.1, PM_{10} = 1.6 g/hr and $PM_{2.5}$ = 1.5 g/hr. Comparisons of these HDDV8 emission values with the overall average values shown in Table 2.1 that were established from a review of the literature reveal that the average field-testing measurements are between 1.7 and 4.4 times larger than those values predicted by MOBILE6 at the 2.5 mph average speed, suggesting that the assumption that idling emissions are equivalent to a truck moving at 2.5 mph is not well justified in the case of idling HDDV8.

To demonstrate the full range of emission rates that are possible at various speeds, the MOBILE6 model was used to generate emission rates for NOx and PM at 5, 10, 20, 40, 50 and 60 mph for the HDDV categories using the original default scenario parameters. The emission factors in units of g/hr were calculated by multiplying the MOBILE6 emission values in units of g/mile by the respective average speed that was used in the input file for the model runs (i.e., 5, 10, 20, 40, 50 and 60 mph). The emissions rates from MOBILE6 were then plotted for all model runs starting at 2.5 mph and going through 60 mph.

Plots of the NOx and PM emission factors in units of g/hr versus highway speed in mph are also shown in Figure 2.2 and Figure 2.3, respectively. The solid-lines shown in the figures represent the MOBILE6 emission factors for the vehicle categories (i.e., HDDV, HDDV7 and HDDV8) as a function of vehicle speed. The dashed horizontal lines shown in the graphs correspond to the average, minimum and maximum overall idling emission rates that were determined by actual long-duration field-testing. These descriptive statistical values were taken from the overall summary section in Table 2.1. Referring to Figure 2.2, it can be seen that the average idling NOx emission rate for the HDDV8 category (i.e., 142 g/hr) occurs closer to 5 mph and not at 2.5 mph. The minimum and maximum idling emission rates (i.e., 19.8 and 353 g/hr, respectively) occurred between 0 and 15 mph.

It must be remembered that MOBILE6 was developed to model on-road vehicle emission inventories. It should not be used to create extended-idling emission factors or model emissions from long-duration idling trucks. Quite frankly, the MOBILE6 User's Guide asserts that it should not be used to model "hoteling" behavior.[1] By itself, "hoteling" was not defined in the guide, but intuitively it must refer to the rest practices and behavior of long-haul truck drivers. To further clarify this issue, the EPA in January 2004 issued guidance for quantifying and using long-duration truck idling emission reductions in SIP and transportation conformity.[29] For purposes of the guidance, long duration idling was defined as the operation of the engine for a period greater than 15 minutes when the truck is not engaged in gear. For use in stationary TSE projects, EPA has also provided long-duration idling emission factors (EF) for NOx and PM.

Between the years 2002 and 2030, the EF that EPA recommends for NOx is 135 g/hr. The EF for PM ranges from 0.33 to 3.68 g/hr depending on the year in which the emission reduction is generated. Table 2.7 lists the EF for PM by year. Referring again to the average values shown in Table 2.1, the current literature review emission factors for NOx and PM were 142 g/hr and 3.33 g/hr, respectively. Note that both values compare favorably with the EPA suggested values. (Also note in Table 2.7, the EPA is anticipating that the HDDV particulate matter emissions will go down approximately 90% by the year 2030.)

The EPA's Office of Transportation and Air Quality is currently developing a new generation mobile source emission model for state and local air management agencies to use in simulating mobile source emissions.[30] The new model is called the Motor Vehicle Emission Simulator (MOVES), and it will replace the current mobile source emission model called MOBILE. The new model will estimate on-road and non-road sources, cover a broad range of pollutants and allow multiple scale analysis. It is anticipated that MOVES will also be able to model cold-start and extended-idling emissions for heavy-duty diesel truck "hoteling" scenarios.

2.5 Overview of Particulate Emissions and Sampling Diesel Exhaust

The typical composition of diesel exhaust, as reported by two different researches, are (1) 41% carbon, 25% unburned oil, 14% sulfate and water, 13% ash and other compounds and 7% unburned fuel[9] and (2) 31% carbon, 40% unburned oil, 14% sulfate and water, 8% other unknown compounds and 7% unburned fuel.[12] Major disagreement among reported compositions were between percent carbon and unburned oil. Soot and unburned fuel are similar concepts as elemental carbon (EC) and organic carbon (OC), respectively. The generally accepted model of diesel engine PM is that of a core of agglomerates of elemental carbon, or soot, onto which is adsorbed a layer of condensed hydrocarbons and sulfuric acid derived from the SO_2 generated from the sulfur in the fuel. Further solid material in the form of metal ash compounds derived mainly from lubricating oil can become entrained in the PM. In addition, water can also condense and adsorb on sulfate species.[31,32] Figure 2.4 shows a schematic representation of diesel PM.

Raw diesel exhaust is typically incompatible with most real-time PM analyzers. The PM concentration in the raw exhaust often exceeds the measurement range of the analyzer. Therefore, dilution-sampling systems are frequently used to measure PM in diesel exhaust, or PM is measured by collecting and weighing on filter paper after a known volume of exhaust gas has been passed through the filter. There is growing evidence that the physical characteristics of the dilution sampling systems may alter the size, mass and composition of the PM, as a result of changes in residence time, temperature, humidity and dilution.[33,34,35] These factors more strongly affect the particle size distribution rather than the mass of the particle because mass tends to be conserved during dilution. Yet it has been also demonstrated that the dilution ratio and cooling can influence the formation of the soluble organic fraction (SOF) component of PM.

The SOF is heavy molecular weight hydrocarbon derived from the diesel fuel and lubricating oil. The term “soluble” originates from the analytical method that is used to measure SOF, which is based on extraction of PM samples using solvents. SOF is not to be confused with the volatile organic fraction (VOF), which is the organic fraction of diesel PM as determined by vacuum evaporation. Depending on the analytical procedure, the VOF may include the organic material (i.e., SOF) as well as some of sulfate particulates, composed primarily of hydrated sulfuric acid, that are also volatile.[36]

The effects of cooling the exhaust gas on mass concentration, composition, number distribution and number-average diameter of diesel PM were analyzed.[37] Results showed that upon cooling the exhaust gas, the mass concentration of the total PM and SOF in the PM was increased. Peak diameter of the PM number distribution was also shifted towards larger PM and the total PM number decreases, whereas the number-average diameter of the PM increased. The important point being made is that the dynamics of PM formation during dilution and cooling are still not clearly understood. Additionally, the dilution-sampling apparatus may introduce extraneous variables into PM measurement.

3 METHODOLOGY

In the present study, cold-start and long-term duration idling emissions were measured in the field from HDDV8B using portable emission monitoring systems (PEMS). Real-time mass emissions of CO, NO, NO_2 and PM were measured and used to generate typical average cold-start and long-duration idling emission factors on a grams per hour basis. The percent CO_2 in the exhaust stream was measured and used to estimate the diesel fuel consumption rates for the test conditions.

3.1 Experimental Protocol

Twenty-four heavy-duty diesel trucks were tested during the summer and fall months between June and November 2004. Important vehicle and engine information are listed in Table 3.1. The truck model years ranged between 1992 and 2004; the odometer readings ranged between 60 and 835,000 miles. Pie charts summarizing truck body and engine manufacturer, model year and engine displacement are shown in Figure 2.5.

All vehicles were tested at ambient environmental conditions at low and high engine idling speeds. Low-idling speeds were between 600 and 800 revolutions per minute (rpm). The as-received condition or the factory idle setting established the low-idling speeds, especially for cold-start testing. The high-idling condition was chosen at 1000 rpm. The rpm was set in each truck using the electronic onboard cruise control module. Each truck was tested with the cab air-conditioner at the maximum output (i.e., AC-On setting) and with the air-conditioner system not operating (i.e., AC-Off setting). The trucks were not subjected to any special maintenance procedures. They were tested as received or as rented and used locally available standard diesel fuel. Each truck was parked overnight in a staging area for at least 12-hours before cold-start testing was conducted the following day. Before engaging the engine for cold-start testing, the air-conditioner switch was set to operate at maximum output (i.e., AC-On setting).

Time-resolved emission measurements during engine cold-start and idling periods were collected. During testing, emissions were shown to reach steady-state condition within two to three hours after starting the engine. After the engine warm-up period, additional idling tests were conducted on each vehicle through the following typical progression: cold-start at low-idle with the AC-On (run time approximately 3-hrs), low-idle with the AC-Off (runtime approximately 2-hrs), high-idle with the AC-Off (run time approximately 1-hr) and finally high-idle with the AC-On (runtime approximately 1-hr). It should be noted that this sequence was chosen, as it typically resulted in a greater load on the engine with each consecutive test.

3.2 Instrumentation

3.2.1 Gaseous Analyzer

Exhaust gasses were measured with an ECOM Model AC-Plus portable analyzer. The instrument was obtained from ECOM America Ltd., 1895 Beaver Ridge Circle, Suite N, Norcross, Georgia. The probe body was approximately 1 foot in length, and the sampling line was 15 feet in length. The analyzer incorporated an internal pump, radiant gas cooler and self-draining moisture trap to condition the gas sample. The pump delivered a fixed flow rate of 2.5 liters per minute (lpm) to separate electrochemical sensors. The analyzer was configured to measure O_2, CO, NO, NO_2 and SO_2 concentrations. Ambient temperature, stack temperature and stack pressure were also measured by the analyzer. The analyzer also reported CO_2 and NOx concentrations, combustion efficiency and excess air (lambda). However these parameters are calculated values rather than measured parameters.

The analyzer was calibrated once per week or more frequently, on an as needed basis. During calibration, a different EPA protocol calibration gas was used for each electrochemical sensor. The analyzer was allowed to acclimate to the ambient temperature and complete the Auto Zero/Span procedure prior to beginning the emission test. The probe was inserted into the designated sampling port in the primary chamber and the analyzer was allowed to draw the gas sample. All parameters were measured continuously. The analyzer reported concentrations in units of actual conditions of temperature, pressure, exhaust moisture and oxygen concentration. The operating parameters for the ECOM analyzer are summarized in Table 3.2.

3.2.2 Particulate Matter Analyzer

The PM was measured with a DataRAM Model DR-4000 portable aerosol analyzer. The instrument was obtained from Thermo Electron Corp., 7 Oak Park, Bedford, Massachusetts. The unit was operated as a single wavelength light scattering photometer at a wavelength of 880 nanometers (nm). The sampling flow rate is user selectable with a range between 1 to 3-lpm. An inline jet-to-plate type impactor head was attached to the DataRAM to measure $PM_{2.5}$ (i.e., PM with an aerodynamic equivalent particle diameter of 2.5 μm or less). The impactor has a cassette filter, which collects the PM that does not pass through the jet-to-plate. The 2.5 μm cut point was obtained at the flow rate of 2 lpm. The analyzer measured instantaneous, average and maximum concentrations of PM. The unit also recorded sample gas temperature and humidity.

The DataRam was also equipped with an internal membrane filter, which was used to collect an integrated sample of $PM_{2.5}$ over the entire test period for any given vehicle that was tested. This provided the ability to gravimetrically determine the mass of $PM_{2.5}$ sampled during the test period. The impactor cassette filter was also weighed, and the data were used to provide an estimation of the PM greater than 2.5 µm. The sum of the weight collected on the internal membrane filter and the impactor cassette filter provided the total mass collected. The gravimetric data from each test was used to calibrate the response of the instrument for each test. The material of composition for both membrane filters was mixed cellulose ester. Specifications for the internal membrane filter were 37 mm in diameter and 0.8 µm for pore size. For the impactor cassette filter, the specifications were 25 mm in diameter and 5.0 µm for pore size. All filters were pre- and post-conditioned in a desiccator before being weighed with a microbalance scale.

The analyzer probe assembly was attached to the inline impactor, which was attached to the dilution chamber. The analyzer was allowed to acclimatize to the ambient temperature and complete the Auto Zero/Span procedure prior to beginning the emission test. The instrument reported concentration in units of actual conditions of temperature, pressure, exhaust moisture and oxygen concentration. A summary of the output and operating parameters for the DataRAM is shown in Table 3.2.

3.2.3 Exhaust Gas Flow Meter

The diesel exhaust flow rate of the vehicle was measured with a Kurz Model 454FT-12-MT insertion flow meter. The instrument was obtained from Kurz Instruments Inc., 2411 Garden Road, Monterey, California. The Kurz flow meter is a point velocity-sensing thermal anemometer that required an in-situ calibration using a velocity traverse of the flow profile. Flow rate from the Kurz meter was reported in units of standard cubic feet per minute (scfm). The Kurz flow meter was field calibrated by conducting velocity traverses inside the primary test chamber using a type S pitot tube. Table 3.2 lists the operating parameters for the Kurz flow meter.

3.2.4 Miscellaneous Equipment

The moisture content of the diesel exhaust was measured with a DigiSense Temperature/Humidity Logger. The DigiSense was obtained from Cole-Parmer Instrument Co., 625 East Bunker Court, Vernon Hills, Illinois. Inputs from the probe also provide exhaust temperature and dew point data.

Engine operational data were collected using a NEXIQ Technology Pro-Link heavy-duty standard communication hardware/software kit. It was obtained from NEXIQ Technologies, 2329 East Walton Boulevard, Auburn Hills, Michigan. The Pro-Link kit connects directly to the electronic control module (ECM) of the engine. It allowed visualization and/or downloading of engine parameter and diagnostic information to a personal computer during testing. Engine parameters that were collected by Pro-Link are coolant and oil temperature, oil pressure, intake manifold temperature, idling speed and operating load.

The dilution air required to cool the exhaust gases to the temperature limit needed for the DataRAM was measured with surface mounted Dwyer Rate-Masters, Model RMC rotameters. The rotameters were obtained from Dwyer Instruments, Inc., 102 Highway 212, Michigan City, Indiana. These devices were necessary to balance the exhaust gas and ambient air into the dilution tunnel at near isokinetic conditions and required for maintaining the temperature of the dilution air at below 120 F. Data collected from this instrumentation were used to calculate the dilution ratio. The rotameters were factory calibrated. Static pressure and temperature were measured in the dilution chamber with surface mounted Dwyer magnahelic gauges and bimetal thermometers, respectively. Data collected from these sensors were necessary to convert the gas flow rates from non-standard gas conditions to standard gas conditions of temperature and pressure.

3.3 Sampling System

A two-stage sampling system was used to measure exhaust emissions. Figure 3.1 illustrates the location of the key components of the sampling system. Gaseous emissions were measured in the primary sampling chamber. The PM emissions were measured in the secondary sampling chamber (or dilution chamber), due to the need to cool the flow by dilution to avoid exceeding the maximum operating temperature of the PM monitor. The vertical muffler of each truck was disconnected from the engine exhaust pipe that ran beneath the cab from the engine turbocharger to the side or the back of the cab. The primary sampling system was connected to the engine exhaust pipe via a flexible stainless steel hose. Approximately 20 feet separated the primary sampling chamber from the turbine outlet. The dilution chamber was attached through the downstream 90-degree elbow of the primary sampling chamber via thin wall stainless-steel tubing.

Figure 3.2 shows the sampling chamber attached to a test truck via the flexible stainless steel hose. In the figure, the Kurz meter is located on the top-front segment of primary sampling chamber. Figure 3.3 shows the overall view of the mobile test stand and the location of all the instrumentation. Figure 3.4 shows the side view of the primary sampling chamber. In this figure, the ECOM analyzer and personal computer, both located beneath the primary sampling chamber on the lower section of the mobile test stand, are clearly visible. Also, the location of the ECOM probe can be seen on the side-rear segment of the primary sampling chamber. Figure 3.5 shows the side view of the secondary sampling chamber. The dilution chamber, which is attached to the 90-degree elbow of the primary sampling chamber, is clearly shown in the figure; the DataRAM and impactor are attached to the dilution chamber.

3.3.1 Primary Sampling System

The primary sampling chamber contains sampling ports for instrumentation and permits bypassing the vertical exhaust muffler of the truck. The dimensions of the sampling chamber are 8 feet in length and 8.25 inches in diameter. It was constructed of 316 stainless steel pipe and fittings. A flexible stainless steel hose was used to join the sampling chamber to the turbine outlet of the truck. Combustion exhaust gas was directed away from the area through a high temperature resistant, polymer flexible pipe, which is attached to the downstream side of the sampling chamber and stretched along the ground. The ECOM gas analyzer probe, the Kurz flow meter sensor and the DigiSense humidity sensor were inserted through sampling ports situated along the side of the primary sampling chamber. The exhaust gas-phase species concentrations, flow rate, temperature and humidity were measured inside the primary sampling chamber.

The dilution chamber and other essential monitoring and recording equipment are also attached to the primary sampling chamber. The entire apparatus was mounted to a 10-foot long by 3-foot high tube steel, mobile cart.

3.3.2 Secondary Sampling (Dilution) System

The dilution chamber was required to continuously extract a representative sample from the primary chamber and then cool it, to well below the safe operating temperature of the DataRAM, by mixing exhaust gas with cleaned and dry ambient air. Dimensions of the secondary sampling system are 3 feet in length and 1 inch in diameter. It was constructed of 316 stainless steel pipe and fittings. Thin wall tubing connected the dilution chamber to the primary chamber and to the PM analyzer, without any bends or changes in direction. The tubes were sized to achieve near isokinetic conditions at the inlet to the dilution chamber and at the inlet to the DataRAM. Two regenerative blowers (or pumps) were used to mix ambient air and exhaust gas. Rotameters were attached to the dilution chamber to control and measure the flow rate of the dilution air. Bypass values were used for coarse flow control. A high-efficiency particulate (HEPA) filter and the desiccant Drierite were used to remove particles and moisture, respectively from the ambient air. Temperature and pressure gauges located adjacent to the rotameters were used to allow correction of the gas flow rates from nonstandard operating conditions to standard gas conditions (i.e., temperature at 68 F and pressure at 1-atmosphere). The DataRAM unit, which attached directly to the opposite end of the dilution chamber, was used for measuring total PM and $PM_{2.5}$ concentration in the exhaust gas.

3.4 Collection and Treatment of Data

The internal data logging capacity of the analytical equipment was utilized to collect all data during actual testing, after which the data were transferred to a personal computer. The truck engine operation during the warm-up period (between starting the engine and until steady-state emissions were reached) constitutes the cold-start period. Emissions were also averaged over the first 5-minute, 10-minute and 15-minute time periods after a cold engine start to generate cold-start 5-minute (CS-5), CS-10 and CS-15 emission factors, respectively. Data collected after emissions reached steady-state constituted the long-duration or extended idling period. Ten-minute averaging periods were selected from the long-duration data at locations in the data where the emission rate was relatively constant on the emission curves. All cold-start and idling emission factors were reported in units of grams (pollutant) per hour (g/hr).

Emission rate calculations for the gaseous pollutants (i.e., CO and NOx) from continuous measurement data were relatively straightforward. Concentration (C_i) measured by the analyzer multiplied by the flow rate (Q_i) as measured in the sampling chamber equals the mass of pollutant emitted per time (M_i), i.e., $M_i = C_iQ_i$. Standard units of concentration and flow rate (e.g., mg/ dry m^3 @ 7% O_2) are not necessary as long as conditions of temperature, pressure, moisture and percent O_2 are consistent for both paired concentration and flow rate value in the equation. The continuous emission rate data for selected time periods were then averaged to derive the typical average cold-start and extended-idling emission rates. Sample calculations for real-time CO and NOx emission rates are shown in Appendix C1.1 and C1.2, respectively.

Determination of the PM emission rates from continuous measurement data were more complex than the calculations for the gaseous pollutants because dilution of the exhaust gas had to be incorporated into the emission rate computations. For the PM system, the actual volumetric flow rate (Q_1) into the dilution chamber and the actual sampling flow rate (Q_4) of the DataRAM were unknown, as well as, the density (ρ) of the gas that resulted from mixing ambient air and exhaust gas inside the dilution chamber. The numerical subscripts refer to the flow locations on the dilution sampler that is shown in Figure 3.1.

The automatic flow rate control of the DataRAM is based on sensing the pressure differential across an orifice at the exhaust of the flow system of the DataRAM. The functional relationship between orifice pressure drop (Δp) and volumetric flow rate (Q) is given by the following equation:

$$\Delta p = k \rho Q^2 \tag{3.1}$$

where,

k = system constant related to discharge coefficient and area of orifice and

ρ = density of air at factory calibration of temperature and pressure conditions.

The user specified sampling flow rate (Q) was fixed at 2-lpm. Conversion from sampling in air to sampling in exhaust gas is as follows:

$$\frac{\Delta p}{k} = \rho Q \qquad \text{and} \qquad \rho Q = \rho_4 Q_4$$

$$\text{thus, } Q_4 = Q\sqrt{\frac{\rho}{\rho_4}} \tag{3.2}$$

where, Q_4 = Actual DataRAM sampling flow rate and

ρ_4 = Density of sample, diluted exhaust gas air.

It will be assumed that the molecular weight of the exhaust gas in the primary chamber and molecular weight the mixture of ambient air and exhaust gas in the dilution chamber are equal. The basis for the assumption of equivalence between the molecular weights of the gases is shown in Figure 3.6. Data used to create the plot were obtained from published thermodynamic gas tables.[38] The plot shows the molecular weight for the complete combustion of several hydrocarbon fuels containing carbon and hydrogen (CH_n) and air as a function of the percent theoretical fuel. The percent theoretical fuel for combustion increases from (i.e., pure air) to 100% (i.e., air-fuel stoichiometric condition). The relation $CH_{1.80}$ is a good approximation for diesel fuel.[18] Values of n, the atomic ratio of hydrogen (H) to carbon (C), were chosen in the range 1.430 to 2.142. The molecular weight values for the diesel fuel were interpolated between the H:C range 1.668 to 1.907, and a best-fit line was drawn through the data points.

As shown in the figure, the slope of the line is relatively flat. Differences in MW are especially small between 10 and 40% theoretical fuel. At the limits between pure air and 100% theoretical fuel, the molecular weight only varied by approximately 0.4%. Since diesel engines always operate less of the stoichiometric condition and engine idling normally occurs at much less than 30% of the theoretical fuel condition, it is believed that the molecular weight assumption was valid. The governing equations and sample calculations for real-time PM emission rates are shown in Appendix C1.3.

Finally, the fuel consumption rate was calculated in gallons per hour (gal/hr) using percent of CO_2 in the exhaust gas as reported from the ECOM analyzer. Remember the ECOM analyzer did not directly measure CO_2. Instead, the analyzer measured the O_2 concentration and calculated CO_2 percent using the following formula:

$$\mathrm{CO_2} = \mathrm{Max\ CO_2}\left(1 - \frac{\mathrm{Measured\ O_2}}{21}\right) \tag{3.3}$$

where, Max CO_2 = stoichiometric percent of CO_2 on a dry basis (i.e., approximately 15.3% using the $CH_{1.80}$ basis), and Measured O_2 = oxygen percent in the exhaust gas as measured by the ECOM analyzer. It must be noted that the fuel consumption rates reported in the present paper are approximations rather than truly measured parameters. Again for illustration purposes, sample calculations are shown for the fuel-consumption rate in Appendix C1.4.

4 RESULTS/DISCUSSION

4.1 Emission Rate Behavior for Heavy-Duty Diesel Vehicles

A graph of the CO, NOx and $PM_{2.5}$ emission rates for an entire testing period is shown in Figure 4.1 for the 1996 Freightliner truck (ID#1) to illustrate the typical response of emissions that occurred during the idling cycles. Notice that when the engine started, NOx emissions peaked between 350 and 400 g/hr, and CO emissions peaked around 100 g/hr. These emission rates gradually declined, over time as the engine warmed or until steady-state was achieved. For NOx, steady-state was reached about three hours after cold-starting the engine, whereas it took only about one hour for the CO emission to reach steady-state. When the engine idling speed was increased from 750 to 1000 rpm and/or the setting of the air-conditioner was switched from “off” to “on” mode, the gaseous emissions also increased in magnitude and remained relatively stable throughout the testing period. As shown in Figure 4.1, the typical gaseous emission rates for the engine idling at 750 rpm with the AC-Off were approximately 140 g/hr NOx and 40 g/hr CO. With the AC-On, they were approximately 250 g/hr NOx and 50 g/hr CO. Typical gaseous emission rates for the engine idling at 1000 rpm were approximately 155 g/hr NOx and 55 g/hr CO with the AC-Off. Emissions were approximately 255 g/hr NOx and 65 g/hr CO with the AC-On.

For PM emissions during the cold-start period, the high initial peak and gradual drop-off in emissions, which were characteristic for gaseous emissions, did not occur for the truck that was illustrated in Figure 4.1. PM emissions also appeared to creep or drift over time during some of the idling test periods. In addition, emissions did not completely achieve steady-state during the engine idling and air-conditioner tests. It should be noted that these characteristics of the PM curve were seen in about 35% of the trucks that were tested. However for the other truck cases, a series of emission spikes that varied in magnitude occurred throughout the cold-start period and engine idling/air-conditioner tests, which were similar to the gaseous emissions curves.

As shown in Figure 4.1, typical $PM_{2.5}$ emission rates for the engine idling at 750 rpm were approximately 4.9 g/hr at the AC-Off setting and approximately 5.4 g/hr for the AC-On setting. Typical $PM_{2.5}$ emission rates for the engine idling at 1000 rpm were noticeably higher for this truck at approximately 8.3 g/hr with the AC-Off and approximately 7.6 g/hr with the AC-On. Also note again, that during the AC-On idling test, the PM emission rate did not completely achieve steady-state.

At present, there is no solid data to explain the cause of the variations in the pattern between the gaseous and PM emission curves. It is possible however that for PM emissions, the engine performs more and more poorly during extended idling. Some evidence seems to suggest that incompletely burned fuel in the form of PM can accumulate in the exhaust system by a phenomenon called wet-stacking.[39] When the engine is operated at low idling speed the exhaust temperature is cooler, which is conducive for the condensation of liquid droplets. Soot particles mix with the liquid droplets and collect on the walls of the exhaust system, which is called wet-stacking. Eventually the material on the wall dehydrates, forming tiny loose projections that can dislodge and reenter the exhaust gas stream. Nevertheless, it is unlikely that the agglomerated materials would be re-entrained as $PM_{2.5}$, rather more likely, it would be re-entrained as larger particulate matter.

It is also speculated that the prior road history of the truck and wet-stacking can influence the amount of PM that is emitted during an engine cold-start episode and/or during extended idling periods. For example, if a truck has been driven on the road at high speed, and after that, it is immediately parked and the engine shut down, then condensate would not have had time to accumulate in the exhaust system. Under this scenario when the engine is started again, the ensuing PM emissions in the exhaust gas only could have derived from the combustion inefficiency of the engine during the cold-start period. However, if the truck was driven at lower speeds or if the truck was idled for a period of time before the engine was shutdown, and then if wet-stacking occurred, a cold-start condition was created that has the potential for the re-entrainment of PM.

Another phenomenon that is related to particle deposition on the exhaust walls or the sample lining system is thermophoresis, which is the movement of a particle derived from forces arising from a temperature gradient. Air molecules at a higher temperature impart more kinetic energy in collisions with a particle than those at a lower temperature, inducing the particle to move in the direction of the cooler surface. Thus, soot particles can form a layer on the cool surfaces of the vehicle exhaust and sampling system and subsequently become re-entrained under changing exhaust temperature conditions.[33] Thermophoretic deposition losses can be minimized by avoiding temperature gradients in sample lines through heating or insulation.

Figure 4.2 is a graph of the CO, NOx and $PM_{2.5}$ emission rates for the 1995 International truck (ID#12) during a segment of the testing period to illustrate the complex nature of the emission curves. The details shown in the curves illustrate the high and low cyclic nature of emissions that occurred during extended idling for the AC-On and AC-Off settings. The overall effect of running the air-condition system is to increase emissions. The action of the air-conditioning compressor also creates cyclic power demands on the engine. Operational and environmental factors inside and outside the cab influence the cyclic nature of the air-conditioning system. The pattern of large spikes appearing in these curves is primarily the result of cyclic power demands that are made on the engine from the radiator coolant fan. It should be noted that the radiator fan of a heavy-duty diesel engine does not normally operate continuously, like the radiator fan on a gasoline engine. The radiator fan clutch of a heavy-duty diesel engine is dependent instead on the coolant temperature of the engine. It is electronically engaged when the set-point temperature of the coolant is reached; it is disengaged when the coolant temperature drops below the set-point temperature. Also, when the set-point pressure of the air-conditioner compressor is exceeded, the radiator fan will engage to lower the temperature and thus the pressure of the Freon in the air-conditioning system.

Graphs of the real-time emission behavior for each test truck are included in Appendix E. Exhaust gas flow rate (FlowRate), temperature (Temp) of the exhaust gas in the primary sampling chamber, percent of O_2 and percent of CO_2 in the exhaust gas are also included in these graphs. In general, exhaust gas flow rate increased with an increase in the engine idling speed and/or with the air-conditioner load applied to the engine. The percent of O_2 in the exhaust gas indicates the relative proportion of excess air, which was occurring during combustion of the fuel. The percent of CO_2 in the exhaust gas is proportional to the fuel-consumption rate.

4.2 Data Analysis

Emission rates and parameters that characterize sampling and exhaust gas factors during the cold-starting and extended idling conditions were determined for each truck tested in the study from the responses shown in Appendix E. Average cold-start and extended-idling emission factors were calculated for CO, NOx and $PM_{2.5}$ emissions, for the ratio of NO_2/NOx emissions and for fuel consumption rates. The average emission rate activities from all truck data are summarized in Table 4.1. The overall extended-idling averages, which are the average values from AC-Off and AC-On for the low- and high-rpm idling conditions (i.e., the average value of columns 6, 7, 8 and 9), are listed in column 10. The cold-start emission rates are listed in columns 2, 3, 4 and 5. Sample calculations are shown in Appendix C. The specific emission rates and other parameters for each truck are also tabulated in Appendix D. Additionally, the average values for the percent of O_2 and CO_2 in the exhaust gas, the combustion equivalence ratio, the sampling dilution gas ratio, the ambient air and exhaust gas temperatures, and the molecular weight of the exhaust gas are shown in Appendix D.

The cold-start emission rates that were determined for the 5-minute, 10-minute and 15-minute periods of the cold-starting episode, as shown in Table 4.1, were higher than the overall extended-idling average emission rates. For example, the CS-5 emission rates were higher than the overall extended idling average emission rates by factors of 2.8 for CO, 1.5 for NOx and 1.7 for $PM_{2.5}$. Cold-start emission rates decreased as the cold-starting period lengthened. In general for the individual extended-idling conditions, the emission rates were greater for the AC-On settings at low and at high idling, when compared to the AC-Off settings, with the high-rpm idling emission rates being greater than the low-rpm idling emission rates, except for $PM_{2.5}$. At high-rpm idling, the $PM_{2.5}$ extended-idling emission rate was higher for the AC-Off condition in comparison to the AC-On condition. Average NOx emissions at low-idling speeds were 120 g/h at AC-Off and 159 g/hr at AC-On. At high-idling speed, average NOx emissions were 164 g/hr at AC-Off and 223 g/hr at AC-On. The overall extended-idling average emission rate for NOx was 167 g/hr.

The ratio of NO_2 to NOx emissions remained fairly constant throughout cold-start and long-term duration idling conditions between values of 0.16 and 0.19. This indicated that the effect of idling speed and the in-cab accessory load (air-conditioner) settings had little noticeable effect on the ratio of NO and NO_2 in the exhaust gas. Fuel consumption rates were approximately 2.0 gal/hr during the first 15 minutes of the cold-starting period, and then it ranged between 1.2 and 1.8 gal/hr for the idling conditions of engine speed and modes of operation for the air-conditioner. The overall extended-idling average for the diesel fuel rate was 1.5 gal/hr. This value was about 50% higher than the literature review average. Remember however, that the fuel rate in this study was calculated using the percent CO_2 as reported from the ECOM analyzer, which was also a calculated value based on the measured percent O_2 (i.e., excess air) in the exhaust gas.

Raw data that were used to generate the summary in Table 4.1 were plotted for the three pollutants and the diesel fuel rate as a function of the engine idling speed and the in-use status of the air-conditioning system. These plots are shown in Figures 4.3 to 4.6 for CO, NOx, $PM_{2.5}$ and for the fuel consumption rate. Best-fit lines were drawn through the data points for the AC-Off and AC-On modes to illustrate the effect on emissions between the two air-conditioner settings and the also the engine rpm effect on emissions. Inspections of these graphs reveal that the highest engine idling speed (i.e., 1000 rpm) and the AC-On setting produced the higher emissions. On the other hand, wide variability also existed in the data, especially at the 1000-rpm engine idling speeds.

Analysis of variance (ANOVA) was performed on the two factors (i.e., engine idling rpm speeds and air-conditioner settings). For the effect of engine idling speed on emissions and fuel consumption, the significance levels (or p-values) were the strongest: CO ($p < 0.0001$), NOx ($p < 0.0001$), $PM_{2.5}$ ($p = 0.008$) and fuel rate ($p < 0.0001$). Generally, p-values less than 0.05 are considered statistically significant, meaning that there is only a 5% probability that an effect this large could occur due to chance alone. For the effect of the air-conditioner at “off” and “on” modes of operation, only NOx was significant ($p = 0.02$). No acceptable significant effects were found for CO ($p = 0.15$), $PM_{2.5}$ ($p = 0.77$) and fuel rate ($p = 0.25$). Additionally, no significant interaction effects were found between engine idling speeds and air-conditioner settings. Interaction effects would have implied that the trend in emissions between air-conditioner factors (i.e., “off” and “on” settings) were not in the same direction for engine idling speed factors (i.e., rpm levels). Referring again to Figures 4.3 through 4.6, if the best-fit lines for AC-Off and AC-On in any graph had crisscrossed, then an interaction effect would have occurred for that element displayed in the graph. Fortunately there were no interactions between factors because some interaction effects are difficult to explain.

Emission rates were normalized by the fuel rate. Table 4.2 shows average mass emissions per unit of diesel fuel consumption for the cold-start and extended-idling conditions. In general, mass emissions per fuel consumed decreased during the cold-starting period as the engine warmed, and mass emissions per fuel consumed increased when the engine idling speed increased or when the air-conditioner was turned on. It is believed that the overall higher fuel consumption rates observed during the cold-starting period were caused because the engine has not reached its peak operating temperature. Proper engine operation temperatures assure more efficient fuel combustion. Some engine designs also allow for excess fuel to be injected into the engine during the cold-starting period to increase the probability of combustion starting (and then being sustained) during the engine warm-up period. This extra fuel is intended to help seal the piston rings and valves for auto-ignition during starting.[16]

Graphs of the average emission factors for the three cold-start periods (i.e., CS-5, CS-10 and CS-15) and the four extended-idling periods (i.e., Low-rpm/AC-Off, Low-rpm/AC-On, High-rpm/AC-Off and High-rpm/AC-On) versus the average fuel consumption rates are shown in Figure 4.7 for each pollutant. Best-fit lines that constrained the intercept to zero were separately applied to the cold-start and extended idling data to demonstrate the linearity of the data and differentiate the two groups (i.e., cold-starting and extended-idling). Equations that define the best-fit lines, R-square values and the p-values for the slope coefficient are also included in the graphs. Units for slope of the linear equation are grams emissions per gallon of diesel fuel consumed. Based on the p-values, all slopes for were significantly different from zero at better than the 0.05 significance level. As can be seen within individual plots, only the slopes for the cold-start and extended-idle conditions for CO versus fuel rate were fairly different. On average for the cold-starting period, approximately 82 grams of CO were emitted per gallon of diesel fuel consumed, and on average for the extended-idling period approximately, 44 grams of CO were emitted per gallon of diesel fuel consumed. Thus, about 1.9 times more CO was emitted per volume of fuel consumed during the cold-starting period than was emitted during the extended-idling period. For NOx and $PM_{2.5}$, mass emissions were essentially equivalent per unit volume of fuel consumed during both cold-start and extended-idling truck sampling periods.

Figures 4.8 through 4.10 are graphs of emission rates as a function of the truck model year and odometer reading for CO, NOx and $PM_{2.5}$, respectively. Each figure contains four plots: the top row of two plots is for model years; the bottom row of plots is for odometer reading; the left column of two plots is for AC-Off setting; the right column is for AC-On setting. Linear equations that define the best-fit lines, R-square values and the p-values for the slope coefficient are included in the graphs. Inspections of the p-values show that only the slopes from the best-fit equations for truck model year and odometer reading for the CO emission rates were statistically significant at less than 0.05 level. However, notice that the value of the slope parameter estimates for odometer reading is approximately 0.0001 for both AC-Off and AC-On settings. Thus, these slope values, even though statistically significant, can essentially be considered zero. For truck model year, there was a tendency for the older trucks to be higher CO emitters. For NOx and PM2.5 emissions there was no tendency for the high mileage trucks and/or the older trucks to also be the high emitting trucks, as would typically be expected.

A comparison between the extended-idling emission factors that were determined in the field by the present study, the EPA suggested emission factors for SIP using TSE and the average values that were calculated from a review of current literature (McCormick, et.al.[21], Brodrick, et.al.[22], Lim[23] and Storey, et.al.[24]) are shown in Table 4.3. The experimental values shown in the first column of this table are the average values from the low- and high-rpm idling conditions at both AC-Off and AC-On settings that were listed in Table 4.1 (i.e., average value of columns 6, 7, 8 and 9). In summary, the NOx emission rates observed in this study and summarized in Table 4.3 were greater than those reported for EPA-SIP purposes and from the literature review by 23.5% and 17.4%, respectively. The $PM_{2.5}$ emission rates observed in this study were less than those reported for EPA-SIP purposes by 3.8% and were greater than those reported in the literature by 6.3%, respectively. The average CO emission rates observed in this study were less than those reported as the average literature review value by 14.1%. Emission rates for CO are not published for EPA-SIP purposes.

There is little documented knowledge as to the extent that truckers increase engine idling speed. A few manufacturers do not recommend that the engine idle below 600 rpm for longer than 5-minutes because of decreased temperature and lack of sufficient lubrication in the engine. Some drivers practice increasing the engine idling speed to keep the batteries charged while using in-cab accessories, because they are in the habit of doing it, or they believe that it keeps the engine in good-working order (i.e., high idling is something that prevents future maintenance). Generally, the factory settings for most heavy-duty diesel engines are somewhere between 600 and 800 rpm. It was for that reason; the same low-idling speed range was selected for the present study. The high-idling speed selected for this study was 1000 rpm. This choice was not entirely arbitrary because 1000 rpm appeared in the literature for the high-idling limit. Some researchers, however, actually used between 1100 and 1200 rpm for their high-idling tests. Currently based on present knowledge, EPA does not provide guidance or characterized low or high engine idling speeds for heavy-duty diesel truck.

To gain additional insight, the average extended-idling emission factors from Table 4.1 (i.e., Low-rpm/AC-Off, Low-rpm/AC-On, High-rpm/AC-Off and High-rpm/AC-On) were compared separately to the EPA-SIP values for NOx and $PM_{2.5}$. These comparisons are shown in Table 4.4. Notice that the low-idle rpm comparisons at AC-Off and AC-On conditions (i.e., Comparisons 1 and 2, respectively) were primarily less than the EPA-SIP values for both NOx and $PM_{2.5}$. The high-idle rpm comparisons (i.e., Comparisons 3 and 4) conversely were greater than the EPA-SIP values for both NOx and $PM_{2.5}$. Based on these evaluations, it is believed more prudent to use the overall extended idling averages for purposes of reporting emission factors.

4.3 Particulate Matter Gravimetric Analysis

Total PM is the sum of $PM_{2.5}$ and PM > 2.5 μm; both were collected on filters during real-time emission testing with the DataRAM analyzer. The ratio of $PM_{2.5}$ to total PM ranged between 0.40 and 0.98. It was determine that on average, about 72.9% of the PM in diesel exhaust was less than 2.5 μm. The standard deviation was ±14.5%, and the percent RSD was 19.9%. The sample size (n) was 23. The gravimetric data for PM are included in Appendix F.

Examples of PM that were collected on filters by the DataRAM for gravimetric analysis are shown in Figures 4.11 and 4.12. The four photographs in the figures are from different truck/testing episodes. Note that each figure contains two photographs for comparison. Each photograph contains two filters from the same truck-testing episode. The larger filter located on the left side of the photograph, was the one that was used to collect an integrated sample of $PM_{2.5}$. The smaller filter was used in the inline jet-impactor to collect PM greater than 2.5 µm. Notice that the appearances of the PM on the filters with respect to color and tint (or shade) are not the same for the four sets of filters. In Figure 4.11, the color of the PM on the 10A filters is dark brown; the PM on the 10B filter samples is light-brown (or beige). In Figure 4.12, the PM is black on the 11A filter samples, and the PM is grayish on the 11B samples. It should be noted that these four sets of filters were selected to be included in the report because they represented the full range of appearances of color and shade that were observed of PM throughout truck testing.

Only 17 trucks were tested for PM emissions. For six of the trucks, the PM collected on the filters was either brown or beige in color; for the remaining 11 trucks, the PM was either black or gray in appearance. It is possible that the difference between the black and gray shaded PM (or between the brown and beige colored PM) simply indicated that more mass was collected, thus, the black or brown appearance relative to the gray or beige appearance. However, the cause for the more unambiguous difference between brown and black PM is not known. It was unlikely that the age of trucks or the mileage contributed to this PM color difference because for two highest mileage trucks (both at > 800,000 miles), one had gray PM, and the other had light brown PM. Possibly, different combinations of unburned fuel to soot to lubricating oil caused the difference between brown and black PM. Again, it is also quite possible that "clean" oil (new) versus "dirty" oil (old) makes a difference in the appearance of PM emitted, but since the ages of the motor oil for the trucks were not known, this hypothesis cannot be verified.

To further investigate this matter, energy-dispersive spectrometry (EDS) was performed on the filter samples shown in Figures 4.11 and 4.12 to quantify the PM material. Plots of the generated spectra are included in Appendix G. In each plot, two curves are shown: one curve is the EDS for a blank (clean) filter, and the other curve is the spectra of the PM sample. Preliminary results of this analysis have established that sulfur was present in the PM, as demonstrated by the sulfur peak for the samples.

It is not believed that sulfur has any direct influence upon PM color. Nonetheless, it should be mentioned that during truck testing, SO_2 was never detected in the exhaust stream of any truck. Yet, the ECOM analyzer was configured to measure SO_2 in the exhaust. Resolution for the monitor was 1-ppm SO_2, and periodic calibration had verified that the monitor was functioning properly. Currently, the sulfur levels in on-road diesel fuels are around 0.05% (i.e., 500-ppm) by weight. Research as been shown that fuel sulfur content has a significant affect on the concentration and distribution of sulfur species in diesel PM, and the distributions of various sulfur species are closely related with engine load.[40,41] Private conservation with the authors of this research have also confirmed the color difference on the filter media from their experiments with diesel engines. However, these researchers did not test different engines. Maybe it is also possible that the engine design (or such things as the air-fuel ratio) can affect the completeness of combustion, and thus, the color of PM.

4.4 Data Quality

All calibration data for the ECOM and DataRAM analyzers are included in Appendix F. Overall, the ECOM analyzer, which measured gaseous emission, operated trouble-free throughout the study and demonstrated 100% data availability. The EPA protocol calibration gases used to challenge the ECOM analyzer were CO = 100.1 ppm, NO = 493 ppm, NOx = 90.6 ppm and SO_2 = 99.5 ppm. Average response of the analyzer to the calibration gases during truck testing were CO = 100.1 ppm, NO = 498.4 ppm, NOx = 90.4 ppm and SO_2 = 98.1 ppm. Thus, it is believed that the emission measurements conducted with the portable ECOM gas analyzer, typically used for emissions inspection and maintenance programs, were reasonably accurate. The response for the instrument was very stable over the 5-month testing period. Since the gaseous emissions were measured in the primary sampling chamber, which did not require dilution with ambient air, the chance for experimental error was also reduced. In addition, gaseous emissions (once formed during engine combustion) remained relatively stable throughout testing because the temperature in the exhaust stream was not high enough to appreciably cause additional free radical reactions involving species forming CO and NOx.

The DataRAM analyzer, which measured PM emissions, had to be returned to the manufacturer for repairs during the early stages of testing. However, after it was repaired and returned, the monitor sustained normal operation and demonstrated 100% data availability for the remainder of trucks tested in the study. The advantage of using the DataRAM was that of the light-scattering technology, making the response of the analyzer almost instantaneous. The drawback of the light scattering technology is that the response from the instrument is very dependent on PM characteristics, such as composition, density, size distribution and index of refraction. If any of these characteristics of PM change, so does the response of the analyzer. The DataRAM was also an ambient monitor that had been adapted to measure diesel particulate from the high temperature raw exhaust stream. This required a dilution-sampling chamber to mix ambient air with exhaust gas to reduce the temperature of the sample to within the DataRAM’s temperature limits.

The calibration factors obtained from the gravimetric field calibration of the DataRAM response to diesel PM were not numerically equivalent across all trucks tested. The range of calibration factors were 0.152 to average calibration factor was 2.539 ± 1.804; %RSD = 71%. That the calibration factors were highly variable was not anticipated. It is impossible to precisely state the cause of this less than satisfactory comparison between calibration factors. The most likely explanation, however is due to the variability of the PM and the dependency of the monitor on particle characteristics. This problem was overcome by calibrating the optical response of the instrument with the gravimetric response of the particles in the environment of interest (i.e., for each truck tested).

Figure 4.13 is a plot of the actual volumetric flow rate as recorded by the Kurz flow meter and the calculated flow rate from data collected during truck testing. The calculated flow rate (Q_A) was approximated using the following equation:

$$\eta_V = \frac{Q_A}{V_S\ N^*} \tag{4.1}$$

where, η_V is the volumetric efficiency (i.e., a measure of the effectiveness of the air induction and exhaust gas process); Q_A is the volumetric flow rate of air with ambient density; V_S is the engine swept volume; N^* is (RPM/2) because two strokes occur per power cycle for a four stroke diesel engine.[16] Assuming volumetric efficiency is 100% (i.e., $\eta_V = 1.0$), V_S is the engine displacement expressed in liters (L), RPM is the engine idling speed during the test and expressing Q_A in cubic feet per minute (CFM), the equation can be re-written as:

$$Q_A = \frac{V_S\left(0.03532\ \mathrm{ft}^3/\mathrm{L}\right)\ \mathrm{RPM}}{2} \tag{4.2}$$

Flow rates for the air-conditioner On and Off modes of operation were plotted separately in Figure 4.13. Best-fit equations that constrained the intercept to zero, R-square and p-values are shown for both modes of operation. A diagonal 45-degree line is also shown in the figure to represent the 1-to-1 relationship between measured and calculated exhaust flow rate. As show in the figure, the measured exhaust flow rate data fell slightly below the calculated (or theoretical) flow rate. However, overall there was very good correspondence between the measured and calculated exhaust flow rates during the test conditions.

5 TRUCK STOP ELECTRIFICATION

5.1 Quantification of Commercial Parking

Several state departments of transportation in the nation are experiencing heavy demand for commercial vehicle parking at public rest areas along the interstate highway system. However, these rest areas were only intended for short-term safety breaks. Normally, it is the commercial truck-travel centers, which sell diesel fuel to truck drivers along the interstate highway system, that also provide facilities for drivers to use for longer-term rest. To assist the state transportation agencies in making decisions, the Transportation Research Board (TRB) conducted a survey to gather information on truck parking capacity and demand at public and commercial rest areas. The primary data source for the TRB report were responses to a detailed questionnaire distributed to highway maintenance engineers in each state. During 2003, the TRB estimates of commercial and public long-haul freight truck/trailer parking spaces for the contiguous US were approximately 284,675 and 30,860, respectively.[42]

5.2 Annual Idling Emission Estimates for Heavy-Duty Diesel Vehicles

Stakeholders for TSE typically use the entire truck fleet or a proportion of the truck fleet to estimate the emission reduction benefits that can be realized from the use of the technology. This practice was followed here just to place the relative magnitude of emissions from extended-idling HDDV8 into perspective. For evaluation purposes, the emissions from idling emissions will be compared to a typical coal fired power plant. The Bull Run coal fired plant, an 870 megawatt plant located in the Tennessee Valley Authority (TVA) system near Oak Ridge Tennessee was chosen as a typical power plant.

Truck counting experiments conducted locally at the Petro Truck Travel Center located on Watt Road in Knoxville, Tennessee were used to establish the average daily fraction of idling trucks at approximately 0.53.[43] Average daily idling fraction is defined as the fraction of available parking spaces occupied all day by idling trucks. Using only half of the daily average fraction of idling trucks (i.e., 0.5 x 0.53 = 0.265) as a conservative estimate, total spaces for the contiguous US and emission factors from the present study, the annual emissions from HDDV8 are approximately 135,000 tons/year for NOx and 2,900 tons/year for $PM_{2.5}$. (Sample calculations are included in the Appendix C2.1.) Annual emissions reported from the Bull Run Creek coal-fired plant during 1999 were 13,343 tons/year for NOx and 2,072 tons/year for $PM_{2.5.}$[44] It is apparent that emissions generated annually from extended-idling in the contiguous US are about 10 times the NOx emission from this 870 megawatt power plant. For these two sources, the $PM_{2.5}$ annual emissions were almost equivalent for the scenario selected for demonstration purposes. It should also be pointed out that the recent addition of NOx control technologies at this power plant and similar plants throughout the southeastern U.S. have the potential to reduce the NOx emissions by 75-80%. Therefore, the emissions from idling trucks will become an increasingly more important and significant source on a relative basis in the future.

5.3 Quantification for Truck Stop Electrification

Large emission reduction benefits are associated with TSE technology. However, reduction benefits from TSE will be slightly smaller when the cold-start emissions and the emissions that are associated with the consumption of electricity used in the TSE have been subtracted from the initial emission benefits. To quantify the actual reduction in emissions that are associated with TSE on a per truck basis, the following relationship was used:

$$\mathrm{AERR}_i = \mathrm{EIER}_i - \left(\mathrm{CSER}_i + \mathrm{EUER}_i \right) \tag{5.1}$$

where, for any pollutant, i,

AERR = Actual emission reduction rate (g/hr),

EIER = Extended-idling emission rate (g/hr),

CSER = Cold-starting emission rate (g/hr) and

EUER = Electricity-use emission rate, (g/hr).

The EIER term is the extended-idling emission factor for the pollutants (i.e., CO, NOx or $PM_{2.5}$). These emission factors have been determined by experimentation and/or listed by federal regulation (e.g., EPA-SIP). These emission factors are ordinarily used to determine the emission reduction benefits that are associated with TSE technology.

The CSER term describes the cold-start emission rate assuming that it has been spread over the entire period of idling, t_A, and is defined by the following equation:

$$\mathrm{CSER}_i = \frac{\left(\dfrac{t_B}{60 \ \mathrm{min}/\mathrm{hr}} \right) \cdot \mathrm{CSEF}}{t_A} \tag{5.2}$$

where, for any pollutant, i,

CSEF = Cold-start emission factor (g/hr),

t_A = Extended-idling rest period or TSE time (hr) and

t_B = Idling time during cold-start period, (min).

The CSEF term is the cold-start emission factor for the pollutants (i.e., CO, NOx or $PM_{2.5}$) that are emitted during the actual time of cold-start, t_B. These emission factors were determined in the current study. Cold-start emissions occur for only a short time period (t_B), between moments that the engine is started and until the driver places the engine in gear causing truck movement or until the engine has warmed, whichever comes first. For illustration purpose here, the cold-start idling time period (t_B) is 5 minutes in duration, and the driver rest period (t_A) is 8 hours.

Approximating the electricity-use emission rate, the following equation was used:

$$\mathrm{EUER}_i = \left(\mathrm{ECES}_i \cdot \frac{453.6\,\mathrm{g}}{\mathrm{lb}}\right) \cdot \left(\mathrm{WP} \cdot \frac{3.412\ \mathrm{Btu}/\mathrm{hr}}{\mathrm{watt}} \cdot \frac{\mathrm{L}}{100}\right) \cdot \frac{1}{\mathrm{e}} \qquad (5.3)$$

where, for any pollutant, i,

ECES = Electric consumption emission standard (lb/106 Btu),

WP = Power utilization by HVAC (watt),

L = Load applied to the HVAC (percent) and

e = Power-plant thermal efficiency (expressed as a fraction).

The ECES term is expressed on a mass of pollutant emitted per heat-input basis. For NOx and $PM_{2.5}$, the ECES values are the NSPS for the Fossil-fuel Electric Utility Steam Generating Facilities (i.e., 0.6 lb NOx/10^6 Btu and 0.03 lb $PM_{2.5}$/10^6 Btu).[20] One should note that the NOx standard is based on the more prudent heat-input value from anthracite or bituminous coal. Since there is no NSPS for CO, the emission factor for CO was taken from AP-42. Using the configuration from external combustion sources for pulverized (bituminous) coal, dry bottom, tangentially fired-furnaces, the AP-42 emission factor for CO is 0.5 lb/ton.[45] Based on an assumed coal Btu value of $26x10^6$ Btu/ton coal, the ECES for CO is approximately 0.02 lb CO/10^6 Btu.

The power demand (WP) of the HVAC unit depends on environmental factors, such as solar load, ambient temperature and cloudiness, etc. When the HVAC unit is initially engaged, the duty cycle will be continuous, until the inside cab temperature attains the thermostat set-point temperature, then the HVAC system starts cycling and the load is reduced. Thermal efficiency (e) is usually expressed as a percentage. It is defined as the energy sought divided by the energy cost, that is, $e = \text{Energy}_{OUT} / \text{Energy}_{IN}$; thus, $\text{Energy}_{IN} = \text{Energy}_{OUT} / e$. The typical terminal efficiency for a coal-fired power plant is approximately 35%.

The HVAC power consumption for a single TSE unit during a 1-hr period was estimated to be 2.2 kilowatt-hours or 2,200 watts. This figure is somewhat high, however, it was based on actual field tests that were conducted during a typical summer day at the fully loaded condition (i.e., L = 100%) at the IdleAire Corp. Research and Development TSE facility located at Interstate-40/Broadway (Knoxville, Tennessee). It must be noted that IdleAire has been attempting to reduce the size of the HVAC systems that are currently being used for TSE.

The emission rates for extended-idling, cold-start, electricity-use and the actual reductions from TSE are shown in Table 5.1 for CO, NOx and $PM_{2.5}$. The table lists the results for the 5-, 10- and 15-minute cold-starting periods. The actual emission reductions that can be expected with TSE are shown in column 6 of the table. This column was obtained by subtracting the cold-start emission rate (column 4) and the electricity-use emission rate (column 5) from the extended-idling emission rate (column 2). (Sample calculations are included in Appendix C2.2, 2.3 and 2.4 for CO, NOx and $PM_{2.5}$, respectively)

Comparisons of the emission rates in the table show that the actual or corrected emission savings (AERR) are slightly less than if one used the extended-idling emission rates (EIER) to estimate total TSE benefits. The corrected or actual emission reductions for CO, NOx and $PM_{2.5}$ using a cold-start period for 5-minutes are approximately 3.2%, 5% and 10% less than the extended-idling emission rate, respectively.

When the cold-start idling period is extended to 10- and 15-minutes, the percent difference between EIER and AERR also increased because the CSEF term becomes larger. Supposing the driver idles the engine for 15-minutes, remember that the cold-start emission rate decreases progressively over time however these are still running emissions that must be subtracted from the TSE emissions benefit. For example, the corrected or actual emission reductions for CO, NOx and $PM_{2.5}$ using a cold-start period for 15-minutes are now approximately 7.3%, 7.7% and 11.9% less than the extended-idling emission rate, respectively. The point being made here is that the TSE benefit progressively decreases the longer the driver allows the engine to idle before leaving the rest area to continue on the freight-hauling trip.

6 CONCLUSIONS

This study measured cold-start and extended-idling emissions of CO, NOx and $PM_{2.5}$ from 24 heavy-duty diesel trucks (HDDV8B) in the field under ambient environmental conditions. Gaseous pollutants were measured directly in the exhaust stream. Ambient air was used to dilute the exhaust gas at the ratio of 3-parts ambient air to 1-part exhaust gas, and PM was measured in the diluted gas mixture. Typical average cold-start and extended-idling emission factors were developed for each pollutant. Historic emission reduction estimates attributable to TSE have generally only included those idling emission savings that are associated with the driver shutting-off the engine and in using TSE during required rest periods. Hence, the equivalent emissions that are associated with the production of electricity for the TSE technology were also determined. To provide for a more realistic comparison between extended-idling and TSE, both the cold-start emissions and the increased emissions associated with the consumption of electricity were subtracted from the usual emission savings associated with TSE technology.

6.1 Impact of Cold-Start

The cold-start emission factors were higher than the extended-idling emission factors for all three pollutants. Immediately after ignition during the cold-start period, emissions increased to maximum emission rate. Then over time, emissions progressively decreased as the engine temperature increased and the combustion process stabilized within the engine. Eventually, emissions reached steady-state, defined here as the period where the emission rate ceases to change over time. The time period for steady-state to be achieved varied among trucks and pollutants. Usually, the range of the steady-state time period was between 1 and 3 hours, and it varied slightly with pollutants. On occasion, the CO emissions reached steady-state before NOx emissions reached steady-state. For some of the test trucks, the PM emissions did not entirely reach steady-state.

A cold-start PM emission spike also did not occur immediately after ignition for some test trucks. At present, there is no obvious explanation for the cause of the variations in the spike pattern between the gaseous and PM emission curves. However, it was speculated that the prior road history of the truck and wet-stacking interacted to influence the amount of PM that was emitted during an engine cold-start episode. When the engine is operated at low idling speed the exhaust temperature is cooler, which is favorable for the condensation of liquid droplets. Incompletely burned fuel in the form of PM mixes with droplets and accumulates in the exhaust system by a phenomenon called wet-stacking. Eventually the material on the wall dehydrates, forming tiny loose projections that can dislodge and reenter the exhaust gas stream. Material may also reenter as liquid droplets.

The cold-start CO emission rate for the three averaging periods selected in this study (i.e., 5-, 10- and 15-minutes) was approximately 2.5 times higher than the average extended-idling emission rate for CO. High CO emissions are likely the key indicator for incomplete combustion during the cold-start episode. The cold-start emission rates for NOx and $PM_{2.5}$ were approximately 1.4 times higher than the average extended-idling emission rates. The cold-start fuel rate was approximately 1.3 times higher than the average extended-idling fuel rate. When comparisons were made between the cold-start and extended-idling periods, using mass emissions per volume of fuel consumed, it was found that more emissions are produced per unit of fuel used during the cold-start period. It was also established that the magnitude of this effect was greatest for CO; the effect was similar in magnitude for NOx and $PM_{2.5}$.

6.2 Extended-Idling Emission Measurements

Overall, the extended-idling emission factors of the present study compared favorably to both the values suggested by EPA for use in State Implementation Plans (SIP) and the average values reported in the literature. The NOx extended-idling emission factor was higher for both the EPA suggested value and the average value reported in the literature. The $PM_{2.5}$ emission factor was smaller than the EPA suggested value, but it was greater than the literature review average. Analysis also indicated a strong dependence of emissions on engine idling speed. A somewhat moderate dependence of emissions on the use of the in-cab air-conditioner was also demonstrated, but it was statistically significant only for NOx emissions. The largest variability of emissions measurements among trucks occurred at the highest engine idling speed. No effect was discerned between the relative magnitude of emissions and model year or odometer reading of the trucks tested in this study for NOx and $PM_{2.5}$ emissions. However, a small deterioration effect was shown to exist for CO emissions based on the model year of the truck.

The ratio of NO_2 to NOx emissions did not vary appreciable throughout cold-start and extended-idling testing conditions. The average ratio was approximately 0.18. This indicated that the effect of idling speed and in-cab accessory load had little effect on the ratio of NO and NO_2 in the exhaust gas. The average diesel fuel consumption rate was 1.5 gal/hr for extended-idling (i.e., the overall average between 600-800 and 1000 rpm) and 2.0 gal/hr for the first 5-minutes of the cold-starting period. The extended-idling fuel rate was about 50% higher than the usually reported literature review value for the extended-idling fuel rate, which is 1.0 gal/hr.

On average about 73% of the PM in the diesel exhaust was less than 2.5 μm. Of the 17 trucks that were tested for particulate emissions, the PM collected on filter media for gravimetric analysis was dark brown or beige in color for 35% of the trucks. The PM was black or gray in appearance for the remaining 65% of the trucks. The cause of this difference is unknown, but it is speculated that different combinations of unburned fuel to soot to lubricating oil caused the difference. It is unlikely that the mileage or age of the truck intrinsically contributed to differences in PM color because two trucks with the highest mileage exhibited different PM color variation. The concentration of SO_2 was also measured in the exhaust stream, as a cursory measurement. However, SO_2 was not detected in the exhaust gas from any truck throughout testing. Nevertheless, preliminary analysis of the PM on the gravimetric filters showed that the PM contained sulfur.

6.3 Truck Stop Electrification Idling Emissions Reduction Benefit

Real or actual emission reductions that can be expected with the TSE technology are needed to support future administrative decisions from standpoints of environmental planning, human health and economic cost. To aid in this end, cold-start emissions and emissions that are associated with the production of electricity, which is necessary to provide TSE in lieu of engine idling, were used to correct or adjust the extended-idling emission factors. In general, it was found that the cold-start emissions and the emissions from electricity were moderately small in comparison with the extended-idling emissions. However if after using TSE, the driver lengthens the idling time between starting the engine and moving the vehicle, then the cold-start emissions are going to be larger and the overall benefit from TSE would be further diminished in magnitude. In general, after the extended-idling emission factors were adjusted to account for the cold-start emissions and the electricity-use emissions, the benefit in applying the TSE technology was only reduced by between 5 and 10% for an 8-hr averaging period, compared to not including these factors in the analysis.

7 RECOMMENDATIONS

7.1 Blow-by Emissions

In all combustion engines, there are several small volumes, usually called crevices, where gas flows during engine operation and as the engine cylinder pressure changes. Volumes between the piston, piston rings and cylinder walls are examples of large crevices. When exhaust gas flow out of these regions into the crankcase, it is called blow-by.[13] For the passenger vehicles powered by a gasoline engine, combustion gases that leak into the crankcase are metered through a positive crankcase ventilation (PCV) valve into the intake manifold of the engine where they are burned in the combustion chamber.[10]

All diesel engines tested in this study vented the crankcase blow-by directly to the atmosphere. The open ventilation system for a heavy-duty diesel truck is shown in Figure 7.1. As can be seen in the photograph, blow-by gases are vented toward the ground under the engine compartment. It is possible that crankcase gases can collect beneath the truck and migrate into the cab. Emissions from blow-by were a source of idling emissions not measured in this study. Crankcase emissions from diesel engines have traditionally been discharged to the atmosphere because there is technological difficulty in re-introducing the emissions into the intake of turbocharged engines.[46] This is an area which needs further study. Relative to TSE, and this study, these emissions provide an even greater reduction as a result of TSE, since the blow-by emissions are also eliminated when the truck is shut off.

7.2 Ambient Conditions for Cold-Starting

The effect of ambient temperature is probably the most important factor affecting the starting of a diesel engine. Required starting torque increases with any given compression ratio. This required increase is needed to overcome the increased viscosity of the oil at low temperatures. The differential expansion and contraction of the different engine parts may also be adding to the friction. The temperature of the cylinder wall and pistons is also lower than during other modes of engine operation.[47]

In the winter months, the cold-start emissions may be higher because the engine idles higher during the warm-up period in winter. Higher idling speeds have been demonstrated to increase emissions. The higher winter idle of the vehicle is a manufactured design because higher idling is used to overcome internal friction while the engine warms-up and until the oil reaches normal operating temperature. Further research needs to be done in this area to determine the magnitude of the cold-start emissions that might occur during winter months. TSE would still be required in the winter for heating the sleeper compartment of the truck. Obviously, a block heater could be used to keep the engine warm during the driver rest (non-idling) period to offset any increased emissions that might be associated with cold-starting the engine under extremely cold ambient conditions.

7.3 Diesel Fuel Sulfur Analysis

Fuel sulfur content may also have a significant affect on the concentration and distribution of sulfur species in diesel PM. The diesel fuel used in the trucks for this study should have been analyzed for sulfur content. The effect of engine idling speed, accessory load and sulfur content also needs to be further investigated. On the other hand, current levels of sulfur in diesel fuel are decreasing due to regulation. Therefore, characterization of PM emissions in the future will dramatically change. Another area, which needs further study, is a detailed analysis of the color difference in diesel PM to determine the basis for the observed differences.

7.4 Shakedown, Instrument Calibration and Repeated Measurements

Only one day of testing was allowed per truck partially because of the availability of funding and other prior commitments made with certain merchants that had kindly loaned their trucks to the project. Given this time frame, a smooth, by-the-book test, was difficult to achieve. For example, one recurring nuisance factor on the newer trucks was the idle-defeat routine in the on-board cruise control that would shutdown the engine after a certain period of idling had transpired.

Thus, the following items would have improved the quality and quantity of the data that were collected had there been more time for the project:

- A shakedown period would have been advantageous to fully understand the various idiosyncrasies of each truck since many different makes and models of trucks were tested.
- At least three, repeated measurements of each truck testing episode would have been desirable to determine the inherent variability in the measurement system.

- Daily pre- and post-calibration tests of the analytical equipment and audits of the volumetric flow rates would have been valuable to evaluate the quality of the emissions data and to remove any bias.

7.5 Modification to the Sampling Chamber

It is believed that the sampling dynamics of the dilution system may also affect the size, mass and composition of diesel PM. It would be beneficial to develop a sampling and/or dilution system that simulates the actual atmospheric dilution process of diesel exhaust as it leaves the exhaust pipe. In any dilution process there are also errors in measurements of flows into and out of the dilution system. An alternate approach would be to pull a sample directly from the exhaust stream using a PM analyzer that can withstand the high exhaust temperatures. Also for comparison, another PM analyzer could sample from somewhere within the emission plume as it leaves the exhaust pipe of the truck.

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APPENDICES

Appendix A

Tables Mentioned in Body of Report

Table 2.1: Summary of Long-Term Idling Emission Data

Researchers	Description	Emissions (g/hr)					Fuel (gal/hr)
		HC	CO	CO_2	NOx	PM	
McCormick, et.al.[21] n = 10	*Average*	7.45	72.8	na	89.9	1.42	na
	% RSD	33.5	40.2	na	17.2	27.2	na
	Minimum	3.60	43.6	na	62.7	1.02	na
	Maximum	12.5	128	na	115	2.16	na
Brodrick, et.al.[22] n = 5	*Average*	23.1	63.9	6,533	170.6	na	0.62
	% RSD	182.4	118.4	43.1	40.2	na	44.0
	Minimum	1.4	14.6	4,034	103.0	na	0.36
	Maximum	86.4	187.7	9,743	254.0	na	0.93
Lim[23] n = 37	*Average*	na	na	8,199	141	na	0.82
	% RSD	na	na	42.1	52.2	na	42.2
	Minimum	na	na	3,915	19.8	na	0.39
	Maximum	na	na	16,577	329	na	1.65
Storey, et.al.[24] n = 32	*Average*	44.0	77.6	9,476	154	3.92	0.95
	% RSD	50.3	80.0	37.4	48.1	120	37.2
	Minimum	9.8	17.1	4,356	51.5	0.83	0.44
	Maximum	89.4	295.0	17,693	353	20.6	1.77
Overall Summary **n = 84**	***Average***	**34.2**	**75.1**	**8,639**	**142**	**3.33**	**0.86**
	% RSD	77.1	76.2	40.7	50.4	127	40.9
	Minimum	1.40	14.6	3,915	19.8	0.83	0.36
	Maximum	89.4	295	17,693	353	20.6	1.77

Note: Relative Standadard Deviation (RSD) units are percent.

Table 2.2: Idling Emission Rates for Engine Accessory Load and RPM Conditions

Description		Air-Condition		Heat		No Load	
		High-rpm (A-H)	Low-rpm (A-L)	High-rpm (H-H)	Low-rpm (H-L)	High-rpm (N-H)	Low-rpm (N-L)
HC (g/hr)	***Average***	**59.5**	**25.7**	**66.6**	**32.5**	**55.3**	**13.1**
	% RSD	45.1	72.8	29.5	41.6	28.7	87.9
	Minimum	20.9	1.4	41.9	20.0	27.0	1.8
	Maximum	86.4	50.3	89.4	50.3	74.3	42.8
CO (g/hr)	*Average*	**101**	**30.3**	**169**	**98.1**	**65.9**	**50.3**
	% RSD	43.8	64.1	49.6	57.4	25.4	67.1
	Minimum	53.3	15.3	102.0	52.8	44.4	14.6
	Maximum	188	68.9	295	194	87.2	128
CO_2 (g/hr)	***Average***	**13,131**	**5,990**	**11,331**	**6,462**	**10,600**	**5,377**
	% RSD	21.4	22.7	8.1	9.1	13.3	36.5
	Minimum	8,078	4,256	10,232	5,688	8,457	3,915
	Maximum	17,693	8,454	13,206	7,163	13,230	11,838
NOx (g/hr)	***Average***	**214**	**113**	**193**	**101**	**169**	**103**
	% RSD	38.9	44.4	42.7	34.7	36.1	30.5
	Minimum	69.3	19.8	64.0	54.8	55.8	62.7
	Maximum	353	176	329	137	241	164
PM (g/hr)	*Average*	**6.67**	**1.34**	**5.77**	**2.68**	**5.87**	**1.39**
	% RSD	118.3	44.9	32.5	46.7	121.7	32.0
	Minimum	1.44	0.83	3.35	1.43	2.20	0.83
	Maximum	20.6	2.26	8.21	4.59	20.4	2.31
Fuel (gal/hr)	***Average***	**1.30**	**0.60**	**1.16**	**0.66**	**1.06**	**0.53**
	% RSD	22.6	22.3	7.7	8.1	13.5	37.7
	Minimum	0.80	0.42	1.02	0.58	0.86	0.36
	Maximum	1.77	0.85	1.33	0.72	1.33	1.18

Note: Relative Standard Deviation (RSD) units are percent.

Table 2.3: Summary of Short-Term Idling Emission Data

Researcher	Description	Emissions (g/hr)				
		HC	CO	CO_2	NOx	PM
Tang, et.al.[25] n = 8	***Average***	**11.1**	**26.0**	**7,531**	**96.2**	**na**
	% RSD	86.1	57.1	50.4	50.8	na
	Minimum	3.0	12.6	4,844	35.4	na
	Maximum	31.2	60.0	16,487	187	na

Note: Relative Standard Deviation (RSD) units are percent.

Table 2.4: Summary of Short-Term Idling NOx Emissions

Researcher	Engine Test Conditions	Range	AC Mode (g/hr)	
			Off	On
Lambert, et,al.[26] n = 40	High Idle (1,000 rpm)	*Minimum*	55	60
		Maximum	275	375
	Curb Idle (< 1,000 rpm)	*Minimum*	55	NA
		Maximum	165	NA

Table 2.5: Idling Emissions and Fuel Consumption Rates (Detail)

Engine Test Conditions (n = 1)	Emission (g/hr)				Fuel
	HC	CO	NOx	CO_2	(gal/hr)
1 - Idle at 600 rpm after 10-min 55 mph cruise	1.8	14.6	103	4,034	0.36
2 - Idle at 600 rpm after 10-min transient cycle	2.9	15.9	105	4,472	0.39
3 - Idle at 600 rpm with AC after 10-min transient cycle	1.4	15.3	166	4,976	0.52
4 - Idle at 1,050 rpm with AC after 10-min transient cycle	NA	86.0	254	9,441	0.88
5 - Idle at 1,050 rpm with AC for 5-hrs	86.4	189.7	225	9,743	0.93
6 - Cruise (or driving) at 55 mph	5.6	65.1	713	60,592	5.92
7 - Cruise (or driving) at 55 mph with AC	3.9	57.4	777	60,320	6.88

Source: Brodrick, et.al.[22, 27]

Table 2.6: HDDV Idling Emission Factors from MOBILE6

Description	Idling Emission Factors						Units
	THC	CO	CO_2	NOx	PM_{10}	$PM_{2.5}$	
HDDV	2.53	18.86	1,445	26.17	0.55	0.51	g/mile
	6.3	***47.1***	***3,613***	***65.4***	***1.4***	***1.3***	***g/hr***
HDDV7	2.32	12.34	1,348	20.38	0.46	0.43	g/mile
	5.8	***30.8***	***3,369***	***50.9***	***1.2***	***1.1***	***g/hr***
HDDV8A	2.57	19.93	1,575	29.90	0.60	0.55	g/mile
	6.4	***49.8***	***3,938***	***74.8***	***1.5***	***1.4***	***g/hr***
HDDV8B	3.25	26.67	1,674	34.70	0.66	0.61	g/mile
	8.1	***66.7***	***4,185***	***86.8***	***1.6***	***1.5***	***g/hr***
HDDV8	3.10	25.19	1,652	33.65	0.65	0.60	g/mile
	7.8	***63.0***	***4,131***	***84.1***	***1.6***	***1.5***	***g/hr***

Note: g/hr = g/mile x 2.5 mph

Table 2.7: EPA Suggested PM Extended-Idling Emission Factors for SIP

Calendar Year	EF (g/hr)	Calendar Year	EF (g/hr)
2006	3.68	**2019**	0.54
2007	3.43	**2020**	0.50
2008	2.94	**2021**	0.47
2009	2.52	**2022**	0.44
2010	2.16	**2023**	0.41
2011	1.88	**2024**	0.39
2012	1.60	**2025**	0.38
2013	1.38	**2026**	0.36
2014	1.10	**2027**	0.35
2015	0.89	**2028**	0.34
2016	0.79	**2029**	0.33
2017	0.71	**2030**	0.33
2018	0.58		

Source: USEPA[29]

Table 3.1: General Description of Test Trucks

ID	Truck	VIN	Year	Engine			
				Model	**HP**	**Disp (L)**	**Odom (mi)**
1	Freightliner	2HSCEAPR25C003739	1996	Cummins N14	460	14	512,926
2	Freightliner	1FUYDSEB6XLB00220	1998	Detroit S60	430	12.7	591,476
3	Volvo	4V4NC9GHX5N381710	2004	Volvo Vectro	465	12.1	287
4	Volvo	4V4NC9GH65N381722	2004	Volvo Vectro	465	12.1	83
5	Mack	1M1AA18Y6XW112584	1999	Mack ASET	460	11.9	416,764
6	Kenworth	1XKADB9X45J087931	2004	Caterpillar ACERT	475	15.2	72
7	International	2HSFHAER5XC086741	1998	Cummins N14	500	14	655,380
8	Kenworth	1XKWDB9X05J081372	2004	Caterpillar ACERT	475	15.2	738
9	Volvo	4V4NC9JH1N259226	2000	Cummins N14	435	14	553,465
10	Freightliner	1FUPDCYB2XL904380	1998	Cummins N14	425	11	341,146
11	Freightliner	1FUJA3CG11LG36966	2000	Detroit S60	430	12.7	420,621
12	International	2HSFBAHR1SC056187	1995	Cummins M11	450	11	814,185
13	International	2HSCEAPR25C003739	2004	Cummins N14	475	15	58
14	Freightliner	1FUYDZYB1NP476082	1992	Detroit S60	450	12.7	279,922
15	Freightliner	1FUYJA6CK04LN3773	2004	Detroit S60	455	14	82,929
16	Freightliner	1FUYSSZB6YLG08382	1999	Detroit S60	500	12.7	568,539
17	Freightliner	1FUJA6CK44LM15160	2003	Detroit S60	435	14	147,334
18	Freightliner*	1FUYDZYB8WL903823	1997	Detroit S60	400	12.7	647,979
19	Mack*	IM1AEO6Y54N019364	2003	Mack ASET	430	11.9	78,960
20	Freightliner	1FUYDSEB1WL896080	1997	Detroit S60	430	12.7	834,028
21	Freightliner	1FUJA6CK54LM13479	2003	Detroit S60	455	14	154,156
22	Freightliner	1FUYSSEB7YLG51490	1999	Detroit S60	430	12.7	482,983
23	Mack*	1M1AE06Y54N019512	2003	Mack ASET	430	11.9	58,047
24	Mack	1M1AE06Y41W008703	2000	Mack ASET	355	11.6	484,108

ID = Identification number; VIN = Vehicle identification number (manufacturer); HP = Rated engine horsepower; Disp = Engine Displacement; L = Liters; Odom = Odometer; mi = miles; *Truck body has day cab only.

Table 3.2: Operating and Reporting Conditions for Emissions Analyzers

PEMS	Parameters	Units	Sensor
ECOM	O_2	%	Electrochemical
	CO, NO, NO_2 & SO_2	ppm	Electrochemical
	Ambient Temperature	F	Positive Temperature Coefficient (Thermistor)
	Duct Temperature	F	Thermocouple
	Duct Pressure	in H_2O	Piezoresistive Electronic
	Sampling Flow Rate	Lpm	Proprietary flow/pressure control (fixed at 2.5 Lpm)
	NOx	ppm	Calculated Values
	CO_2	%	
	Combustion Efficiency	%	
	Excess Air (lambda)	%	
	Losses	%	
DataRAM	PM	mg/m^3	Photometric
	Duct Temperature	F	Thermocouple
	Relative Humidity	%	Capacitive
	Sampling Flow Rate	Lpm	Proprietary flow (variable range 1 - 3 Lpm)
Kurz	Volumetric Flow	SCFM	Thermal Anemometer
	Duct Temperature	F	Thermocouple

Table 4.1: Average Cold-Start and Extended-Idling Emission Factors

Description	Cold-start (at Low-Idling)				Low-Idling		High-Idling		(Overall) Extended Idling Average
	CS-SS	CS-5	CS-10	CS-15	(600-800 rpm)		(1000 rpm)		
	AC-On				AC-Off	AC-On	AC-Off	AC-On	
CO (g/hr)	78.6	180	163	145	36.9	47.6	74.6	98.9	64.5
Fuel rate (gal/hr)	1.6	2.0	2.0	1.9	1.2	1.4	1.6	1.8	1.5
NOx (g/hr)	187	248	237	225	120	159	164	223	167
Ratio: NO_2/NOx	0.17	0.17	0.17	0.17	0.17	0.16	0.19	0.18	0.18
$PM_{2.5}$ (g/hr)	2.83	5.99	5.00	4.14	2.55	3.13	4.37	4.11	3.54

Notes: CS-SS = Engine cold-start to reach steady-state condition, typically 1-3 hours in duration; CS-5, CS-10 and CS-15 = Engine cold-start during the first 5, 10 and 15 minutes, respectively; AC = Air-conditioner at Off and On settings.

Table 4.2: Average Mass Emissions per Unit Fuel Consumption Rate

Description	Cold-start (at Low-Idling)				Low-Idling		High-Idling	
	CS-SS	CS-5	CS-10	CS-15	(600-800 rpm)		(1000 rpm)	
	AC-On				AC-Off	AC-On	AC-Off	AC-On
CO	48.6	89.3	81.4	74.8	30.7	33.9	47.5	54.0
NOx	116	123	118	116	100	113	105	122
$PM_{2.5}$	1.75	2.97	2.50	2.14	2.12	2.23	2.78	2.25

Notes: Units = (gal/hr); CS-SS = Engine cold-start to reach steady-state condition, typically 1-3 hours in duration; CS-5, CS-10 and CS-15 = Engine cold-start during the first 5, 10 and 15 minutes, respectively; AC = Air-conditioner at Off and On settings.

Table 4.3: Comparison of Overall Extended-Idling Emission Factors

Description	(Overall) Extended Idling Average	EPA Recommended (SIP)	Literature Review Average	Percent Difference (Exp - EPA)	Percent Difference (Exp - LitRev)
CO (g/hr)	64.5	NA	75.1	NA	-14.1%
Fuel rate (gal/hr)	1.5	NA	1.0	NA	50.2%
NOx (g/hr)	167	135	142	23.5%	17.4%
$PM_{2.5}$ (g/hr)	3.54	3.68	3.33	-3.8%	6.3%

Notes: Exp = experimental values (determined from this study) and LitRev = literature review values.

Table 4.4: Within Comparison of Extended-Idling Emission Factors

Description	EPA Recommended (SIP)	Comparison 1		Comparison 2		Comparison 3		Comparison 4	
		Low-Idle 600-800 rpm AC-Off	Percent Difference (Exp - EPA)	Low-Idle 600-800 rpm AC-On	Percent Difference (Exp - EPA)	High-Idle 1000 rpm AC-Off	Percent Difference (Exp - EPA)	High-Idle 1000 rpm AC-On	Percent Difference (Exp - EPA)
NOx (g/hr)	135	120	-10.9%	159	17.8%	164	21.7%	223	65.4%
$PM_{2.5}$ (g/hr)	3.68	2.55	-30.7%	3.13	-14.9%	4.37	18.6%	4.11	11.8%

Note: Exp = experimental values (determined from this study).

Table 5.1: Actual Emission Reductions Using TSE Technology

CS-n	Pollutant	Extended-Idling (EIER)	Cold-Start (CSER)	Electric-Use (EUER)	Actual Emission Reduction (AERR)	Percent Difference
n = 5	CO	64.5	1.88	0.19	62.4	3.2%
	NOx	167	2.58	5.84	158	5.0%
	$PM_{2.5}$	3.54	0.062	0.29	3.19	10.0%
n = 10	CO	64.5	3.39	0.19	60.9	5.5%
	NOx	167	4.93	5.84	156	6.5%
	$PM_{2.5}$	3.54	0.104	0.29	3.14	11.2%
n = 15	CO	64.5	4.52	0.19	59.8	7.3%
	NOx	167	7.04	5.84	154	7.7%
	$PM_{2.5}$	3.54	0.129	0.29	3.12	11.9%

Note: Units = (g/hr) except where the percent symbols are shown.

Appendix B

Figures Mentioned in Body of Report

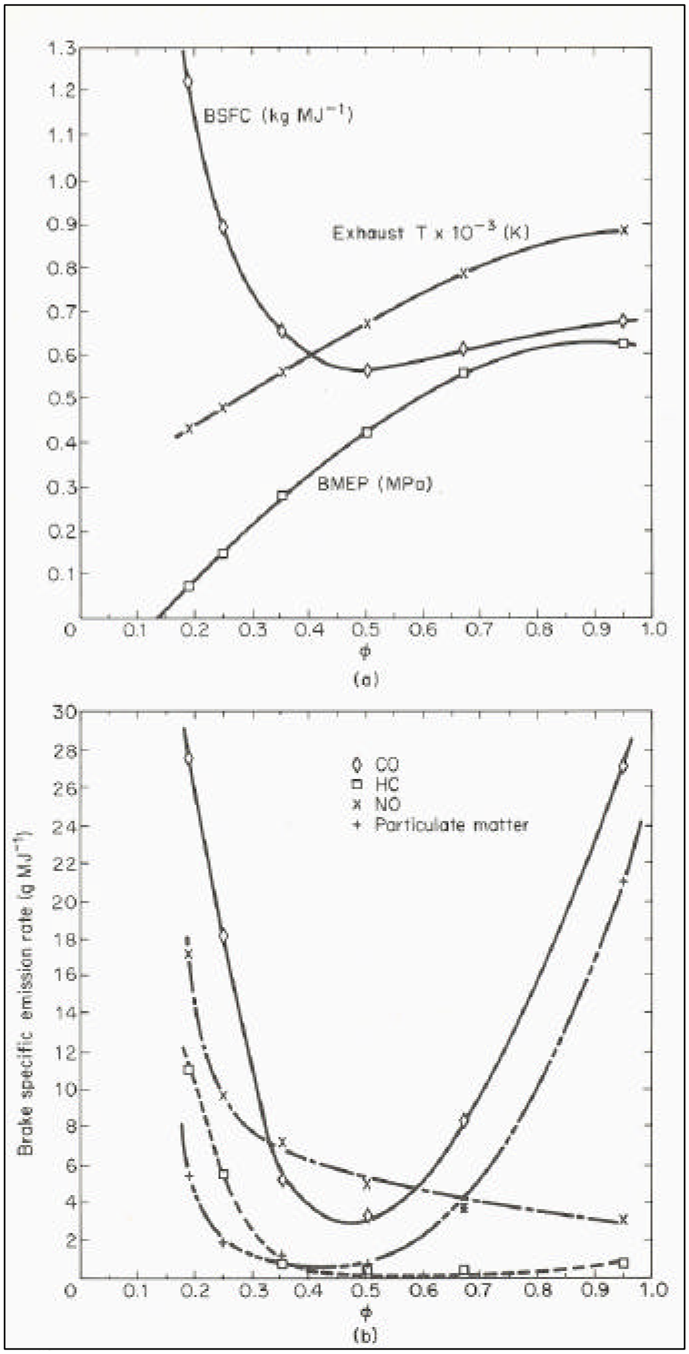


Figure 1.1. Influence of the equivalence ratio (f) on light-duty diesel engine performance and emissions.

Note: part (a) is for performance, and part (b) is for emissions. Source: Flagan, et.al.[14]

Figure 1.2. Truck stop electrification at parking lot (rest) area.

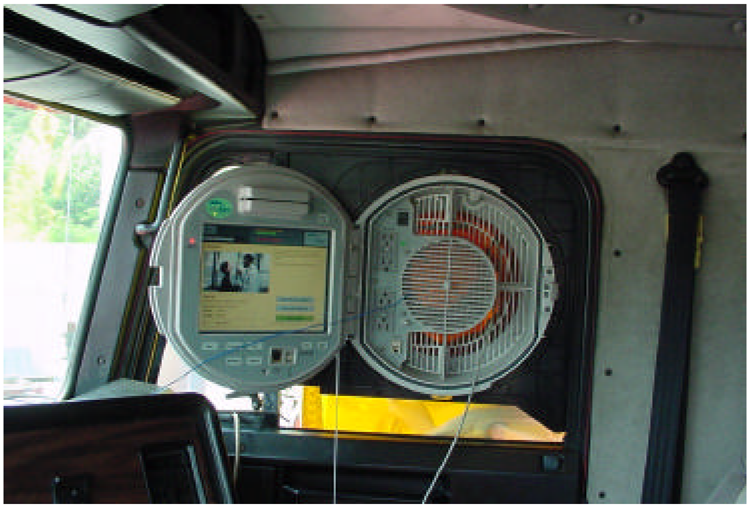
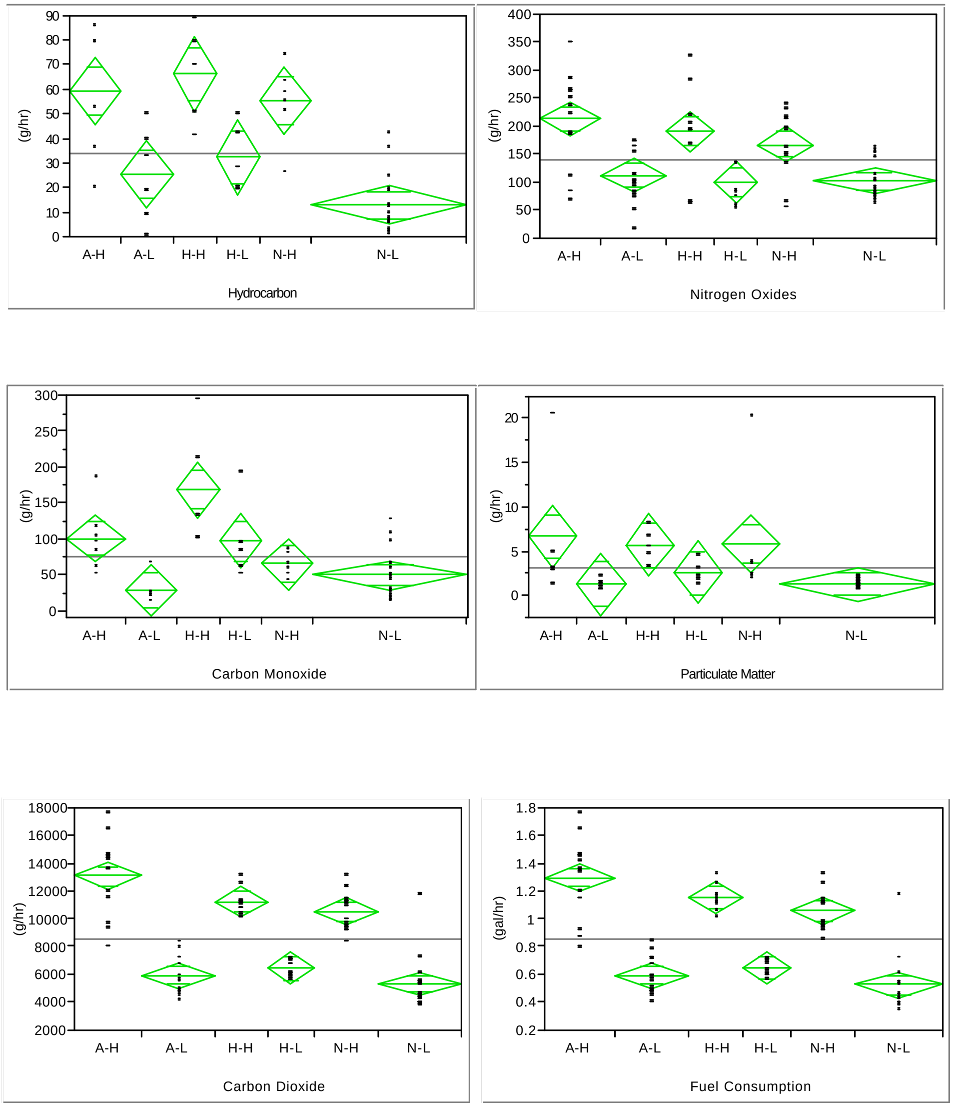


Figure 1.3. IdleAire in-cab HVAC module and computer terminal.



A-H = Air-condition, High rpm
H-H = Heater, High rpm
N-H = No-load, High rpm
A-L = Air-condition, Low rpm
H-L = Heater, Low rpm
N-L = No-load, Low rpm

Figure 2.1. Engine load and RPM conditions for emissions and fuel consumption rates for long-duration HDDV8 idling.

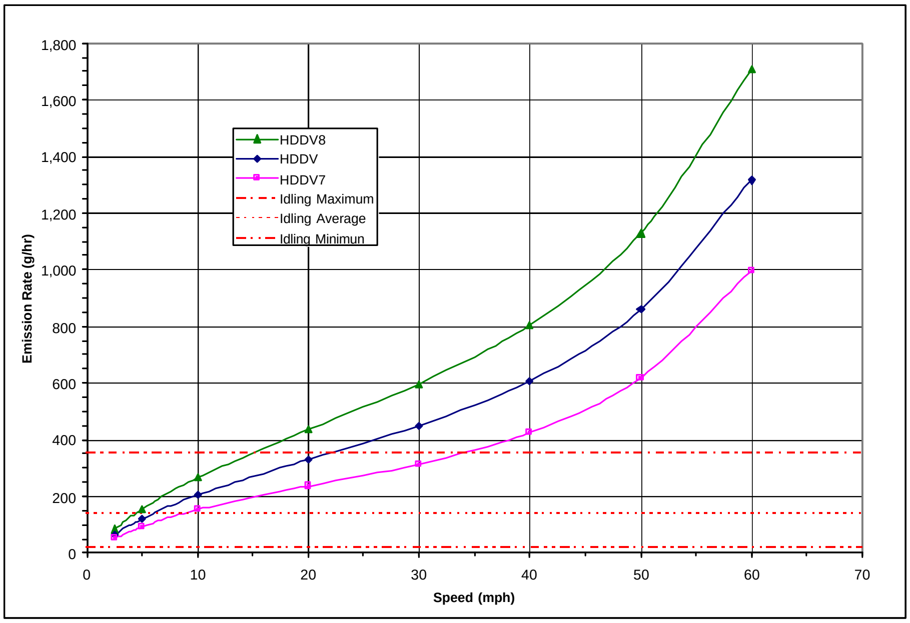


Figure 2.2. MOBILE6 - NOx emission rates as a function of vehicle speed.

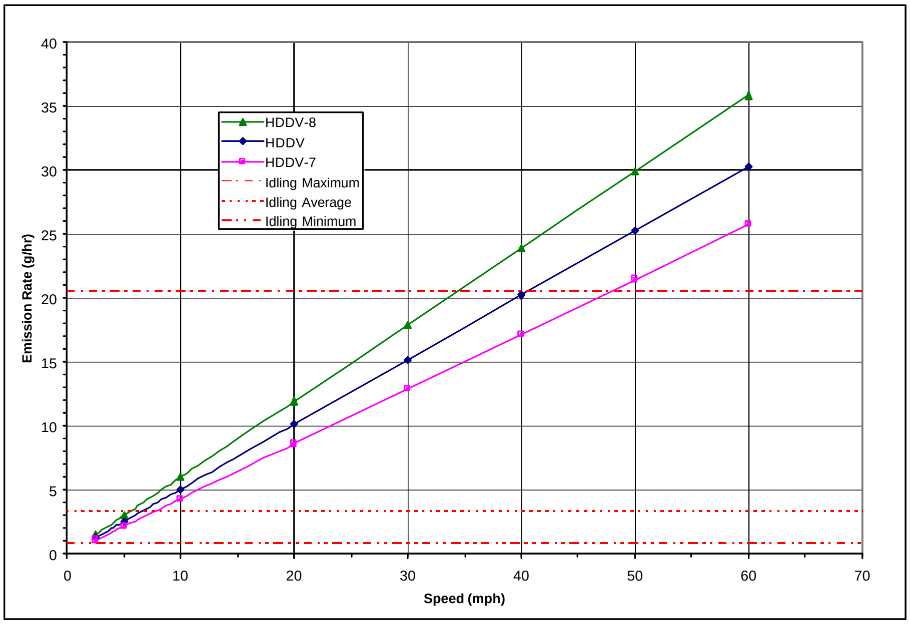


Figure 2.3. MOBILE6 - PM emission rates as a function of vehicle speed.

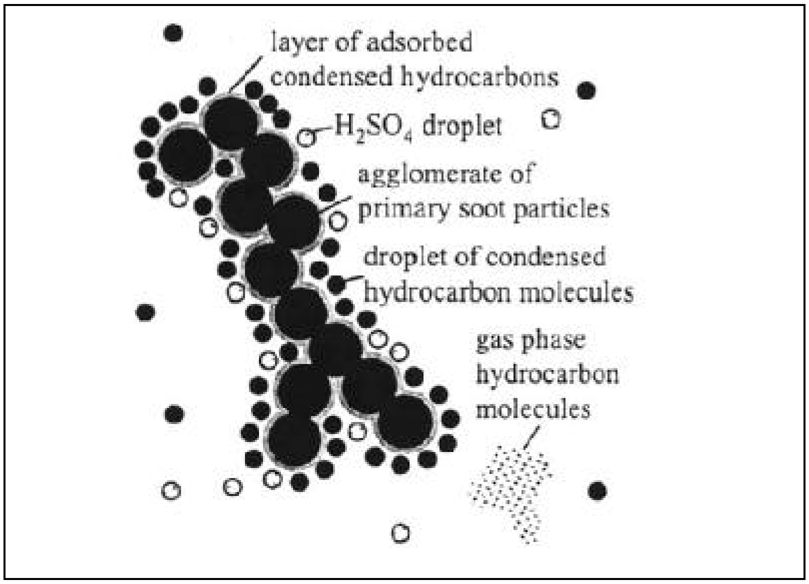


Figure 2.4. Schematic representation of aggregate diesel PM. Source: Walker[31]

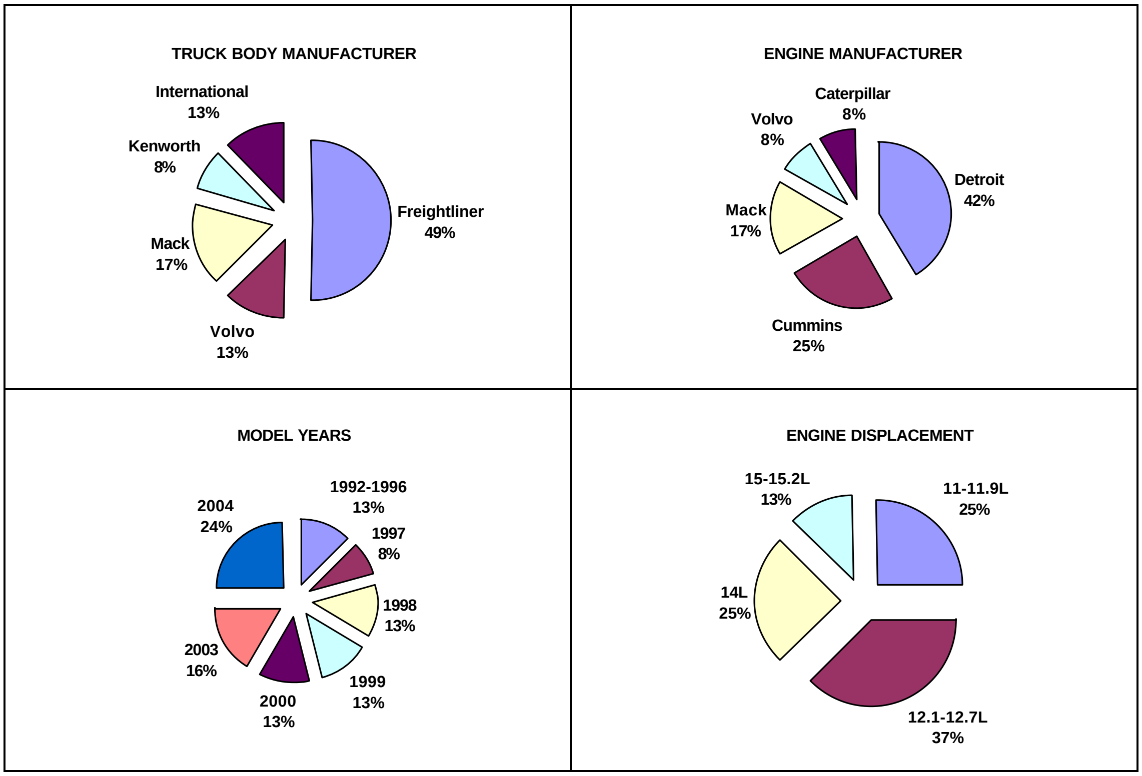


Figure 2.5. Characteristics of test trucks.

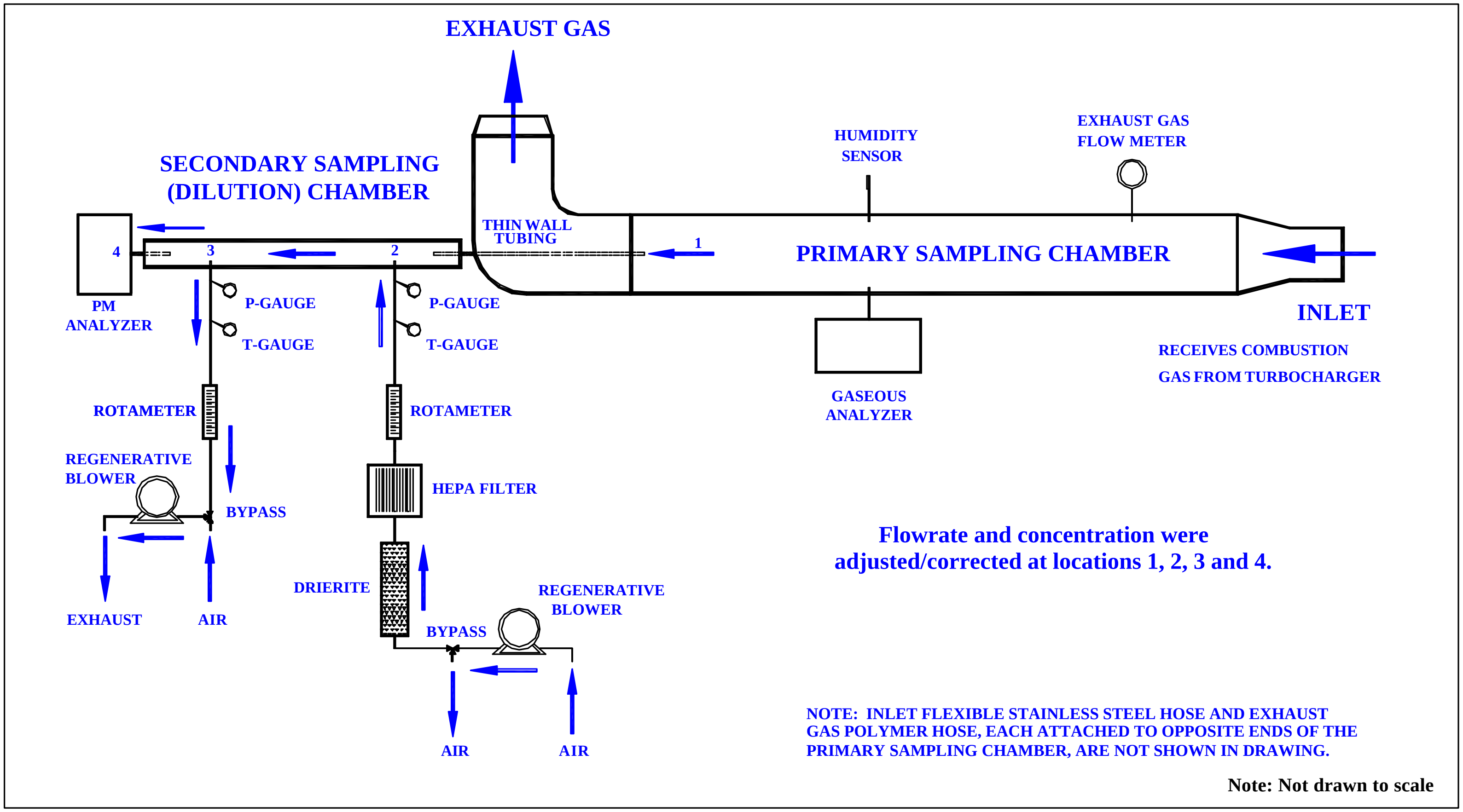


Figure 3.1. Diagram of sampling system and equipment layout.

Figure 3.2. Test truck attached to primary sampling chamber.

Figure 3.3. Overall view of mobile test stand and all instrumentation.

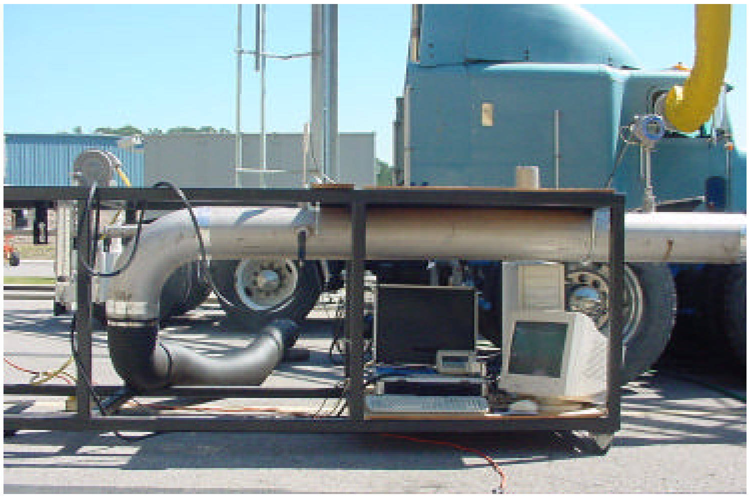


Figure 3.4. Side view of primary sampling chamber.

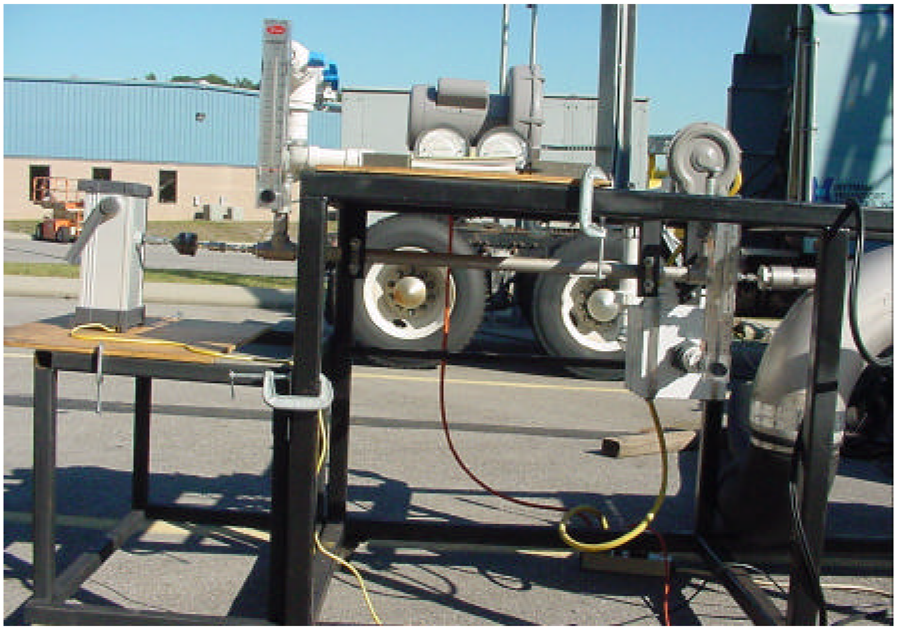


Figure 3.5. Side view of secondary (or dilution) sampling chamber.

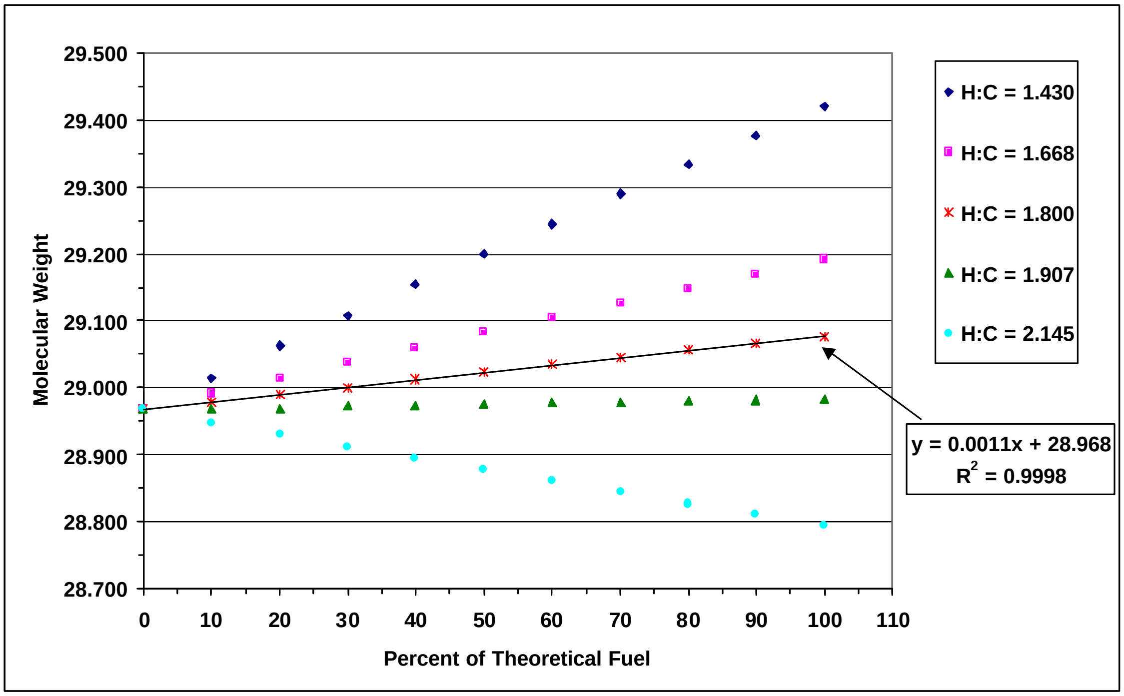


Figure 3.6. Molecular weight of exhaust gas versus percent theoretical fuel for four hydrogen-carbon ratios. Note: MW_{Air} ~ 29. Source: Keenan, et.al.[38]

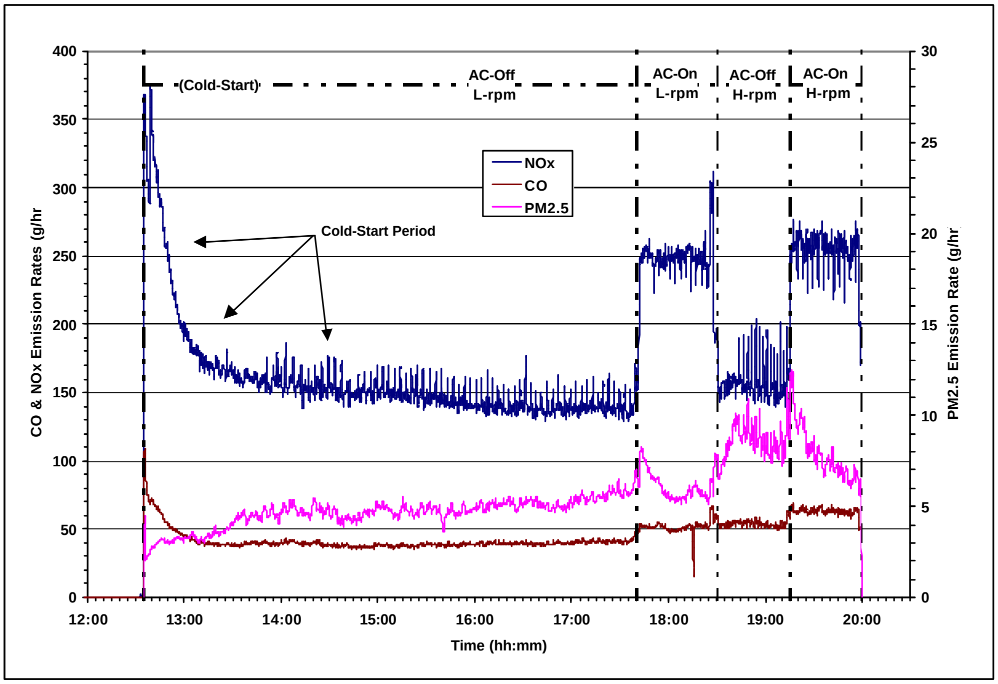


Figure 4.1. Emission rate behavior for 1996 Freightliner truck.

Notes: L-rpm = 750 rpm, H-rpm = 1000 rpm and AC = Air-conditioner mode of operation.

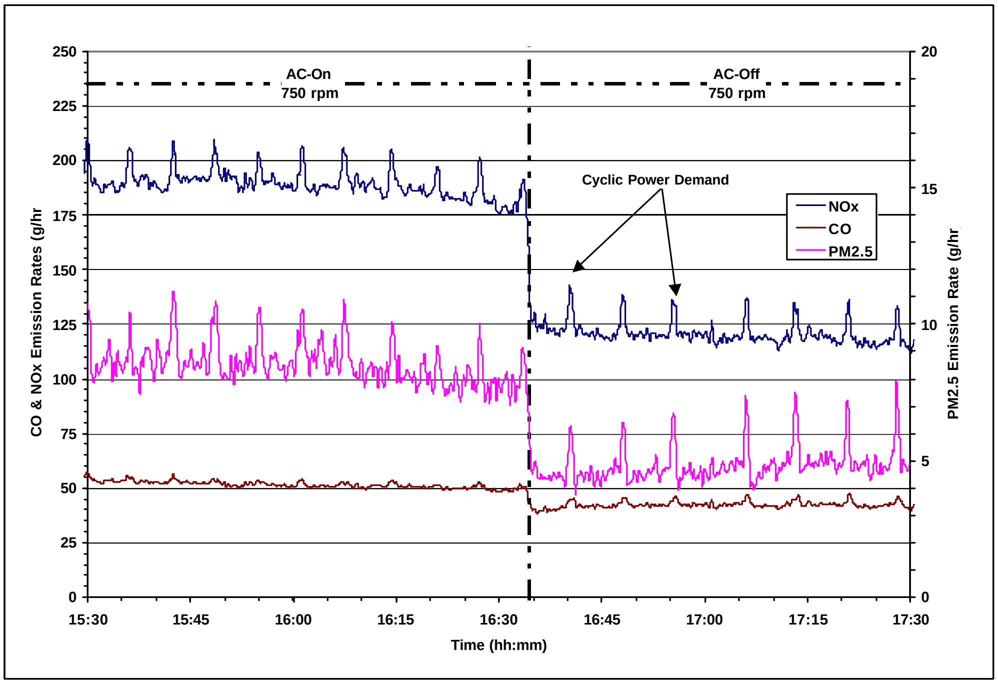


Figure 4.2. Emission rate behavior for 1995 International truck (detail).

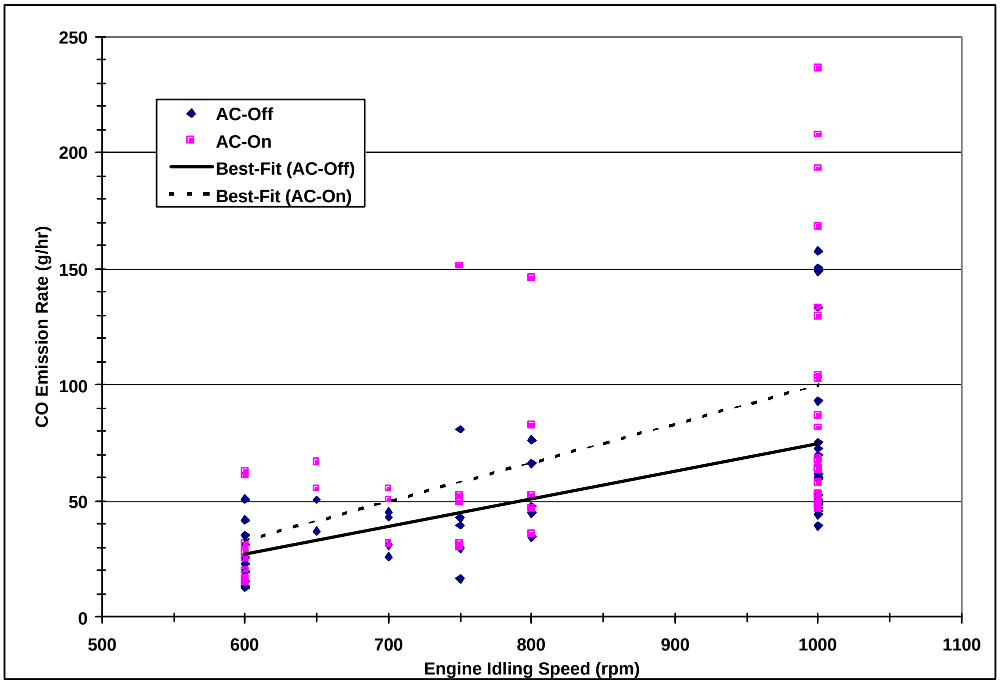


Figure 4.3. CO emission rate versus idling speed for air-conditioner settings.

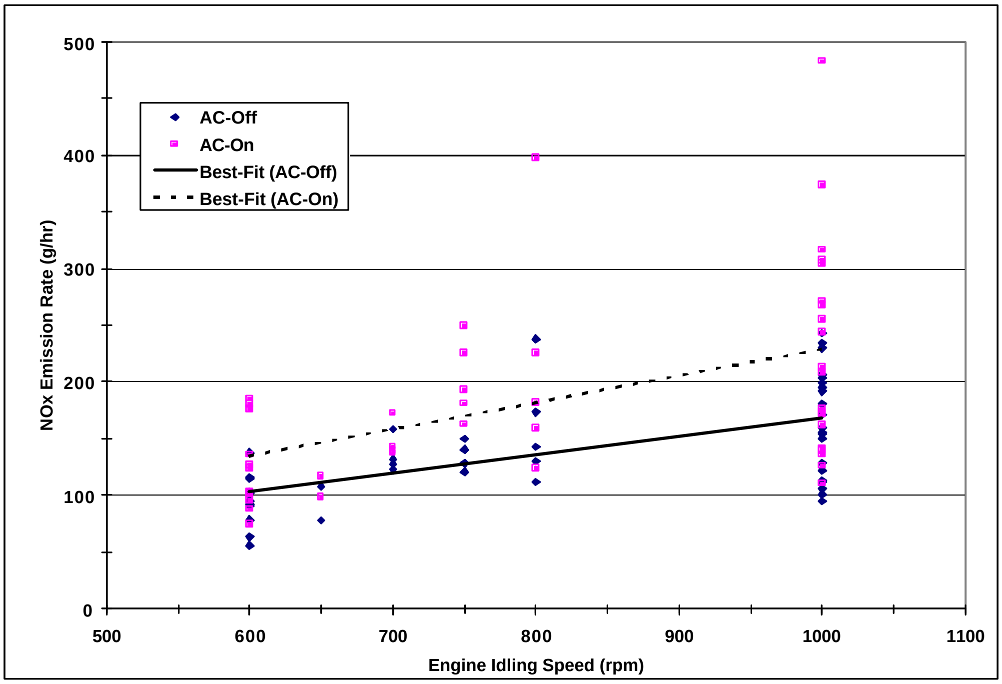


Figure 4.4. NOx emission rate versus idling speed for air-conditioner settings.

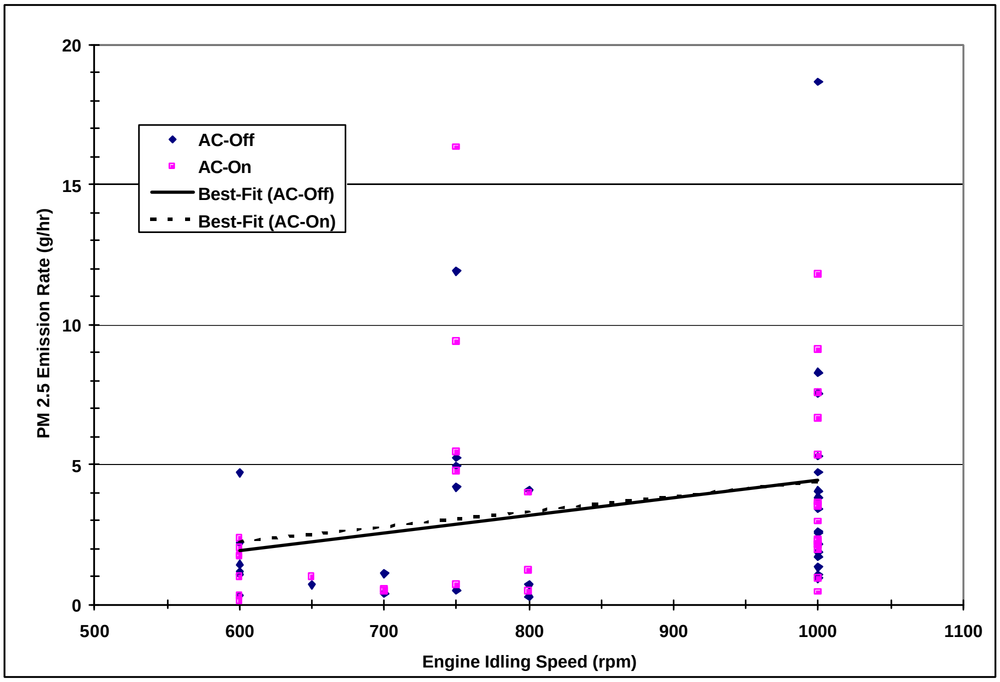


Figure 4.5. PM$_{2.5}$ emission rate versus idling speed for air-conditioner settings.

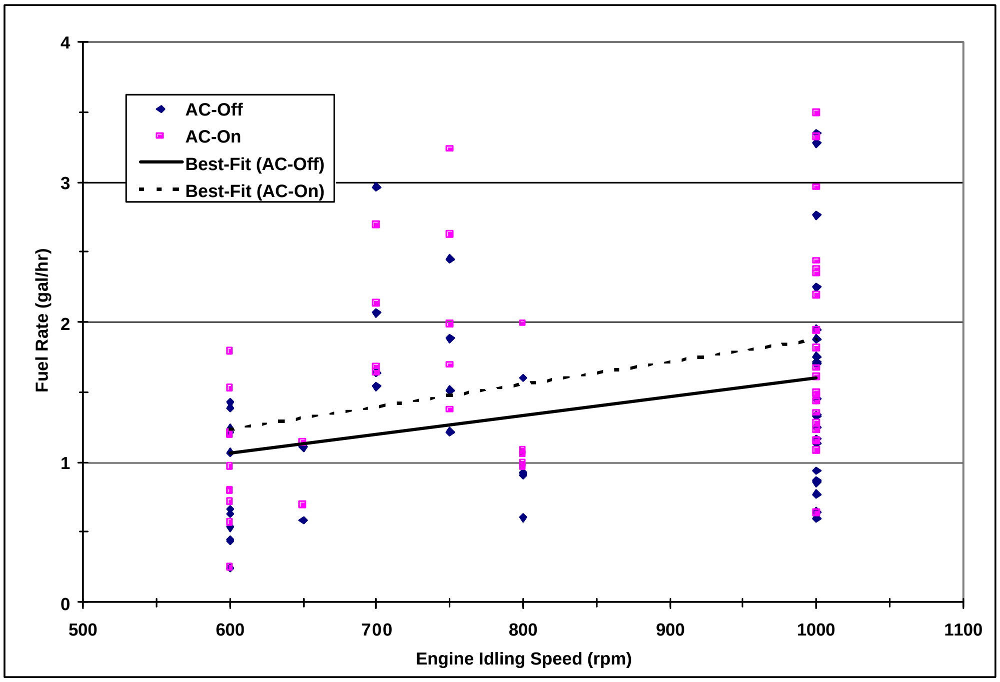


Figure 4.6. Fuel consumption rate versus idling speed for air-conditioner settings.

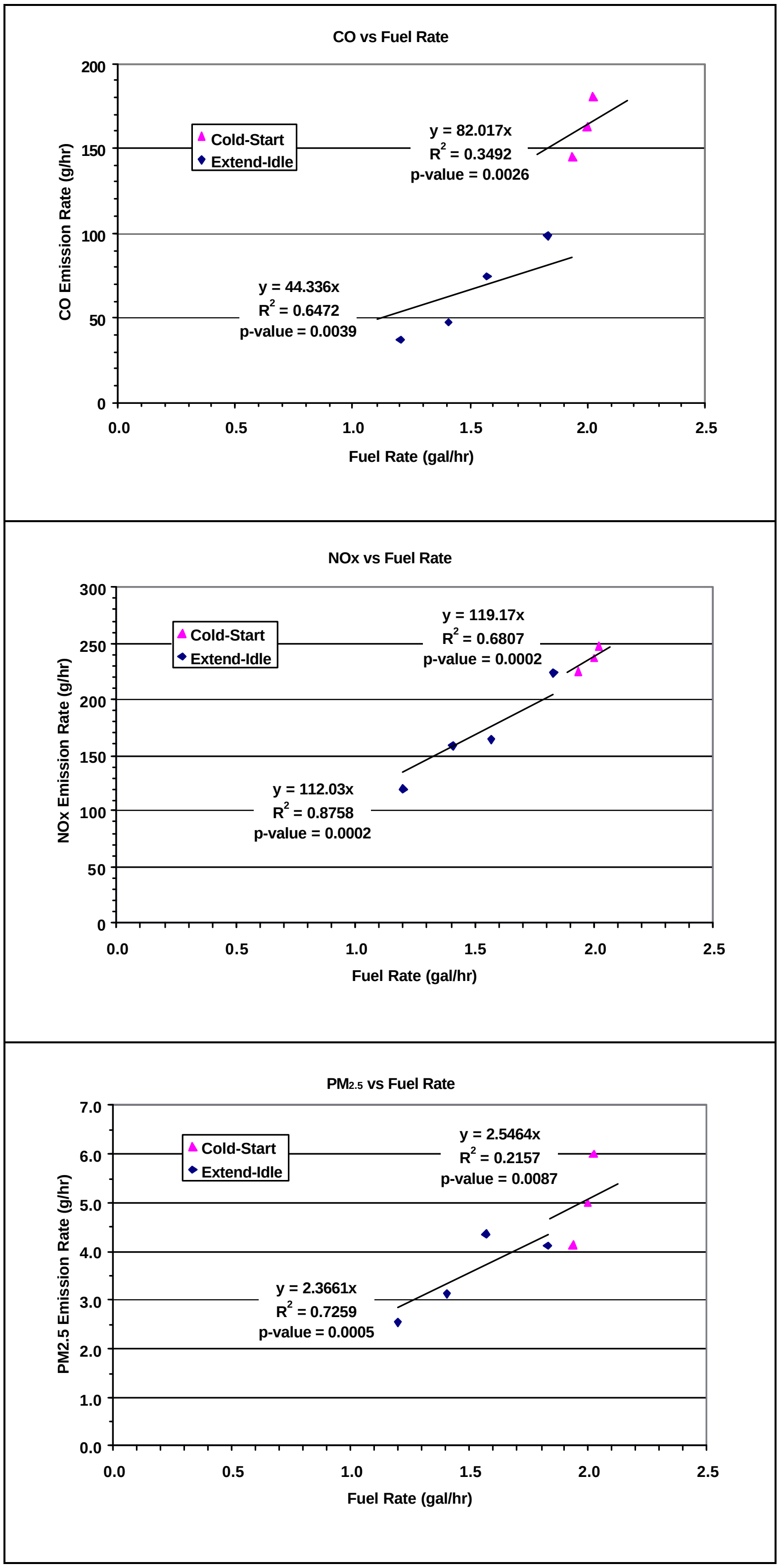
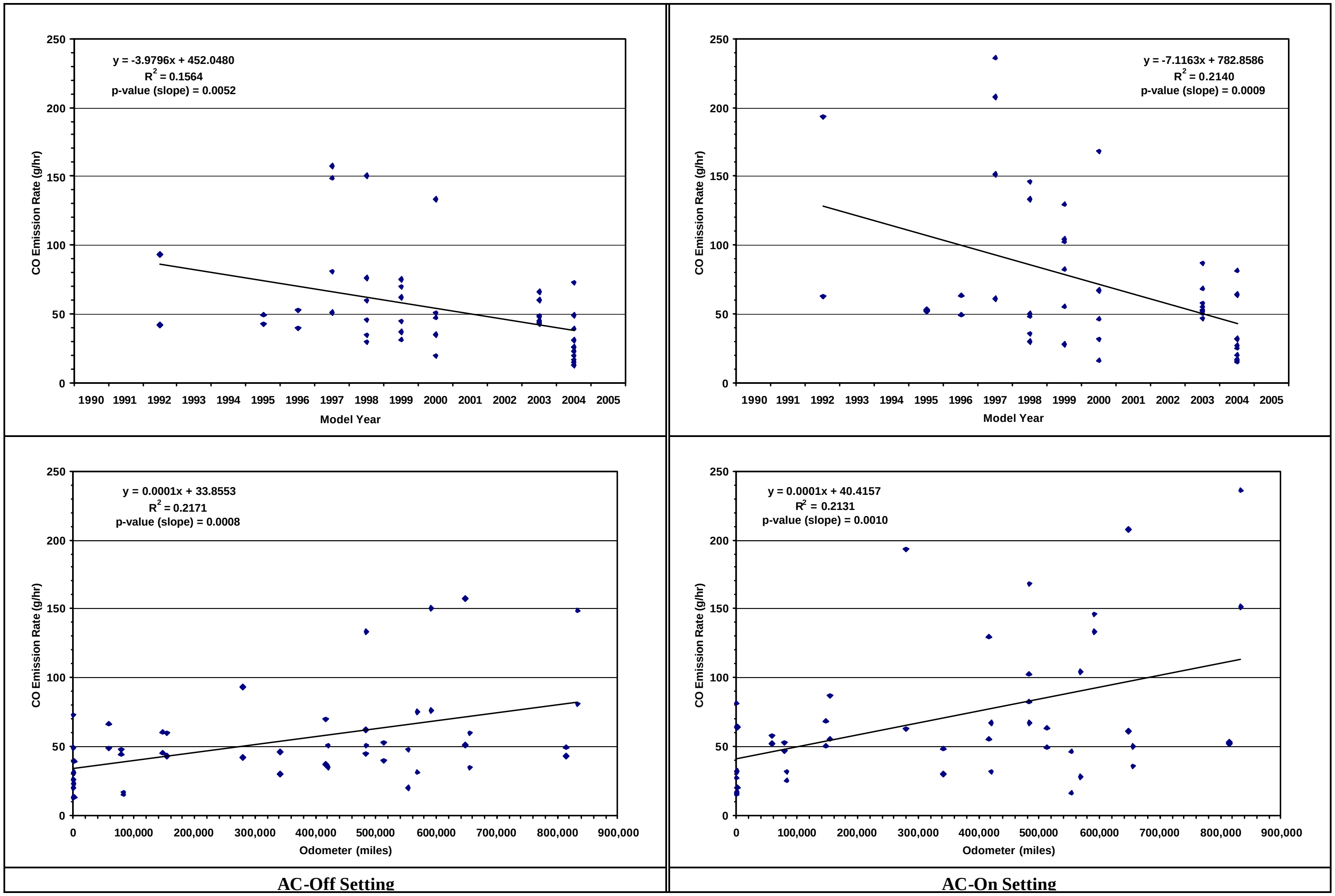


Figure 4.7. CO, NOx and $PM_{2.5}$ emission rates versus diesel fuel rate.

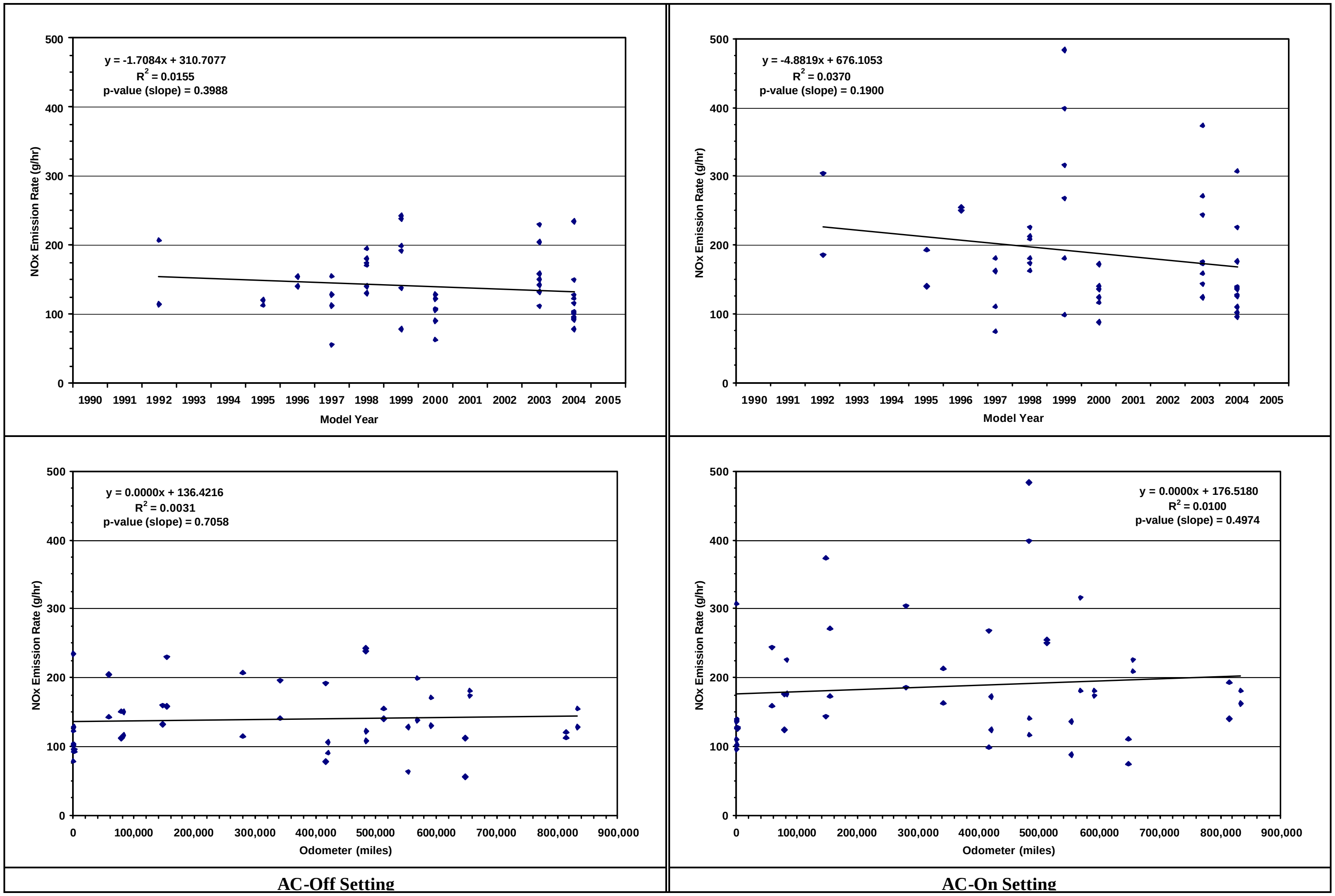


AC-Off Setting

AC-On Setting

Figure 4.8. CO emission rates for truck model year and odometer reading at AC-Off and AC-On settings.

Note: Top pair of graphs compares truck model year and bottom pair of graphs compares odometer reading.



AC-Off Setting

AC-On Setting

Figure 4.9. NOx emission rates for truck model year and odometer reading at AC-Off and AC-On settings.

Note: Top pair of graphs compares truck model year and bottom pair of graphs compares odometer reading.

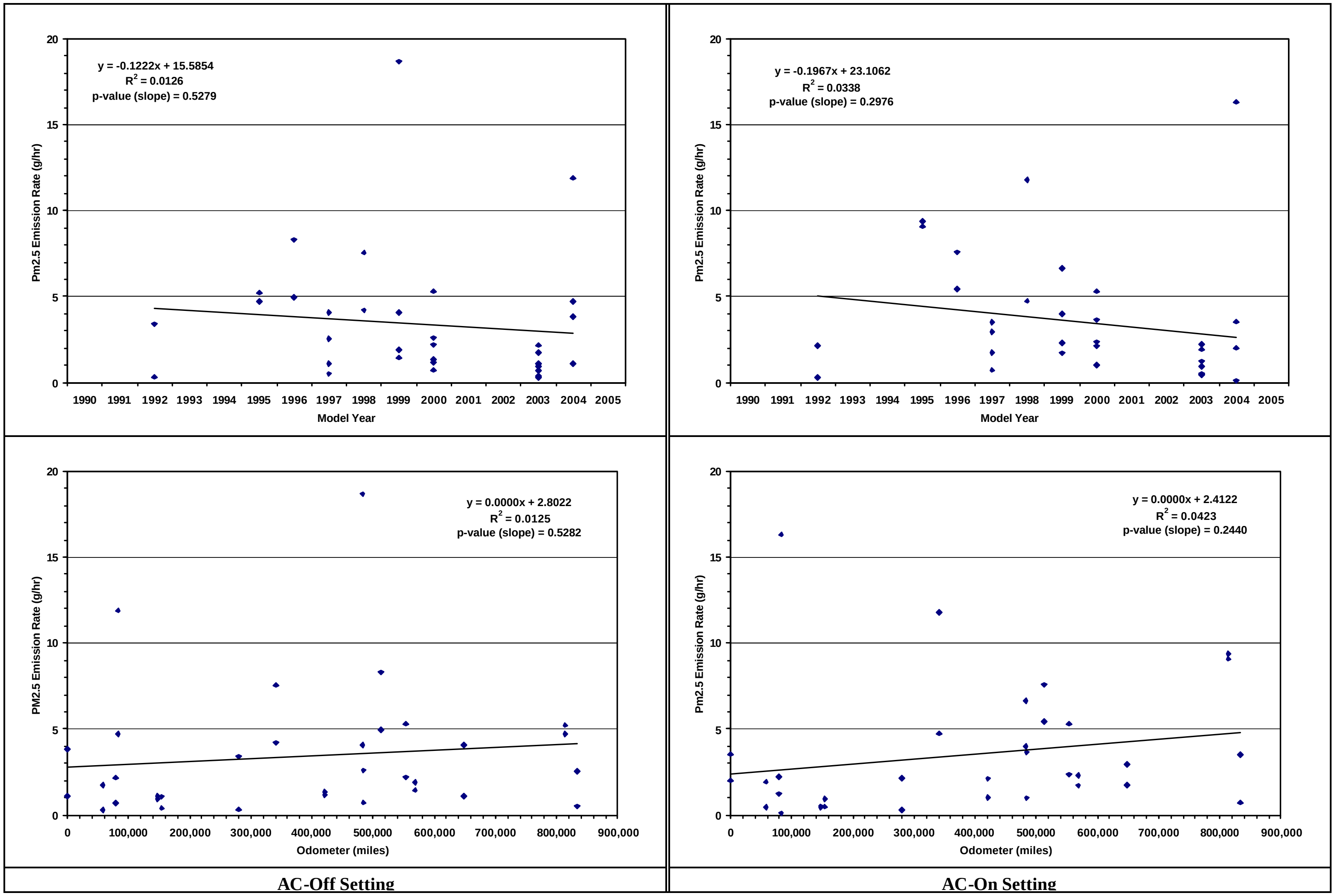
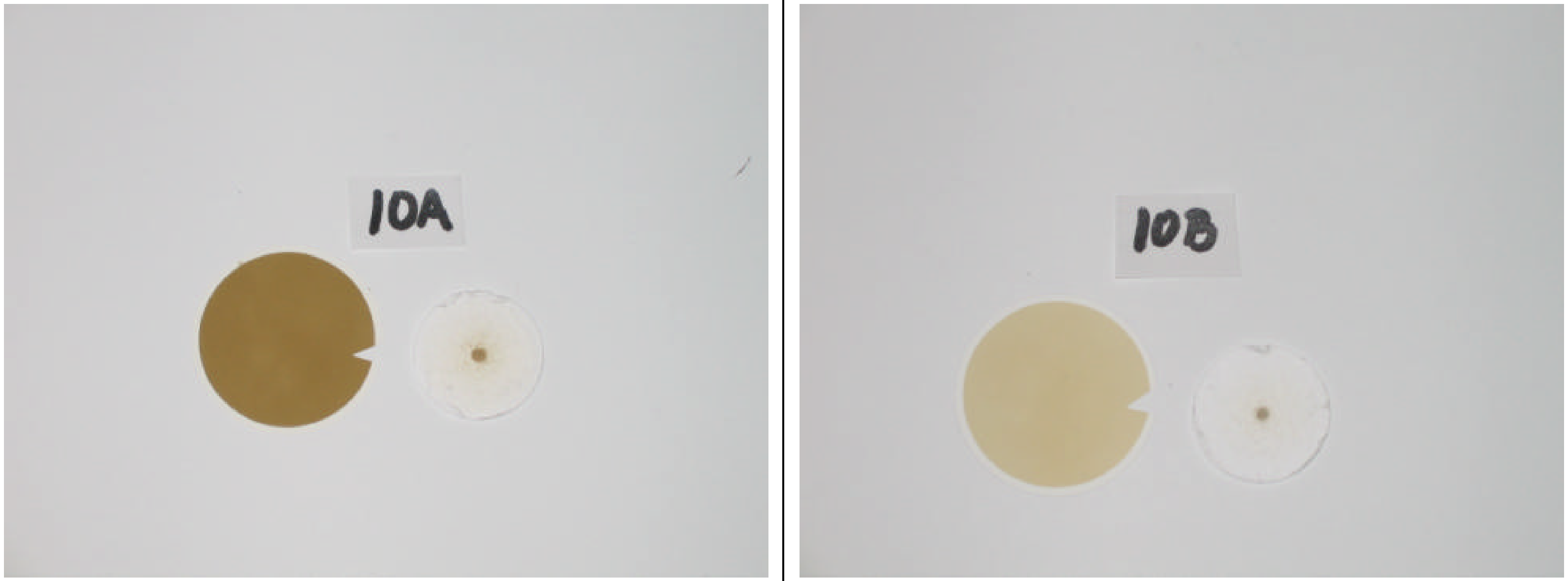


Figure 4.10. PM$_{2.5}$ emission rates for truck model year and odometer reading at AC-Off and AC-On settings.

Note: Top pair of graphs compares truck model year and bottom pair of graphs compares odometer reading.

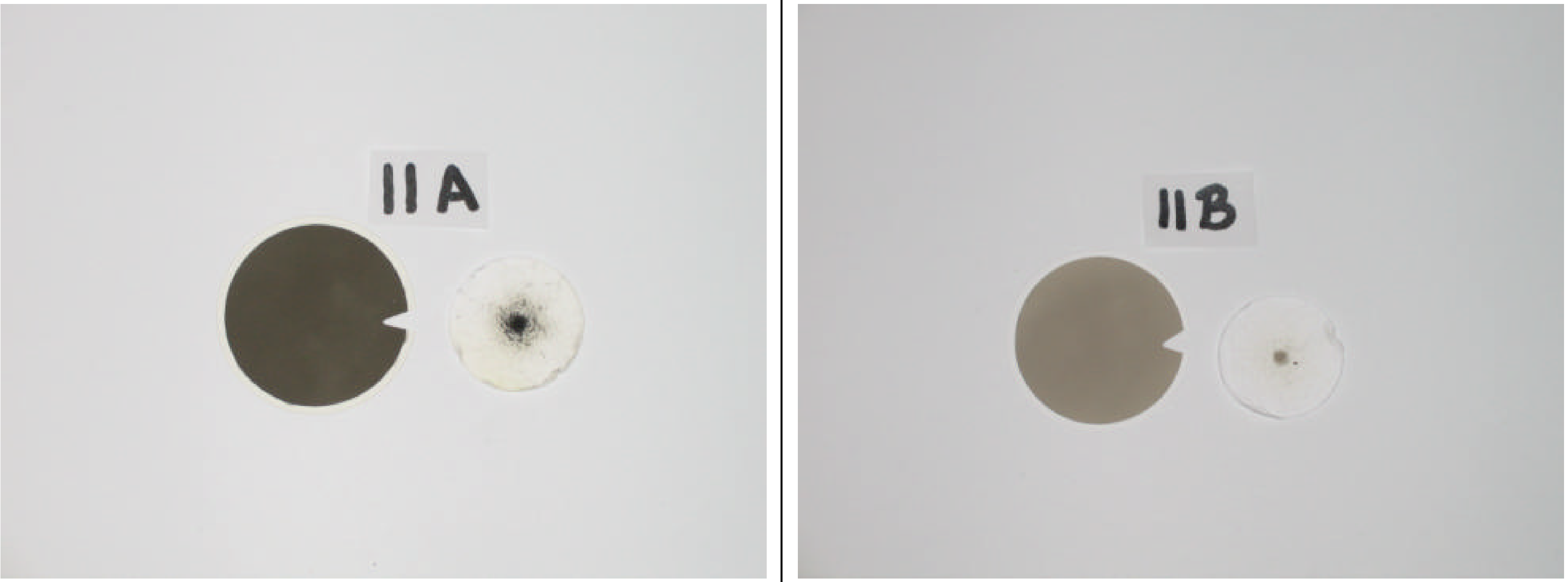


1997 Freightliner (834,028 miles)

2003 Freightliner (154,156 miles)

Figure 4.11. Brown and beige PM collected on filter media during emission testing.

Notes: Diameter of large filter and small filter are 37 mm and 25 mm, respectively; each frame represents a different test truck.



1999 Freightliner (482,983 miles)

2003 Mack (58,047 miles)

Figure 4.12. Black and gray PM collected on filter media during emission testing.

Notes: Diameter of large filter and small filter are 37 mm and 25 mm, respectively; each frame represents a different test truck.

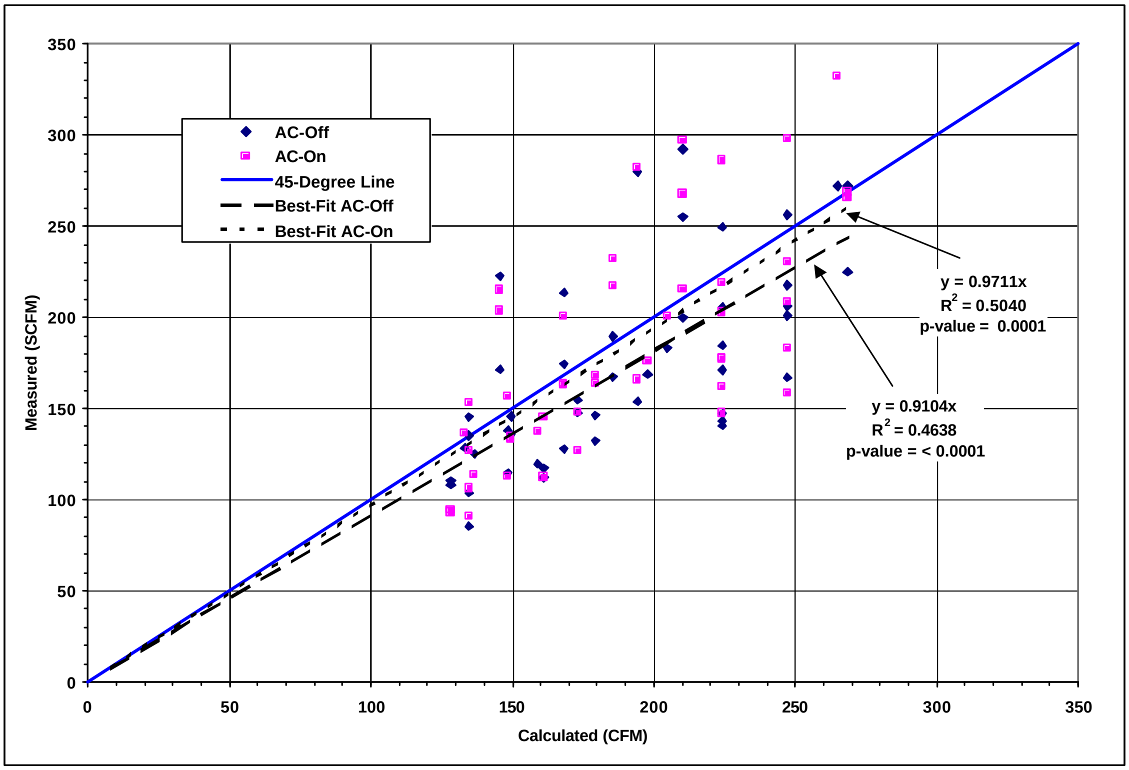


Figure 4.13. Measured versus calculated diesel exhaust flow rate.

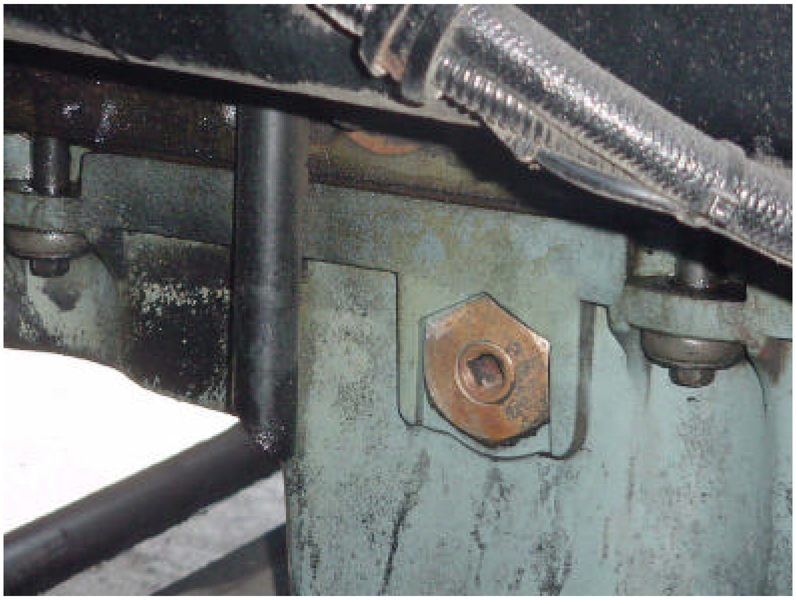


Figure 7.1. Diesel-engine blow-by ventilation.

Note: Vertical blow-by tube is located to the left of large bolt-shaped object centered in photograph.

Appendix C

Sample Calculations

C1: Emission and Fuel Consumption Rates

C1.1: Carbon Dioxide Emission Rate

The CO concentration, as measured by the ECON analyzer, was 89.3 parts-per-million (ppm). The diesel-exhaust volumetric flow rate, as measured by the Kurz meter, was 272 standard cubic feet per minute (scfm). Both measuring locations were inside the primary sampling chamber.

For this example, the emission rate for CO was approximately 48 g/hr.

$$\mathrm{CO}_{\text{Emission Rate}} = \frac{89.3}{10^6} \cdot \left[\frac{28\,\text{g/mole}}{24.1\,\text{L/mole}}\right] \cdot \frac{\text{L}}{0.0353\,\text{ft}^3} \cdot \frac{272\,\text{ft}^3}{\text{min}} \cdot \frac{60\,\text{min}}{\text{hr}} \approx 48\,\frac{\text{g}}{\text{hr}}$$

Note: 28 g/mole is the gram molecular weight of CO; 24.1 L/mole is the volume of gas at standard conditions [i.e., temperature 68 F (20 C) and 1-atmosphere], which are the temperature and pressure conditions for reporting flow by the Kurz meter; [(L/0.0353 ft^3) and (60 min/hr)] are conversion factors.

C1.2: Nitrogen Oxide Emission Rate

The NO and NO_2 concentrations, as measured by the ECON analyzer, were 276 ppm and 24 ppm, respectively. The diesel-exhaust volumetric flow rate, as measured by the Kurz meter, was 272 scfm. Both measuring locations were inside the primary sampling chamber.

For this example, the emission rate for NOx, reported, as NO_2, was approximately

265 g/hr;

$$\mathrm{NOx}_{\text{ Emission Rate}} = \frac{(276+24)}{10^6}\cdot\left[\frac{46\,\mathrm{g/mole}}{24.1\mathrm{L/mole}}\right]\cdot\frac{\mathrm{L}}{0.0353\,\mathrm{ft}^3}\cdot\frac{272\,\mathrm{ft}^3}{\mathrm{min}}\cdot\frac{60\,\mathrm{min}}{\mathrm{hr}}\approx 265\,\frac{\mathrm{g}}{\mathrm{hr}}$$

Note: 46 g/mole is the gram molecular weight of NO_2; 24.1 L/mole is the volume of gas at the standard conditions [i.e., temperature 68 F (20 C) and 1-atmosphere], which are the temperature and pressure conditions for reporting flow by the Kurz meter; [(L/0.0353 ft^3) and (60 min/hr)] are conversion factors.

C1.3: Particulate Matter Emission Rate

The PM could not be measured directly in the primary sampling chamber because the exhaust gas temperature was above the recommended operating temperature for the PM analyzer. Thus, ambient air was mixed with exhaust gas in the dilution chamber to reduce the temperature of the exhaust gas. This dilution system required additional flow components to provide information about the mixing ratio and to coordinate the functions of the system. The flow rates in the dilution chamber were measured by rotameters. They were factory calibrated to operate at specific conditions, which required correction for the calibration to be valid. Equation 1 was used to convert the observed readings (OBS) on the rotameter to standard conditions (STD) of temperature and pressure. Standard conditions for air are 1-atmoshpere of pressure and 68 F (20 C) of temperature. Equation 2 was used to convert the standard conditions to the actual conditions (ACT) of temperature and pressure. It is assumed that pressure was identical at all conditions. Thus, both equations reduce to a function of the temperatures.

$$Q_{STD} = Q_{OBS}\sqrt{\frac{P_{OBS}\cdot T_{STD}}{P_{STD}\cdot T_{OBS}}} \approx Q_{OBS}\sqrt{\frac{T_{STD}}{T_{OBS}}} \qquad (1)$$

$$Q_{STD} = Q_{OBS}\sqrt{\frac{P_{OBS}\cdot T_{STD}}{P_{STD}\cdot T_{OBS}}}\cdot\left[\left(\frac{P_{STD}}{P_{ACT}}\right)\cdot\left(\frac{T_{ACT}}{T_{STD}}\right)\right] \approx Q_{OBS}\sqrt{\frac{T_{STD}}{T_{OBS}}}\cdot\left(\frac{T_{ACT}}{T_{STD}}\right) \qquad (2)$$

where, Q is flow rate in units of volume per time, and P and T are absolute pressure and temperature, respectively.

The DataRAM analyzer measured $PM_{2.5}$ concentration inside the dilution chamber. Flow rate control for the analyzer was automatic; constant flow was maintained by sensing differential pressure across an orifice and using the pressure drop signal to control a variable pump motor. The function relationship between the orifice pressure drop (ΔP) and volumetric flow rate (Q) is given by the equation: $\Delta P = k\rho Q^2$;

where k is a system constant related to the characteristics of the orifice; ρ is the air density during the factory calibration for conditions of temperature and pressure, which existed at the time of calibration. Here, these conditions are assumed to be at the average room conditions for ambient air [i.e., temperature 70 F (21.1 C) and pressure 1-atmosphere]. Similar to the equations for the rotameters, flow rate at the inlet to the PM analyzer must also be converted to actual conditions of temperature and pressure, which will be demonstrated in subsequent examples.

The functional relationship between orifice pressure and flow rate: $\frac{?\,P}{k} = ?\,Q^2$

Thus, $?_{AIR}Q_{DR}^2 = ?_4 Q_4^2$

and $Q_4 = Q_{DR}\sqrt{\frac{?_{AIR}}{?_4}}$

where,

ρ_{AIR} = air density (g/m^3) at factory calibration of temperature and pressure conditions,

ρ_4 = density of sample diluted exhaust gas (g/m^3)

Q_{DR} = user specified (fixed) sampling flow rate (2 L/min), and

Q_4 = actual sampling flow rate (L/min).

The unknown values are Q_1, Q_4, ρ_3 and ρ_4. In the mixing region of the dilution chamber, it is assumed that $\rho_3 = \rho_4$. Hence, there are 3-unknowns quantities and 3-equations. The following approach only relied on the mass balance equation. It was assumed that the molecular weights of air, diesel exhaust gas, and the mixture of ambient air and diesel exhaust gas were all equivalent. The basis for this assumption was discussed in the body of the report. The numerical subscripts refer to the flow locations on the dilution-sampler; also see Figure 3-1.

Mass balance: $\dot{M}_1 + \dot{M}_2 = \dot{M}_3 + \dot{M}_4$

where, $\dot{M}_i$ = mass flow rate (g/hr) and $\dot{M}_i = ?_i Q_i$

where, ρ_i = density (g/m^3) and Q_i = volumetric flow rate (m^3/hr)

Thus, $?_1 Q_1 + ?_2 Q_2 = ?_3 Q_3 + ?_4 Q_4$ (3)

From the Ideal Gas Law: $? = \frac{m}{V} = \frac{P\ MW}{R\ T}$

where, ρ = density (kg/m^3),

m = mass (kg),

V = volume (m^3),

P = absolute pressure (atm),

MW = molecular weight (g/gmol),

R = universal gas constant (0.08206 atm-L/gmol-K) and

T = absolute temperature (K).

The ideal gas equation was substitution into Equation 3, yielding:

$$\frac{P_1\ MW_1}{R\ T_1} Q_1 + \frac{P_2\ MW_2}{R\ T_2} Q_2 = \frac{P_3\ MW_3}{R\ T_3} Q_3 + \frac{P_4\ MW_4}{R\ T_4} Q_4 \qquad (4)$$

Assumptions: $MW_1 = MW_2 = MW_3 = MW_4 = MW_{AIR}$ and $P_1 = P_2 = P_3 = P_4 = P_{AIR}$

Simplification of Equation 4, yields: $\frac{Q_1}{T_1} + \frac{Q_2}{T_2} = \frac{Q_3}{T_3} + \frac{Q_4}{T_4}$

Q_1 is the unknown, thus $Q_1 = T_1 \left[\left(\frac{Q_3}{T_3} + \frac{Q_4}{T_4} \right) - \frac{Q_2}{T_2} \right]$ (5)

Next, the DataRAM and rotameter temperature corrections were applied to Equation 5.

(Again, the assumption that all molecular weights and pressures are equivalent.)

$$Q_4 = Q_{DR}\sqrt{\frac{?_{AIR}}{?_4}} = Q_{DR}\sqrt{\frac{P_{AIR}\ MW_{AIR} \big/ R\ T_{AIR}}{P_4\ MW_4 \big/ R\ T_4}} \approx Q_{DR}\sqrt{\frac{T_4}{T_{AIR}}}$$

and

$$Q_2\ \ \&\ \ Q_3 \quad \Rightarrow \quad Q_{2\ or\ 3}^{STD} = Q_{OBS}\sqrt{P_{OBS}T_{STD} \big/ P_{STD}T_{OBS}} = Q_{2\ or\ 3}\sqrt{T_{STD} \big/ T_{2\ or\ 3}}$$

Substitution of Q_2, Q_3 and Q_4, yields:

$$Q_1 = T_1\left[\left(\frac{Q_3\sqrt{T_{STD} \big/ T_3}}{T_3} + \frac{Q_{DR}\sqrt{T_4 \big/ T_{AIR}}}{T_4}\right) - \frac{Q_2\sqrt{T_{STD} \big/ T_2}}{T_2}\right]$$

Since the conditions in the original equation were at actual temperatures, and the conditions in the above equation for Q_2 and Q_3 are at standard conditions, the conditions for Q_2 and Q_3 must be converted to actual conditions of temperature.

$$Q_1 = T_1\left[\left(\frac{Q_3\sqrt{T_{STD} \big/ T_3}\cdot\left(\frac{T_3}{T_{STD}}\right)}{T_3} + \frac{Q_{DR}\sqrt{T_4 \big/ T_{AIR}}}{T_4}\right) - \frac{Q_2\sqrt{T_{STD} \big/ T_2}\cdot\left(\frac{T_2}{T_{STD}}\right)}{T_2}\right] \qquad (6)$$

Finally, simplifying Equation 6, yields:

$$Q_1 = T_1\left[\left(\frac{Q_3\sqrt{T_{STD} \big/ T_3}}{T_{STD}} + \frac{Q_{DR}\sqrt{T_4 \big/ T_{AIR}}}{T_4}\right) - \frac{Q_2\sqrt{T_{STD} \big/ T_2}}{T_{STD}}\right]$$

Now that the flow rate into the dilution chamber (Q_1) is known, the concentration of PM (C_1) in the primary sampling chamber can be determined from the following mass balance equation:

Mass balance: $C_1Q_1 + C_2Q_2 = C_3Q_3 + C_4Q_4$ (7)

where, C_i = PM concentration ($\mu g/m^3$)

Since the dilution air was filtered with a HEPA filter at location 2 in Figure 3-1; $C_2 = 0$.

The PM concentration as measured by DataRAM was C_4.

Inside the mixing chamber, $C_4 = C_3$; thus, Equation 7 can be reduced, yielding:

$$C_1 = C_4 \frac{(Q_3 + Q_4)}{Q_1}$$

It should be noted that the C_iQ_i pairs must be evaluated at the same conditions of temperature, so Q_3, Q_4 and C_4 will be evaluated here at standard temperature conditions.

Using the following values for this example calculation:

$T_1 = (460 + 229.2) = 689.2$ R
$T_3 = (460 + 64.5)$ 524.5 R
$T_{AIR} = (460 + 70) = 530$ R
$Q_2 = 30$ cfh
$Q_{DR} = 4.24$ cfh (2 Lpm)

$T_2 = (460 + 57.3) = 517.3$ R
$T_4 = (460 + 86) = 546$ R
$T_{STD} = (460 + 68)$ 528 R
$Q_3 = 35$ cfh
$C_4 = 1{,}481$ $\mu g/m3$

$$Q_1^{ACT} = 689.2\left[\left(\frac{35\frac{ft^3}{hr}\sqrt{528/524.5}}{528} + \frac{4.24\frac{ft^3}{hr}\sqrt{546/530}}{546}\right) - \frac{30\frac{ft^3}{hr}\sqrt{528/517.3}}{528}\right] \approx 11.71\frac{ft^3}{hr}$$

$$Q_3^{STD} = Q_3\sqrt{T_{STD}/T_3} = 35\frac{ft^3}{hr}\sqrt{528/524.5} \approx 35.12\frac{ft^3}{hr}$$

$$Q_4^{STD} = Q_{DR}\sqrt{T_4/T_{AIR}} \cdot \left(\frac{T_{STD}}{T_4}\right) = 4.24\frac{ft^3}{hr}\sqrt{546/530} \cdot \left(\frac{528}{546}\right) \approx 4.162\frac{ft^3}{hr}$$

Thus, the actual concentration in the primary sampling chamber is:

$$C_1^{ACT} = C_4\left(\frac{T_4}{T_{STD}}\right)\cdot\frac{\left(Q_3^{STD}+Q_4^{STD}\right)}{Q_1^{ACT}} = 1{,}481\frac{\mu g}{m^3}\left(\frac{546}{528}\right)\cdot\frac{(35.12+4.162)}{11.71} \approx 5{,}138\frac{\mu g}{m^3}$$

The dilution ratio for this example is approximately 3.4:

where, $Q_2^{ACT} = Q_2\sqrt{{T_{STD}}/{T_2}}\cdot\left(\frac{T_2}{T_{STD}}\right) = 30\sqrt{{528}/{517.3}}\cdot\left(\frac{517.3}{528}\right) \approx 29.69\,\frac{ft^3}{hr}$

$$\text{Dilution Ratio} = \frac{Q_2^{STD}}{Q_1^{STD}} = \frac{Q_2^{ACT}\left({T_{STD}}/{T_2}\right)}{Q_1^{ACT}\left({T_{STD}}/{T_1}\right)} = \frac{Q_2^{ACT}\ T_1}{Q_1^{ACT}\ T_2} = \frac{29.69\,(689.2)}{11.71\,(517.3)} \approx 3.38$$

Finally, the PM emission rate was calculated by multiplying the adjusted PM concentration (C_1) by the Kurz flow rate from the primary sampling chamber.

For this example, the emission rate for $PM_{2.5}$ is approximately 3.1 g/hr.

$$PM_{\text{Emission Rate}} = \frac{5{,}138\,\mu g}{m^3}\cdot\left(\frac{460+229.2}{528}\right)\cdot\frac{g}{10^6\mu g}\cdot\frac{m^3}{35.3\,ft^3}\cdot\frac{272\,ft^3}{min}\cdot\frac{60\,min}{hr} \approx 3.1\frac{g}{hr}$$

Note: the temperature ratio [(460 + 229)/528] converted temperature into standard conditions, which is equivalent to the Kurz flow meter (i.e., 272 scfm); the values [(35.3 ft^3/m^3) and ($g/10^6$ μg)] are conversion factors.

Finally, the PM emission rate is adjusted by the integrated gravimetric sample that was collected on the internal filter. For example, if the time weighted average (TWA) reading on the DataRAM was 4.2426 mg/m^3 for a reference period (T_R) of 359.5 minutes (~ 6 hrs) and the sampling flow rate for the DataRAM (Q_{DR}) was 2-lpm, then the calculated average gravimetric concentration (C_G), is as follows:

$$C_G = \frac{m}{T_R\ Q_{DR}} = \frac{3.4\,mg}{359.5\,min\,(2\,lpm)}\cdot\frac{1000\,L}{m^3} \approx 4.7\frac{mg}{m^3}$$

The calibration factor (CAL) for this testing period, is as follows:

$$\mathrm{CAL} = \frac{\mathrm{C_G}}{\mathrm{TWA}} = \frac{4.7\,\mathrm{mg}/\mathrm{m}^3}{4.2426\,\mathrm{mg}/\mathrm{m}^3} \approx 1.1$$

Thus, the corrected PM emission rate is approximately 3.4 g/hr

$$\mathrm{PM}_{\text{Emission Rate}} = (1.1)\cdot 3.1\frac{\mathrm{g}}{\mathrm{hr}} \approx 3.4\frac{\mathrm{g}}{\mathrm{hr}}$$

Note: For purposes of this paper, the Molecular Weight (MW) of the exhaust gas can be approximated by the following equations.

$$\%\mathrm{N}_2 = 100 - (\%\mathrm{O}_2 + \%\mathrm{CO}_2)$$

$$\mathrm{MW}_{\text{Exhaust Gas}} = 32\left(\frac{\%\mathrm{O}_2}{100}\right) + 44\left(\frac{\%\mathrm{CO}_2}{100}\right) + 28\left(\frac{\%\mathrm{N}_2}{100}\right)$$

where, $\%O_2$ = Percent oxygen as measured by ECOM analyzer,

$\%CO_2$ = Percent carbon dioxide as calculated/reported by ECOM analyzer and

$\%N_2$ = Percent nitrogen also approximated.

For example, $\%O_2 = 16.5$ and $\%CO_2 = 3.3$:

$$\mathrm{MW}_{\text{Exhaust Gas}} = 32\left(\frac{16.5}{100}\right) + 44\left(\frac{3.3}{100}\right) + 28\left(\frac{100-(16.5+3.3)}{100}\right) \approx 29.19$$

C1.4: Diesel Fuel Consumption Rate

The Ideal Gas Law {PV = (m_i/MW_i)RT} was used to convert the percent of carbon dioxide (CO_2), which was measured in the exhaust of the vehicle, into concentration at standard conditions of pressure and temperature:

$$\frac{m_{CO2}}{V_{AIR}} = \frac{V_{CO2}}{V_{AIR}}\left(\frac{P \cdot MW_{CO2}}{R_U \cdot T}\right)$$

where,

m_{CO2} = mass of carbon dioxide (CO_2)

V_{AIR} = volume of air

V_{CO2} = volume of CO_2

P = absolute pressure of air

MW_{CO2} = molecular weight of CO_2

R = universal gas constant, using (0.08208 atm L/gmol K)

T = absolute temperature of air

From the ECON analyzer, CO_2 = 2.31%, thus, the concentration of CO_2 in air is:

$$\frac{m_{CO2}}{V_{AIR}} = \frac{2.31}{100}\left(\frac{1\text{atm} \cdot (44\,\text{g/mole}) \cdot (1{,}000\,\text{L/m}^3)}{(0.08208\,\text{atm - L/mole - K}) \cdot (273 + 20)\,\text{K}}\right) = 42.3\frac{\text{g}}{\text{m}^3}$$

Using the vehicle exhaust gas flow rate (Q) and the CO_2 concentration, the production of CO_2 (on an average per hour basis) can be calculated:

$$\dot{M}_{CO_2} = Q\frac{m_{CO2}}{V_{AIR}}$$

where, M_{CO2} = mass flow rate of CO_2

Q = volumetric vehicle exhaust flow rate

From the Kurz flow meter, Q = 137.44 scfm,

thus, the mass flow rate of CO_2 from the exhaust of the vehicle is approximately :

$$\dot{M}_{CO_2} = \left(137.44\frac{ft^3}{min}\cdot\frac{m^3}{35.32\,ft^3}\cdot\frac{60\,min}{hr}\right)42.3\frac{g}{m^3} = 9{,}867\frac{g}{hr}$$

The mass of carbon in diesel fuel ($M_{C/D}$) in units of (g/gal) was calculated with:

$$M_{C/D} = \left(WF_{C/D}\right)?_{DIESEL}$$

where, ρ_{DIESEL} = density of diesel fuel (~3,212 g/gal) and

$WR_{C/D}$ = weight fraction of carbon in diesel fuel from the relation $CH_{1.80}$

$$WF_{C/D} = \frac{12.011}{[12.011 + (1.80\cdot 1.008)]} = 0.869$$

thus, $M_{C/D} = \left(0.869\right)\cdot 3{,}212\ g/gal = \frac{2{,}791\,g}{gal}$

Finally, the average diesel fuel rate (FR) in units of (gal/hr) was calculated using:

$$\overline{FR} = \frac{\dot{M}_{CO2}\cdot WF_{C/CO2}}{M_{C/D}}$$

where, $WF_{C/CO2}$ = weight fraction of carbon in carbon dioxide (i.e., 12.011/44.099)

$$\overline{FR} = \frac{9{,}867\ g/hr\cdot(12.011/44.009)}{2{,}791\,g/gal} \approx 0.965\frac{gal}{hr}$$

Thus, for this example, the diesel fuel rate was approximately 0.97 gal/hr.

C2: Truck Stop Electrification Estimates

C2.1: Annual Idling Emissions for Heavy-Duty Diesel Vehicles

A set of sample calculations is demonstrated below using the average NOx emission factor from the current study (i.e., 167 g/hr).

Estimated daily average idling NOx emissions are 0.00441 tons/day for a single truck:

$$\text{Single Truck} = \frac{167\,\text{g}}{\text{hrs}} \cdot \frac{24\,\text{hrs}}{\text{day}} \cdot \frac{\text{lbs}}{454\,\text{g}} \cdot \frac{\text{ton}}{2{,}000\,\text{lbs}} = 0.00441\frac{\text{tons}}{\text{day}}$$

Estimated annual NOx emissions for a single truck are 1.61 tons/year:

$$\text{Single Truck} = 0.00441\frac{\text{ton}}{\text{day}} \cdot \frac{365\,\text{day}}{\text{year}} = 1.61\frac{\text{tons}}{\text{year}}$$

Total parking spaces for the contiguous US are approximately 315,535 spaces.[42] (284,675 commercial spaces + 30,860 public spaces = 315,535 total spaces)

Using only half of the daily average fraction of idling trucks (i.e., 0.53) from truck counting experiments[43] conducted locally at the Petro Truck Travel Center, as a conservative estimate (i.e., 0.5 x 0.53 = 0.265), the average idling NOx emissions are approximately 135,000 tons/year:

$$\text{NOx Emissions Contiguous US} \approx (0.265 \cdot 315{,}535\,\text{spaces}) \cdot \frac{1.61\,\text{tons}}{\text{year}} \approx 135{,}000\,\frac{\text{tons}}{\text{year}}$$

C2.2: Carbon Monoxide at Cold-Start

Cold-Start Emission Rate (CSER) - Example for CS-5

$$\mathrm{CSER}_{\mathrm{i}} = \frac{\mathrm{CSEF} \cdot \left(\dfrac{t_{\mathrm{B}}}{60 \ \mathrm{min}/\mathrm{hr}} \right)}{t_{\mathrm{A}}}$$

$$\mathrm{CSER}_{\mathrm{CO}} = \frac{180 \ \mathrm{g}/\mathrm{hr} \cdot \left(\dfrac{5 \, \mathrm{min}}{60 \ \mathrm{min}/\mathrm{hr}} \right)}{8 \, \mathrm{hr}} = 1.88 \ \mathrm{g}/\mathrm{hr}$$

Electricity-Use Emission Rate (EUER)

$$\mathrm{EUER}_{\mathrm{CO}} = \left(\mathrm{ECES}_{\mathrm{CO}} \cdot \frac{453.6 \ \mathrm{g}}{\mathrm{lb}} \cdot \frac{1}{\mathrm{e}} \right) \cdot \left(\mathrm{WP} \cdot \frac{3.412 \ \mathrm{Btu}/\mathrm{hr}}{\mathrm{watt}} \cdot \frac{\mathrm{L}}{100} \right)$$

$$\mathrm{EUER}_{\mathrm{CO}} = \left(0.5 \ \mathrm{lb}/\mathrm{ton} \cdot \left(\frac{\mathrm{ton}}{26\mathrm{x}10^{6} \ \mathrm{Btu}} \right) \cdot \frac{453.6 \ \mathrm{g}}{\mathrm{lb}} \cdot \frac{1}{0.35} \right) \cdot \left(2{,}200 \ \mathrm{watts} \cdot \frac{3.412 \ \mathrm{Btu}/\mathrm{hr}}{\mathrm{watt}} \cdot \frac{100}{100} \right)$$

$$= 0.19 \ \mathrm{g}/\mathrm{hr}$$

Actual Emission Reduction Rate (AERR)

$$\mathrm{AERR}_{\mathrm{CO}} = \mathrm{EIER}_{\mathrm{CO}} - \left(\mathrm{CSER}_{\mathrm{CO}} + \mathrm{EUER}_{\mathrm{CO}} \right)$$

$$\mathrm{AERR}_{\mathrm{CO}} = 64.5 \ \mathrm{g}/\mathrm{hr} - \left(1.88 \ \mathrm{g}/\mathrm{hr} + 0.19 \ \mathrm{g}/\mathrm{hr} \right) = 62.4 \ \mathrm{g}/\mathrm{hr}$$

C2.3: Nitrogen Oxides at Cold-Start

Cold-Start Emission Rate (CSER) - Example for CS-5

$$\mathrm{CSER}_{\mathrm{NOx}} = \frac{248\ {}^{\mathrm{g}}\!/_{\mathrm{hr}} \cdot \left(\dfrac{5\,\mathrm{min}}{60\ {}^{\mathrm{min}}\!/_{\mathrm{hr}}} \right)}{8\,\mathrm{hr}} = 2.58\,{}^{\mathrm{g}}\!/_{\mathrm{hr}}$$

Electricity-Use Emission Rate (EUER)

$$\mathrm{EUER}_{\mathrm{NOx}} = \left(0.6\ {}^{\mathrm{lb}}\!/_{10^{6}\,\mathrm{Btu}} \cdot \frac{453.6\,\mathrm{g}}{\mathrm{lb}} \cdot \frac{1}{0.35} \right) \cdot \left(2{,}200\ \mathrm{watts} \cdot \frac{3.412\ {}^{\mathrm{Btu}}\!/_{\mathrm{hr}}}{\mathrm{watt}} \cdot \frac{100}{100} \right)$$

$$= 5.84\ {}^{\mathrm{g}}\!/_{\mathrm{hr}}$$

Actual Emission Reduction Rate (AERR)

$$\mathrm{AERR}_{\mathrm{NOx}} = 167\ {}^{\mathrm{g}}\!/_{\mathrm{hr}} - \left(2.58\ {}^{\mathrm{g}}\!/_{\mathrm{hr}} + 5.84\ {}^{\mathrm{g}}\!/_{\mathrm{hr}} \right) = 159\ {}^{\mathrm{g}}\!/_{\mathrm{hr}}$$

C2.4: Particulate Matter at Cold-Start

Cold-Start Emission Rate (CSER) - Example for CS-5

$$\mathrm{CSER}_{\mathrm{PM2.5}} = \frac{5.99\ {}^{\mathrm{g}}\!/_{\mathrm{hr}} \cdot \left(\dfrac{5\,\mathrm{min}}{60\ {}^{\mathrm{min}}\!/_{\mathrm{hr}}} \right)}{8\,\mathrm{hr}} = 0.0624\,{}^{\mathrm{g}}\!/_{\mathrm{hr}}$$

Electricity-Use Emission Rate (EUER)

$$\mathrm{EUER}_{\mathrm{PM2.5}} = \left(0.03 \ {}^{\mathrm{lb}}\!\big/_{10^6\,\mathrm{Btu}} \cdot \frac{453.6\ \mathrm{g}}{\mathrm{lb}} \cdot \frac{1}{0.35}\right) \cdot \left(2{,}200\ \mathrm{watts} \cdot \frac{3.412\ {}^{\mathrm{Btu}}\!\big/_{\mathrm{hr}}}{\mathrm{watt}} \cdot \frac{100}{100}\right)$$

$$= 0.29\ {}^{\mathrm{g}}\!\big/_{\mathrm{hr}}$$

Actual Emission Reduction Rate (AERR)

$$\mathrm{AERR}_{\mathrm{PM2.5}} = 3.54\ {}^{\mathrm{g}}\!\big/_{\mathrm{hr}} - \left(0.0624\ {}^{\mathrm{g}}\!\big/_{\mathrm{hr}} + 0.29\ {}^{\mathrm{g}}\!\big/_{\mathrm{hr}}\right) = 3.19\ {}^{\mathrm{g}}\!\big/_{\mathrm{hr}}$$

Appendix D

Summary of Truck Data

Table D.1: CO cold-start and extended idling emission factors at engine rpm speeds and air-conditioner settings

ID	Vehicle	CS-SS	CS-5	CS-10	CS-15	600		650		700		750		800		1000	
						AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On
1	Freightliner	41.47	79.02	72.82	67.69							39.55	49.27			52.57	63.34
2	Freightliner	217.72	334.44	318.78	300.79									76.10	145.92	150.23	133.15
3	Volvo	32.58	21.46	24.11	24.33	22.86	16.66			30.91	31.71						
4	Volvo	32.15	43.00	35.92	32.02	19.58	16.03			25.77	31.33						
5	Mack	73.44	118.02	90.17	79.49			36.82	55.17							69.65	129.58
6	Kenworth	21.33	26.08	24.47	23.34	12.84	14.96									48.78	64.00
7	International	55.65	82.69	71.64	67.14									34.38	35.48	59.75	49.97
8	Kenworth	30.61	38.00	35.98	34.43	12.92	20.20									39.18	63.74
9	Volvo	36.91	76.28	64.29	59.05	19.62	16.14									47.33	46.28
10	Freightliner	43.71	47.44	50.71	49.67							29.58	29.93			45.67	48.16
11	Freightliner	57.01	89.11	80.08	77.74	34.92	31.46									50.63	67.03
12	International	86.69	137.50	116.90	109.49							42.65	52.03			49.20	52.88
13	International	32.99	34.78	33.78	33.35	25.35	27.13									72.60	81.52
14	Freightliner	83.67	155.20	125.25	110.40	41.78	62.54									93.05	193.24
15	Freightliner	37.55	107.42	87.24	78.03	15.20	25.07					16.50	31.57				
16	Freightliner	52.65	168.10	160.95	151.41	31.15	27.88									74.91	104.03
17	Freightliner	74.71	198.76	169.67	138.18					45.21	50.37					60.31	68.20
18	Freightliner	162.69	1002	827	666	50.78	60.93									157.53	207.67
19	Mack	61.95	156.54	146.49	135.49									47.60	46.44	44.06	52.48
20	Freightliner	260.58	686.91	696.52	577.09							80.67	151.17			148.72	236.13
21	Freightliner	101.79	179.71	158.75	149.33					42.99	55.23					59.52	86.68
22	Freightliner	107.57	145.93	127.58	130.91									44.61	82.47	61.80	102.42
23	Mack	92.24	158.29	156.09	160.58									66.14	52.03	48.64	57.60
24	Mack	89.19	243.42	229.31	217.05			50.53	66.86							133.12	168.19
	Average =	78.6	180	163	145	26.1	29.0	43.7	61.0	36.2	42.2	41.8	62.8	53.8	72.5	74.6	98.9
	Stdev =	59.4	223	198	161	12.3	17.1	9.69	8.26	9.38	12.4	24.0	50.4	17.0	44.6	38.4	57.6
	%RD =	75.6	123	122	112	47.3	59.0	22.2	13.5	25.9	29.5	57.5	80.3	31.5	61.6	51.5	58.3
	n =	24	24	24	24	11	11	2	2	4	4	5	5	5	5	21	21

Notes: Emission factors units = (g/hr); CS-SS = Engine cold-start to reach steady-state condition, typically 1-3 hours in duration; CS-5, -10 & -15 = Engine cold-start during the first 5, 10 & 15 minutes, respectively; AC = Air-conditioner at Off and On settings; %RD = Percent relative standard deviation (Stdev/Average)x100.

Table D.2: NOx cold-start and extended idling emission factors at engine rpm speeds and air-conditioner settings

ID	Vehicle	CS-SS	CS-5	CS-10	CS-15	600		650		700		750		800		1000	
						AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On
1	Freightliner	169.59	335.36	323.91	305.56							139.99	249.50			154.64	255.31
2	Freightliner	198.36	243.64	226.27	216.02									130.14	181.14	170.93	173.28
3	Volvo	347.87	152.44	183.88	173.82	102.05	102.19			127.61	138.89						
4	Volvo	132.01	199.77	189.66	179.12	103.30	101.09			122.72	137.16						
5	Mack	122.15	146.50	135.23	127.93			77.87	98.62							191.65	267.53
6	Kenworth	109.14	112.30	110.80	110.44	78.31	95.59									101.02	110.04
7	International	277.88	336.02	317.56	306.42									173.62	225.58	180.54	208.85
8	Kenworth	143.14	169.95	157.93	153.36	92.49	126.81									94.76	125.87
9	Volvo	113.60	138.07	139.38	141.16	63.05	87.53									128.17	135.64
10	Freightliner	204.03	222.79	241.26	234.47							140.46	162.48			195.38	212.84
11	Freightliner	185.04	262.50	251.93	249.50	90.32	123.83									105.45	171.73
12	International	273.53	544.72	454.48	385.65							120.48	192.54			112.60	139.54
13	International	134.46	154.19	152.82	148.06	95.21	135.64									234.18	307.26
14	Freightliner	217.55	269.85	262.27	255.31	114.38	185.09									206.95	304.08
15	Freightliner	226.75	329.14	312.82	294.56	115.58	175.79					149.87	225.33				
16	Freightliner	198.99	321.19	316.43	315.35	137.71	180.64									199.17	316.36
17	Freightliner	149.83	293.64	272.46	235.15					132.01	142.92					159.36	373.72
18	Freightliner	64.65	88.44	76.17	83.52	55.74	74.03									111.94	110.27
19	Mack	153.17	261.27	253.76	242.11									111.52	123.82	150.36	175.53
20	Freightliner	162.74	158.35	180.06	164.56							128.08	180.77			154.94	161.68
21	Freightliner	170.62	257.98	216.18	199.97					158.16	172.50					229.88	271.26
22	Freightliner	373.81	397.49	412.24	411.21									237.87	398.10	242.77	483.33
23	Mack	186.07	310.15	295.33	276.87									142.57	158.83	204.07	243.65
24	Mack	169.63	239.35	193.69	193.69			107.88	116.34							122.18	140.37
	Average =	187	248	237	225	95.3	126	92.9	107	135	148	136	202	159	217	164	223
	Stdev =	72.8	103	92.2	83.9	23.7	39.2	21.2	12.5	15.8	16.6	11.5	35.0	49.5	107	46.5	96.5
	%RD =	39.0	41.7	39.0	37.3	24.9	31.0	22.8	11.7	11.7	11.2	8.49	17.3	31.1	49.4	28.3	43.2
	n =	24	24	24	24	11	11	2	2	4	4	5	5	5	5	21	21

Notes: Emission factors units = (g/hr); CS-SS = Engine cold-start to reach steady-state condition, typically 1-3 hours in duration; CS-5, -10 & -15 = Engine cold-start during the first 5, 10 & 15 minutes, respectively; AC = Air-conditioner at Off and On settings; %RD = Percent relative standard deviation (Stdev/Average)x100.

Table D.3: PM cold-start and extended idling emission factors at engine rpm speeds and air-conditioner settings

ID	Vehicle	CS-SS	CS-5	CS-10	CS-15	600		650		700		750		800		1000	
						AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On
1	Freightliner	3.97	2.37	2.66	2.82							4.94	5.42			8.29	7.57
2	Freightliner																
3	Volvo																
4	Volvo																
5	Mack																
6	Kenworth																
7	International																
8	Kenworth																
9	Volvo	1.70	0.88	1.00	1.15	2.17	2.34									5.27	5.28
10	Freightliner	7.47	3.31	3.55	4.07							4.17	4.71			7.48	11.69
11	Freightliner	1.80	2.23	2.16	1.99	1.15	1.00									1.33	2.11
12	International	7.03	3.02	3.85	3.99							5.20	9.32			4.68	9.02
13	International	1.68	1.08	1.05	1.11	1.08	1.98									3.80	3.51
14	Freightliner	0.32	0.26	0.29	0.29	0.32	0.28									3.37	2.11
15	Freightliner	7.06	7.15	3.82	2.92	4.69	NA					11.87	16.38				
16	Freightliner	0.92	1.25	1.11	0.99	1.44	1.71									1.88	2.28
17	Freightliner	0.60	2.11	1.23	0.88					1.11	0.52					0.93	0.44
18	Freightliner	5.07	48.6	33.8	25.2	1.09	1.75									4.07	2.95
19	Mack	1.58	5.49	3.13	2.21									0.70	1.22	2.18	2.21
20	Freightliner	3.65	9.15	17.51	15.02							0.51	0.72			2.54	3.48
21	Freightliner	1.30	8.90	5.49	4.09					0.41	0.47					1.07	0.93
22	Freightliner	2.34	1.19	1.24	1.20									4.08	3.99	18.6	6.63
23	Mack	0.40	2.46	1.41	1.03									0.28	0.46	1.72	1.93
24	Mack	1.17	2.39	1.67	1.40			0.71	0.98							2.60	3.64
	Average =	2.83	5.99	5.00	4.14	1.71	1.51	0.71	0.98	0.76	0.50	5.34	7.31	1.69	1.89	4.37	4.11
	Stdev =	2.44	11.3	8.40	6.39	1.43	0.75			0.50	0.03	4.11	5.92	2.08	1.86	4.38	3.13
	%RD =	86.4	189	168	154	83.6	49.4			65.4	6.48	77.0	81.0	123	98.2	100	76.1
	n =	17	17	17	17	7	6	1	1	2	2	5	5	3	3	16	16

Notes: Emission factors units = (g/hr); CS-SS = Engine cold-start to reach steady-state condition, typically 1-3 hours in duration; CS-5, -10 & -15 = Engine cold-start during the first 5, 10 & 15 minutes, respectively; AC = Air-conditioner at Off and On settings; %RD = Percent relative standard deviation (Stdev/Average)x100.

Table D.4: NO_2/NOx ratio during cold-start and extended idling at engine rpm speeds and air-conditioner settings

ID	Vehicle	CS-SS	CS-5	CS-10	CS-15	600		650		700		750		800		1000	
						AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On
1	Freightliner	0.15	0.16	0.16	0.16							0.16	0.15			0.18	0.17
2	Freightliner	0.22	0.22	0.22	0.22									0.20	0.20	0.25	0.24
3	Volvo	0.15	0.20	0.15	0.14	0.19	0.14			0.20	0.17						
4	Volvo	0.15	0.16	0.15	0.15	0.16	0.14			0.16	0.14						
5	Mack	0.17	0.18	0.18	0.17			0.20	0.22							0.18	0.19
6	Kenworth	0.04	0.05	0.04	0.04	0.03	0.03									0.01	0.01
7	International	0.14	0.13	0.13	0.13									0.15	0.14	0.18	0.16
8	Kenworth	0.07	0.07	0.07	0.07	0.06	0.08									0.01	0.03
9	Volvo	0.13	0.09	0.10	0.11	0.17	0.14									0.18	0.17
10	Freightliner	0.11	0.09	0.09	0.10							0.13	0.12			0.14	0.14
11	Freightliner	0.11	0.10	0.10	0.10	0.14	0.12									0.17	0.14
12	International	0.16	0.14	0.14	0.15							0.19	0.18			0.20	0.19
13	International	0.20	0.16	0.16	0.17	0.23	0.20									0.22	0.20
14	Freightliner	0.22	0.22	0.22	0.21	0.25	0.22									0.27	0.27
15	Freightliner	0.11	0.15	0.14	0.14	0.12	0.12					0.11	0.11				
16	Freightliner	0.14	0.16	0.15	0.15	0.15	0.13									0.18	0.16
17	Freightliner	0.18	0.19	0.19	0.18					0.20	0.17					0.20	0.18
18	Freightliner	0.29	0.46	0.45	0.34	0.26	0.23									0.29	0.32
19	Mack	0.21	0.17	0.18	0.19									0.24	0.22	0.21	0.21
20	Freightliner	0.24	0.27	0.25	0.24							0.19	0.21			0.22	0.27
21	Freightliner	0.21	0.21	0.22	0.23					0.17	0.17					0.19	0.18
22	Freightliner	0.14	0.12	0.12	0.12									0.13	0.13	0.15	0.13
23	Mack	0.23	0.16	0.18	0.20									0.25	0.20	0.19	0.18
24	Mack	0.21	0.22	0.27	0.27			0.21	0.23							0.33	0.34
	Average =	0.17	0.17	0.17	0.17	0.16	0.14	0.21	0.23	0.18	0.17	0.15	0.15	0.20	0.18	0.19	0.18
	Stdev =	0.06	0.08	0.08	0.07	0.07	0.06	0.01	0.00	0.02	0.01	0.03	0.04	0.05	0.04	0.07	0.08
	%RD =	34.8	48.2	47.9	39.6	45.0	42.9	3.65	1.82	11.8	8.96	22.5	26.2	26.2	23.2	40.0	42.5
	n =	24	24	24	24	11	11	2	2	4	4	5	5	5	5	21	21

Notes: NO_2/NOx ratio (unitless); CS-SS = Engine cold-start to reach steady-state condition, typically 1-3 hours in duration; CS-5, -10 & -15 = Engine cold-start during the first 5, 10 & 15 minutes, respectively; AC = Air-conditioner at Off and On settings; %RD = Percent relative standard deviation (Stdev/Average)x100.

Table D.5: Fuel consumption rates for cold-start and extended idling at engine rpm speeds and air-conditioner settings

ID	Vehicle	CS-SS	CS-5	CS-10	CS-15	600		650		700		750		800		1000	
						AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On
1	Freightliner	1.31	2.19	2.05	1.95							1.22	1.69			1.72	2.38
2	Freightliner	2.28	2.61	2.52	2.47									1.60	1.99	2.25	2.19
3	Volvo	1.52	1.84	2.12	2.10	1.24	1.20			1.64	1.64						
4	Volvo	1.71	1.97	1.97	1.96	1.21	1.19			1.54	1.68						
5	Mack	3.11	1.58	2.33	2.96			1.11	1.14							0.86	1.15
6	Kenworth	0.70	0.71	0.71	0.71	0.44	0.57									1.25	1.48
7	International	1.36	1.68	1.56	1.51									0.92	1.08	1.17	1.23
8	Kenworth	0.95	1.05	1.01	1.00	0.54	0.79									1.14	1.61
9	Volvo	0.39	0.58	0.53	0.52	0.24	0.24									0.60	0.64
10	Freightliner	1.60	1.63	1.79	1.78							1.22	1.37			1.70	1.81
11	Freightliner	1.14	1.50	1.45	1.44	0.63	0.80									0.87	1.35
12	International	2.49	3.62	3.22	2.99							1.51	1.98			1.45	1.67
13	International	1.06	1.08	1.10	1.09	0.67	0.97									1.76	2.44
14	Freightliner	0.84	1.13	1.03	0.99	0.44	0.71									0.77	1.27
15	Freightliner	2.77	3.86	3.66	3.55	1.43	1.79					1.88	2.62				
16	Freightliner	1.71	2.19	2.29	2.36	1.39	1.52									1.95	2.34
17	Freightliner	2.77	4.38	4.26	3.72					2.97	2.69					3.35	3.32
18	Freightliner	1.42	3	3	3	1.07	1.21									1.88	1.94
19	Mack	1.05	1.28	1.24	1.20									0.90	0.97	1.33	1.50
20	Freightliner	3.54	3.99	4.40	3.92							2.45	3.24			3.28	3.49
21	Freightliner	2.11	2.56	2.27	2.19					2.07	2.14					2.76	2.96
22	Freightliner	1.17	1.35	1.33	1.35									0.60	1.05	0.64	1.16
23	Mack	1.03	1.23	1.17	1.13									0.92	0.99	1.33	1.43
24	Mack	0.76	1.21	1.08	1.02			0.59	0.69							0.94	1.08
	Average =	1.62	2.02	2.00	1.94	0.85	1.00	0.85	0.92	2.05	2.04	1.66	2.18	0.99	1.21	1.57	1.83
	Stdev =	0.83	1.08	1.06	0.97	0.43	0.44	0.37	0.32	0.65	0.49	0.52	0.75	0.37	0.44	0.80	0.76
	%RD =	51.3	53.7	53.2	50.1	50.7	44.2	43.5	34.7	31.6	24.0	31.5	34.3	37.1	35.9	50.7	41.6
	n =	24	24	24	24	11	11	2	2	4	4	5	5	5	5	21	21

Notes: Fuel consumption rate units = (gal/hr); CS-SS = Engine cold-start to reach steady-state condition, typically 1-3 hours in duration; CS-5, -10 & -15 = Engine cold-start during the first 5, 10 & 15 minutes, respectively; AC = Air-conditioner at Off and On settings; %RD = Percent relative standard deviation (Stdev/Average)x100.

Table D.6: Exhaust gas O_2 percent during cold-start and idling at engine rpm speeds and air-conditioner settings

ID	Vehicle	CS-SS	CS-5	CS-10	CS-15	600		650		700		750		800		1000	
						AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On
1	Freightliner	18.08	17.06	17.28	17.42							18.18	17.70			17.98	17.38
2	Freightliner	15.20	14.47	14.63	14.76									16.10	15.56	16.10	16.15
3	Volvo	13.64	13.66	13.36	13.38	15.90	15.34			16.00	15.41						
4	Volvo	13.39	12.19	12.53	12.70	15.90	15.25			15.86	15.35						
5	Mack	15.03	14.29	14.30	14.63			17.00	16.49							19.09	18.58
6	Kenworth	18.17	17.81	17.93	18.01	19.20	18.75									18.93	18.54
7	International	17.67	16.85	17.11	17.28									18.60	18.28	18.42	17.98
8	Kenworth	18.03	17.34	17.55	17.69	18.90	18.55									18.73	18.32
9	Volvo	19.60	18.82	19.03	19.16	20.10	19.99									19.78	19.79
10	Freightliner	18.02	17.72	17.79	17.85							18.60	18.20			18.30	18.09
11	Freightliner	17.79	17.24	17.50	17.60	18.86	18.20									18.88	18.27
12	International	16.15	15.13	15.40	15.64							17.08	16.59			16.80	16.49
13	International	17.43	17.06	17.15	17.23	18.47	17.83									18.16	17.71
14	Freightliner	18.65	18.37	18.40	18.43	19.70	18.90									19.64	19.00
15	Freightliner	15.32	13.67	13.86	13.97	16.40	15.87					16.00	15.59				
16	Freightliner	14.21	13.02	13.29	13.46	15.00	14.58									14.93	14.49
17	Freightliner	11.12	10.46	10.64	10.76					12.00	11.52					12.00	11.61
18	Freightliner	14.68	13.53	13.67	13.73	15.40	15.07									15.30	15.10
19	Mack	18.11	16.59	16.96	17.22									18.69	18.38	18.68	18.48
20	Freightliner	11.68	10.70	10.93	11.07							12.40	12.08			12.40	12.18
21	Freightliner	14.15	13.11	13.44	13.64					15.00	14.53					14.99	14.63
22	Freightliner	17.77	16.60	16.86	17.08									18.90	18.17	18.89	18.07
23	Mack	18.61	17.03	17.35	17.59									19.09	18.78	18.99	18.81
24	Mack	18.50	17.10	17.42	17.61			18.90	18.73							18.72	18.62
	Average =	16.3	15.4	15.6	15.7	17.6	17.1	18.0	17.6	14.7	14.2	16.5	16.0	18.3	17.8	17.4	17.1
	Stdev =	2.4	2.4	2.4	2.4	1.9	1.9	1.3	1.6	1.9	1.8	2.5	2.4	1.2	1.3	2.3	2.2
	%RD =	14.6	15.7	15.5	15.3	10.8	11.2	7.5	9.0	12.7	12.9	15.1	15.2	6.7	7.2	13.1	13.2
	n =	24	24	24	24	11	11	2	2	4	4	5	5	5	5	21	

Notes: Concentration units = (percent); CS-SS = Engine cold-start to reach steady-state condition, typically 1-3 hours in duration; CS-5, -10 & -15 = Engine cold-start during the first 5, 10 & 15 minutes, respectively; AC = Air-conditioner at Off and On settings; %RD = Percent relative standard deviation (Stdev/Average)x100.

Table D.7: Exhaust gas CO_2 percent during cold-start and idling at engine rpm speeds and air-conditioner settings

ID	Vehicle	CS-SS	CS-5	CS-10	CS-15	600		650		700		750		800		1000	
						AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On
1	Freightliner	2.16	2.90	2.73	2.62							2.11	2.40			2.20	2.63
2	Freightliner	4.25	4.78	4.66	4.57									3.60	4.01	3.60	3.55
3	Volvo	5.39	5.38	5.60	5.58	3.70	4.16			3.70	4.12						
4	Volvo	5.58	6.46	6.21	6.02	3.70	4.22			3.74	4.16						
5	Mack	4.29	4.91	4.73	4.55			2.90	3.31							1.41	1.76
6	Kenworth	2.08	2.33	2.25	2.20	1.30	1.66									1.51	1.81
7	International	2.43	3.04	2.85	2.73									1.80	2.02	1.91	2.22
8	Kenworth	2.18	2.68	2.53	2.43	1.50	1.79									1.66	2.00
9	Volvo	1.04	1.62	1.44	1.36	0.70	0.72									0.91	0.91
10	Freightliner	2.18	2.38	2.34	2.30							1.80	2.10			2.00	2.12
11	Freightliner	2.35	2.75	2.56	2.49	1.54	2.08									1.54	2.00
12	International	3.55	4.30	4.10	3.92							2.91	3.21			3.10	3.31
13	International	2.61	2.90	2.83	2.77	1.83	2.31									2.12	2.41
14	Freightliner	1.72	1.95	1.92	1.89	1.00	1.54									1.02	1.47
15	Freightliner	4.16	5.39	5.24	5.15	3.40	3.77					3.70	3.97				
16	Freightliner	4.99	5.84	5.65	5.53	4.40	4.72									4.47	4.76
17	Freightliner	7.25	7.74	7.61	7.52					6.60	6.96					6.60	6.90
18	Freightliner	4.64	5	5	5	4.10	4.36									4.20	4.32
19	Mack	2.13	3.24	2.97	2.77									1.71	1.94	1.72	1.84
20	Freightliner	6.83	7.56	7.38	7.28							6.30	6.53			6.30	6.48
21	Freightliner	5.01	5.78	5.55	5.40					4.40	4.74					4.41	4.67
22	Freightliner	2.37	3.23	3.04	2.88									1.50	2.06	1.51	2.15
23	Mack	1.75	2.91	2.68	2.50									1.41	1.62	1.50	1.58
24	Mack	1.84	2.88	2.63	2.48			1.50	1.67							1.69	1.77
Average =		3.4	4.1	4.0	3.8	2.5	2.8	2.2	2.5	4.6	5.0	3.4	3.6	2.0	2.3	2.6	2.9
Stdev =		1.7	1.8	1.8	1.8	1.4	1.4	1.0	1.2	1.4	1.3	1.8	1.8	0.9	1.0	1.7	1.6
%RD =		50.3	43.2	44.8	46.0	56.0	49.6	45.0	46.4	29.6	26.8	53.5	48.7	45.2	40.9	63.1	57.0
n =		24	24	24	24	11	11	2	2	4	4	5	5	5	5	21	21

Notes: Concentration units = (percent); CS-SS = Engine cold-start to reach steady-state condition, typically 1-3 hours in duration; CS-5, -10 & -15 = Engine cold-start during the first 5, 10 & 15 minutes, respectively; AC = Air-conditioner at Off and On settings; %RD = Percent relative standard deviation (Stdev/Average)x100.

Table D.8: Equivalence ratio during cold-start and extended idling at engine rpm speeds and air-conditioner settings

ID	Vehicle	CS-SS	CS-5	CS-10	CS-15	600		650		700		750		800		1000	
						AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On
1	Freightliner	0.14	0.19	0.18	0.17							0.13	0.16			0.14	0.17
2	Freightliner	0.28	0.31	0.30	0.30									0.23	0.26	0.23	0.23
3	Volvo	0.35	0.35	0.36	0.36	0.24	0.27			0.24	0.27						
4	Volvo	0.36	0.42	0.40	0.39	0.24	0.27			0.24	0.27						
5	Mack	0.28	0.32	0.31	0.30			0.19	0.21							0.09	0.12
6	Kenworth	0.13	0.15	0.15	0.14	0.09	0.11									0.10	0.12
7	International	0.16	0.20	0.19	0.18									0.11	0.13	0.12	0.14
8	Kenworth	0.14	0.17	0.16	0.16	0.10	0.12									0.11	0.13
9	Volvo	0.07	0.10	0.09	0.09	0.04	0.05									0.06	0.06
10	Freightliner	0.14	0.16	0.15	0.15							0.11	0.13			0.13	0.14
11	Freightliner	0.15	0.18	0.17	0.16	0.10	0.13									0.10	0.13
12	International	0.23	0.28	0.27	0.25							0.19	0.21			0.20	0.21
13	International	0.17	0.19	0.18	0.18	0.12	0.15									0.14	0.16
14	Freightliner	0.11	0.13	0.12	0.12	0.06	0.10									0.06	0.10
15	Freightliner	0.27	0.35	0.34	0.33	0.22	0.24					0.24	0.26				
16	Freightliner	0.32	0.38	0.37	0.36	0.29	0.31									0.29	0.31
17	Freightliner	0.47	0.50	0.49	0.49					0.43	0.45					0.43	0.45
18	Freightliner	0.30	0.36	0.35	0.35	0.27	0.28									0.27	0.28
19	Mack	0.14	0.21	0.19	0.18									0.11	0.12	0.11	0.12
20	Freightliner	0.44	0.49	0.48	0.47							0.41	0.43			0.41	0.42
21	Freightliner	0.33	0.38	0.36	0.35					0.29	0.31					0.29	0.30
22	Freightliner	0.15	0.21	0.20	0.19									0.10	0.13	0.10	0.14
23	Mack	0.11	0.19	0.17	0.16									0.09	0.11	0.10	0.10
24	Mack	0.12	0.19	0.17	0.16			0.10	0.11							0.11	0.11
	Average =	0.2	0.3	0.3	0.2	0.2	0.2	0.1	0.2	0.3	0.3	0.2	0.2	0.1	0.2	0.2	0.2
	Stdev =	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	%RD =	50.4	43.2	44.8	46.0	56.2	49.4	44.0	46.6	29.8	26.9	54.6	49.0	45.1	40.8	63.4	57.0
	n =	24	24	24	24	11	11	2	2	4	4	5	5	5	5	21	21

Notes: Ratio units = (unitless); CS-SS = Engine cold-start to reach steady-state condition, typically 1-3 hours in duration; CS-5, -10 & -15 = Engine cold-start during the first 5, 10 & 15 minutes, respectively; AC = Air-conditioner at Off and On settings; %RD = Percent relative standard deviation (Stdev/Average)x100.

Table D.9: Dilution ratio during cold-start and extended idling at engine rpm speeds and air-conditioner settings

ID	Vehicle	CS-SS	CS-5	CS-10	CS-15	600		650		700		750		800		1000	
						AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On
1	Freightliner	0.96	0.95	0.95	0.95							0.96	0.96			0.96	0.96
2	Freightliner																
3	Volvo																
4	Volvo																
5	Mack																
6	Kenworth																
7	International																
8	Kenworth																
9	Volvo	3.40	3.41	3.40	3.40	3.40	3.41									3.42	3.41
10	Freightliner	3.40	3.40	3.40	3.40							3.41	3.41			3.44	3.42
11	Freightliner	3.40	3.40	3.40	3.40	3.41	3.39									3.41	3.43
12	International	3.41	3.40	3.40	3.40							3.41	3.43			3.43	3.40
13	International	3.42	3.41	3.41	3.41	3.43	3.42									3.43	3.43
14	Freightliner	3.38	3.37	3.37	3.37	3.40	3.39									3.44	3.41
15	Freightliner	3.36	3.33	3.34	3.34	3.46	3.40					3.41	3.38				
16	Freightliner	3.35	3.34	3.34	3.34	3.38	3.37									3.46	3.49
17	Freightliner	3.34	3.34	3.34	3.34					3.38	3.39					3.44	3.45
18	Freightliner	3.35	3.35	3.34	3.35	3.37	3.36									3.38	3.43
19	Mack	3.36	3.35	3.36	3.36									3.38	3.36	3.37	3.47
20	Freightliner	3.35	3.36	3.37	3.37							3.38	3.37			3.49	3.43
21	Freightliner	3.33	3.31	3.32	3.32					3.35	3.34					3.36	3.38
22	Freightliner	3.36	3.35	3.35	3.35									3.40	3.38	3.41	3.40
23	Mack	3.36	3.35	3.35	3.36									3.38	3.37	3.40	3.44
24	Mack	3.36	3.34	3.34	3.34			3.38	3.38							3.40	3.39
	Average =	3.37	3.36	3.37	3.37	3.41	3.39	3.38	3.38	3.36	3.37	3.40	3.40	3.38	3.37	3.42	3.42
	Stdev =	0.03	0.03	0.03	0.03	0.03	0.02			0.03	0.04	0.01	0.03	0.01	0.01	0.03	0.03
	%RD =	0.81	0.91	0.86	0.83	0.93	0.61			0.78	1.11	0.44	0.87	0.33	0.34	0.99	0.87
	n =	16	16	16	16	7	7	1	1	2	2	4	4	3	3	15	15

Notes: Ratio units = (unitless); CS-SS = Engine cold-start to reach steady-state condition, typically 1-3 hours in duration; CS-5, -10 & -15 = Engine cold-start during the first 5, 10 & 15 minutes, respectively; AC = Air-conditioner at Off and On settings; %RD = Percent relative standard deviation (Stdev/Average)x100.

Table D.10: Exhaust gas temperature during cold-start and idling at engine rpm speeds and air-conditioner settings

ID	Vehicle	CS-SS	CS-5	CS-10	CS-15	600		650		700		750		800		1000	
						AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On
1	Freightliner	214.53	166.83	178.10	184.93							221.82	226.86			248.34	252.51
2	Freightliner	194.88	155.27	171.54	180.83									208.42	206.32	218.33	219.49
3	Volvo	183.93	123.34	172.64	198.09	174.58	188.32			193.12	203.18						
4	Volvo	204.98	155.90	179.91	194.89	181.24	193.00			198.43	207.57						
5	Mack	167.18	144.76	157.64	163.60			187.83	181.88							216.76	223.02
6	Kenworth	161.96	120.38	136.53	146.97	187.00	187.82									261.83	239.29
7	International	191.87	146.13	165.82	175.91									199.33	207.22	222.35	247.36
8	Kenworth	159.53	109.93	128.25	140.00	195.07	187.95									257.40	246.37
9	Volvo	170.36	134.43	144.78	151.63	190.30	191.73									233.00	230.67
10	Freightliner	214.77	206.97	208.68	210.27							205.10	219.15			230.61	243.50
11	Freightliner	187.63	162.79	175.61	182.74	170.37	189.07									205.24	223.88
12	International	192.65	153.23	170.97	178.93							190.59	203.02			211.02	233.70
13	International	204.54	183.97	191.73	196.11	205.95	213.25									259.85	254.14
14	Freightliner	178.01	143.48	155.56	162.60	176.97	190.38									216.60	219.31
15	Freightliner	199.90	170.67	187.92	193.87	177.14	181.31					206.70	207.02				
16	Freightliner	167.27	157.03	172.88	177.62	159.80	170.42									208.38	220.07
17	Freightliner	176.97	150.30	170.47	177.40					181.27	184.90					213.02	214.65
18	Freightliner	167.84	160.76	171.67	174.86	172.56	177.38									211.10	209.78
19	Mack	175.59	127.17	138.90	146.74									169.13	179.45	191.72	207.17
20	Freightliner	177.29	159.43	172.85	175.89							181.00	185.05			207.34	206.12
21	Freightliner	170.48	147.97	162.68	166.71					177.22	179.08					216.48	213.27
22	Freightliner	197.45	161.79	180.19	186.07									199.85	206.73	217.32	236.07
23	Mack	177.06	122.10	135.13	140.90									187.58	200.03	209.42	217.15
24	Mack	160.45	119.62	132.17	139.11			163.44	170.15							206.88	208.27
Average =		183	149	165	173	181	188	176	176	188	194	201	208	193	200	222	227
Stdev =		16.8	22.3	20.4	20.2	12.8	10.7	17.2	8.30	9.93	13.8	15.7	16.1	15.2	11.8	19.5	15.6
%RD =		9.16	15.0	12.4	11.7	7.10	5.70	9.82	4.71	5.29	7.14	7.83	7.72	7.88	5.92	8.77	6.86
n =		24	24	24	24	11	11	2	2	4	4	5	5	5	5	21	21

Notes: Temperature units = (degree F); CS-SS = Engine cold-start to reach steady-state condition, typically 1-3 hours in duration; CS-5, -10 & -15 = Engine cold-start during the first 5, 10 & 15 minutes, respectively; AC = Air-conditioner at Off and On settings; %RD = Percent relative standard deviation (Stdev/Average)x100.

Table D.11: Ambient air temperature during cold-start and idling at engine rpm speeds and air-conditioner settings

ID	Vehicle	CS-SS	CS-5	CS-10	CS-15	600		650		700		750		800		1000	
						AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On
1	Freightliner	90.60	88.88	89.29	88.60							89.39	97.12			87.26	85.11
2	Freightliner	72.31	71.39	71.52	71.72									73.58	73.75	73.96	71.77
3	Volvo	69.97	69.23	69.44	69.89	74.75	73.75			76.22	76.38						
4	Volvo	68.04	67.01	67.43	67.48	75.44	72.60			78.07	80.30						
5	Mack	76.99	75.72	76.53	76.76			83.25	81.93							82.21	85.74
6	Kenworth	79.97	79.62	79.74	79.95	84.37	82.85									81.64	77.46
7	International	85.96	84.31	85.14	85.48									88.38	87.46	85.00	81.16
8	Kenworth	77.70	76.99	77.45	77.67	85.36	82.83									87.15	87.55
9	Volvo	82.74	81.72	81.68	81.71	81.84	83.58									80.82	79.03
10	Freightliner	82.94	81.77	81.63	81.91							84.22	84.11			83.75	82.78
11	Freightliner	75.91	74.57	74.79	74.89	74.82	74.57									75.07	77.88
12	International	79.60	78.42	78.81	78.65							82.80	82.04			80.84	78.96
13	International	86.76	86.23	86.06	86.30	88.77	87.90									91.62	91.38
14	Freightliner	81.68	81.83	81.90	81.89	83.23	82.52									84.08	82.25
15	Freightliner	53.99	49.46	50.01	50.59	62.57	63.58					60.77	57.89				
16	Freightliner	44.62	39.72	40.17	40.52	52.87	48.69									56.32	58.26
17	Freightliner	43.74	38.15	38.64	39.08					56.92	52.09					59.04	61.43
18	Freightliner	47.02	43.82	44.17	44.44	55.87	51.04									58.57	60.31
19	Mack	46.24	44.71	44.92	44.84									50.49	48.65	53.22	56.35
20	Freightliner	45.19	39.66	40.31	40.69							55.06	51.32			57.22	57.25
21	Freightliner	38.21	35.57	35.96	36.27					47.57	42.95					53.92	57.73
22	Freightliner	49.10	43.64	44.05	44.43									62.17	57.84	62.52	68.42
23	Mack	52.45	48.52	49.24	49.15									62.09	56.59	63.63	68.57
24	Mack	54.99	52.80	53.03	53.21			64.50	61.50							68.23	64.24
	Average =	66.1	63.9	64.2	64.4	74.5	73.1	73.9	71.7	64.7	62.9	74.4	74.5	67.3	64.9	72.7	73.0
	Stdev =	17.1	18.5	18.4	18.3	12.3	13.4	13.3	14.4	14.9	18.3	15.4	19.2	14.3	15.6	12.9	11.4
	%RD =	25.8	28.9	28.6	28.4	16.5	18.3	17.9	20.1	23.0	29.0	20.7	25.8	21.3	24.0	17.7	15.6
	n =	24	24	24	24	11	11	2	2	4	4	5	5	5	5	21	21

Notes: Temperature units = (degree F); CS-SS = Engine cold-start to reach steady-state condition, typically 1-3 hours in duration; CS-5, -10 & -15 = Engine cold-start during the first 5, 10 & 15 minutes, respectively; AC = Air-conditioner at Off and On settings; %RD = Percent relative standard deviation (Stdev/Average)x100.

Table D.12: MW of exhaust gas (dry basis) for cold-start and idling at engine rpm speeds and air-conditioner settings

ID	Vehicle	CS-SS	CS-5	CS-10	CS-15	600		650		700		750		800		1000	
						AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On	AC-Off	AC-On
1	Freightliner	29.07	29.15	29.13	29.12							29.06	29.09			29.07	29.12
2	Freightliner	29.29	29.34	29.33	29.32									29.22	29.26	29.22	29.21
3	Volvo	29.41	29.41	29.43	29.43	29.23	29.28			29.23	29.27						
4	Volvo	29.43	29.52	29.49	29.47	29.23	29.29			29.23	29.28						
5	Mack	29.29	29.36	29.33	29.31			29.14	29.19							28.99	29.03
6	Kenworth	29.06	29.09	29.08	29.07	28.98	29.02									29.00	29.03
7	International	29.10	29.16	29.14	29.13									29.03	29.05	29.04	29.07
8	Kenworth	29.07	29.12	29.11	29.10	29.00	29.03									29.02	29.05
9	Volvo	28.95	29.01	28.99	28.98	28.92	28.91									28.94	28.94
10	Freightliner	29.07	29.09	29.09	29.08							29.03	29.06			29.05	29.06
11	Freightliner	29.09	29.13	29.11	29.10	29.00	29.06									29.00	29.05
12	International	29.21	29.29	29.27	29.25							29.15	29.18			29.17	29.19
13	International	29.11	29.15	29.14	29.13	29.03	29.08									29.07	29.09
14	Freightliner	29.02	29.05	29.04	29.04	28.95	29.00									28.95	28.99
15	Freightliner	29.28	29.41	29.39	29.38	29.20	29.24					29.23	29.26				
16	Freightliner	29.37	29.46	29.44	29.42	29.30	29.34									29.31	29.34
17	Freightliner	29.61	29.66	29.64	29.63					29.54	29.57					29.54	29.57
18	Freightliner	29.33	29.42	29.41	29.40	29.27	29.30									29.28	29.30
19	Mack	29.06	29.18	29.15	29.13									29.02	29.05	29.02	29.03
20	Freightliner	29.56	29.64	29.62	29.61							29.50	29.53			29.50	29.52
21	Freightliner	29.37	29.45	29.43	29.41					29.30	29.34					29.31	29.33
22	Freightliner	29.09	29.18	29.16	29.14									29.00	29.06	29.00	29.07
23	Mack	29.02	29.15	29.12	29.10									28.99	29.01	29.00	29.01
24	Mack	29.03	29.14	29.12	29.10			29.00	29.02							29.02	29.03
	Average =	29.20	29.27	29.26	29.25	29.10	29.14	29.07	29.10	29.33	29.37	29.20	29.22	29.05	29.09	29.12	29.14
	Stdev =	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.2	0.2
	%RD =	0.6	0.6	0.6	0.6	0.5	0.5	0.4	0.4	0.5	0.5	0.6	0.6	0.3	0.3	0.6	0.6
	n =	24	24	24	24	11	11	2	2	4	4	5	5	5	5	21	21

Notes: Molecular weight units = (unitless); CS-SS = Engine cold-start to reach steady-state condition, typically 1-3 hours in duration; CS-5, -10 & -15 = Engine cold-start during the first 5, 10 & 15 minutes, respectively; AC = Air-conditioner at Off and On settings; %RD = Percent relative standard deviation (Stdev/Average)x100.

Appendix E

Truck Real Time Emission Rate Behavior

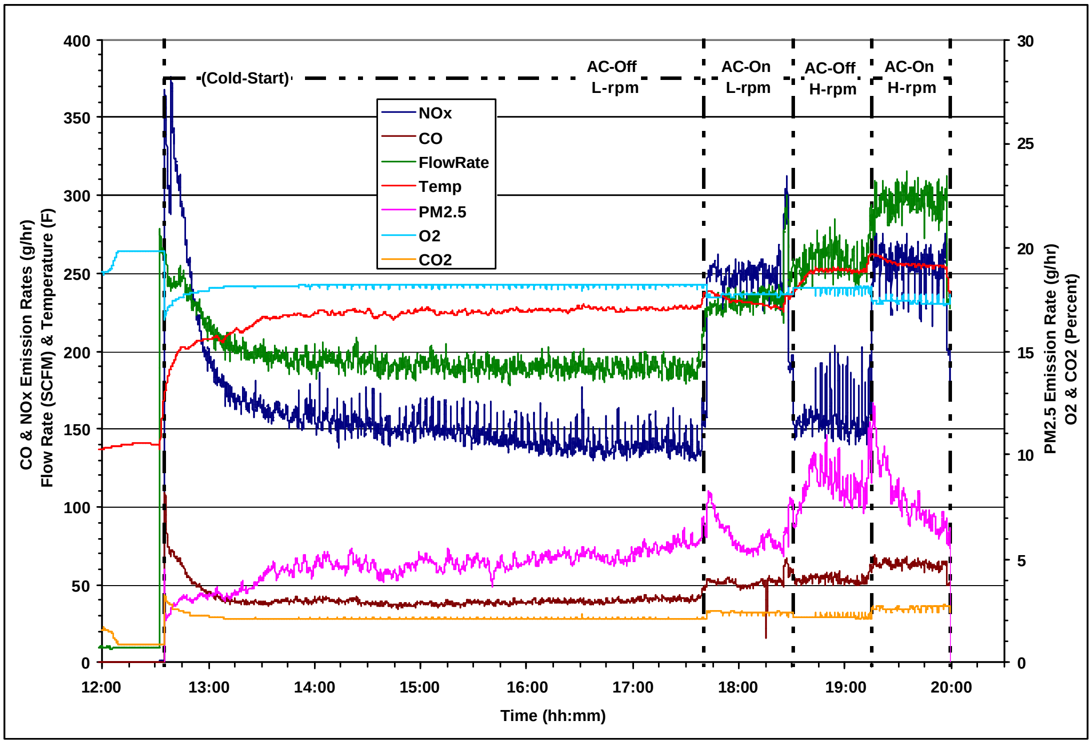


Figure E.1. Emission and flow rate behavior for 1996 Freightliner truck (ID#1).
Note: L-rpm = 750 and H-rpm = 1000.

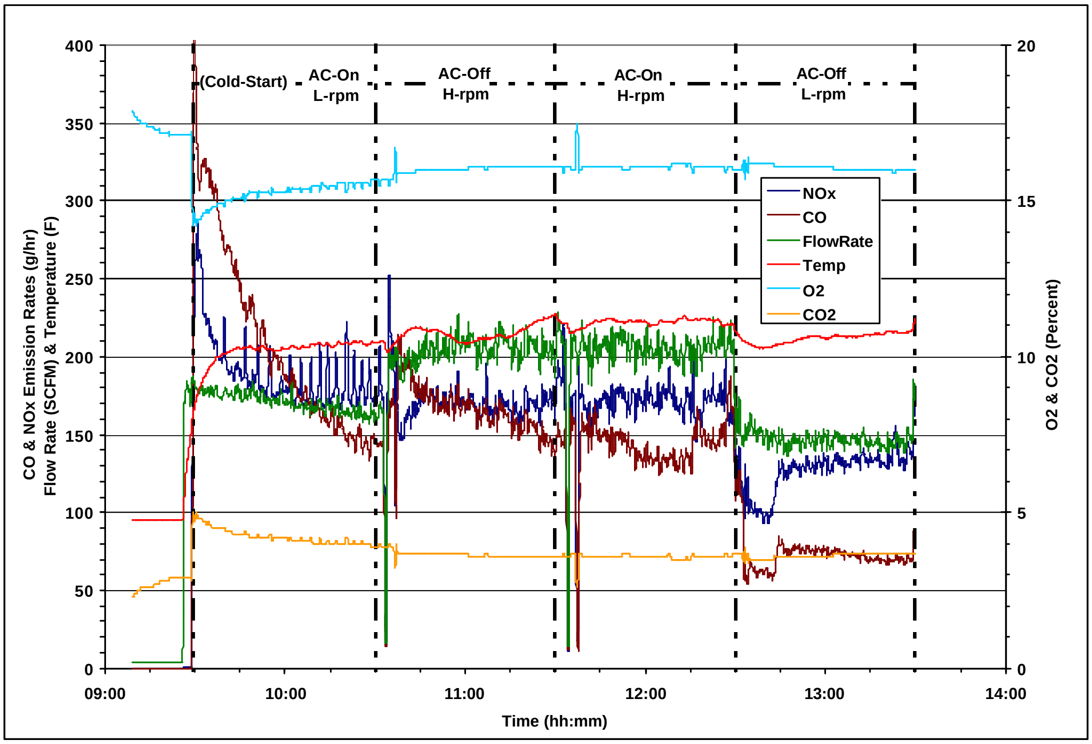


Figure E.2: Emission and flow rate behavior for 1998 Freightliner truck (ID#2).
Notes: L-rpm = 800 and H-rpm = 1000; PM data not available.

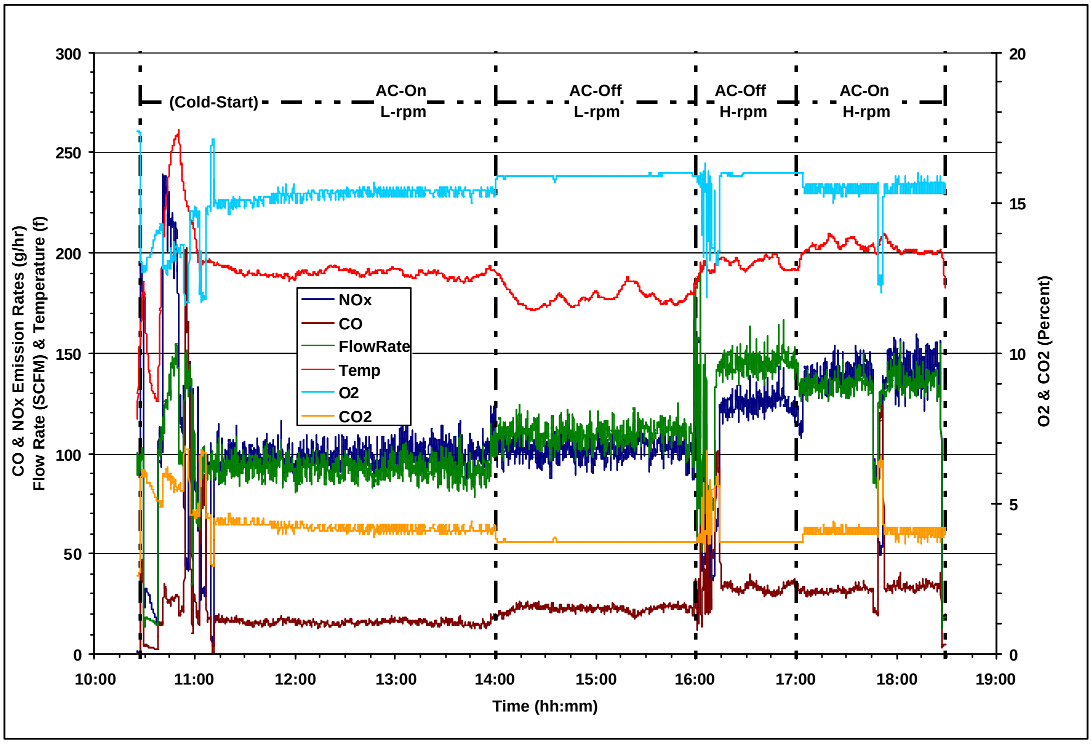


Figure E.3. Emission and flow rate behavior for 2004 Volvo truck (ID#3).
Notes: L-rpm = 600 and H-rpm = 700; PM data not available.

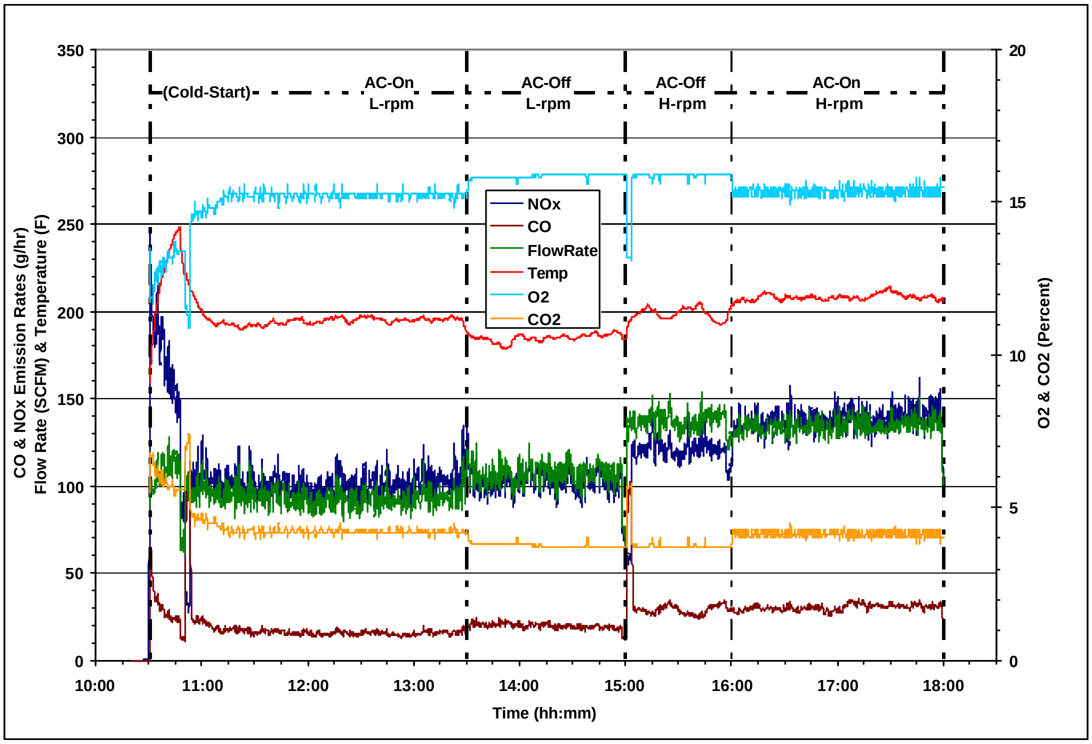


Figure E.4. Emission and flow rate behavior for 2004 Volvo truck (ID#4).
Notes: L-rpm = 600 and H-rpm = 700; PM data not available.

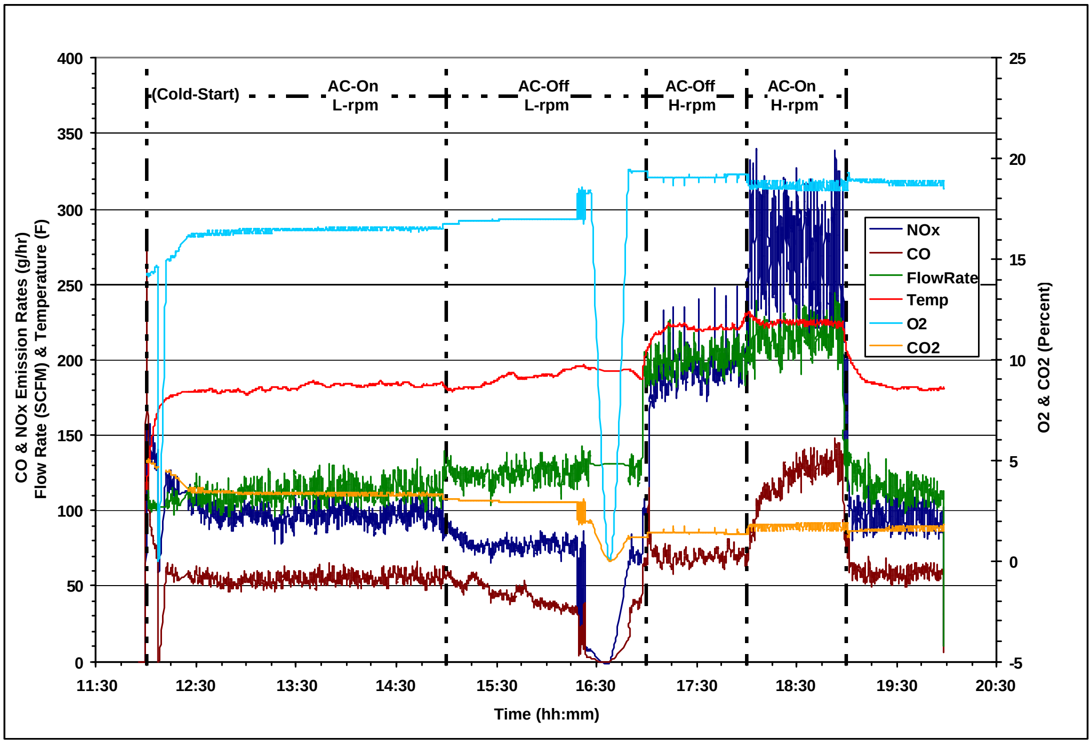


Figure E.5. Emission and flow rate behavior for 1999 Mack truck (ID#5).
Notes: L-rpm = 650 and H-rpm = 1000; PM data not available.

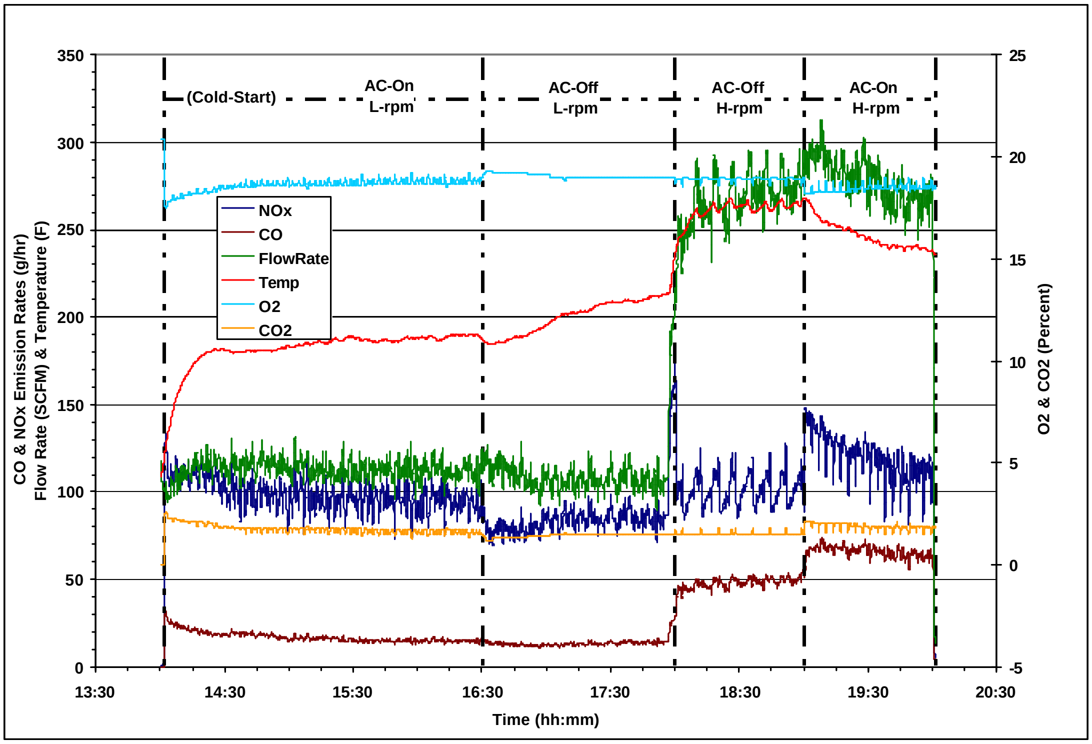


Figure E.6. Emission and flow rate behavior for 2004 Kenworth truck (ID#6).
Notes: L-rpm = 600 and H-rpm = 1000; PM data not available.

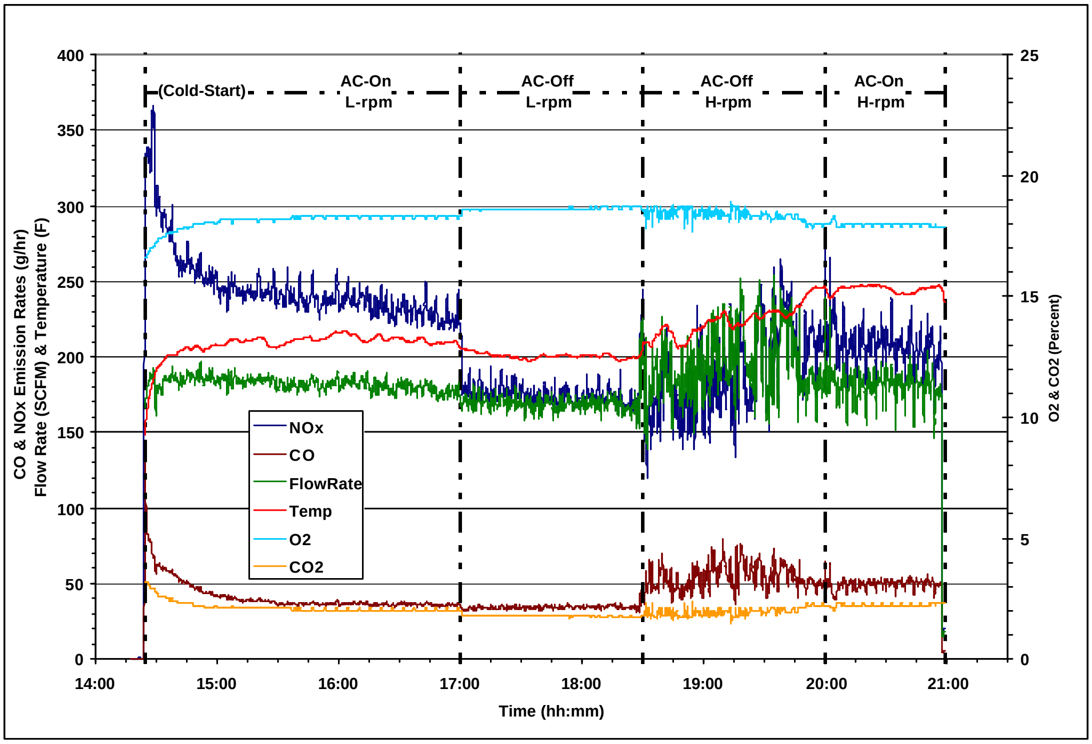


Figure E.7. Emission and flow rate behavior for 1998 International truck (ID#7).
Notes: L-rpm = 800 and H-rpm = 1000; PM data not available.

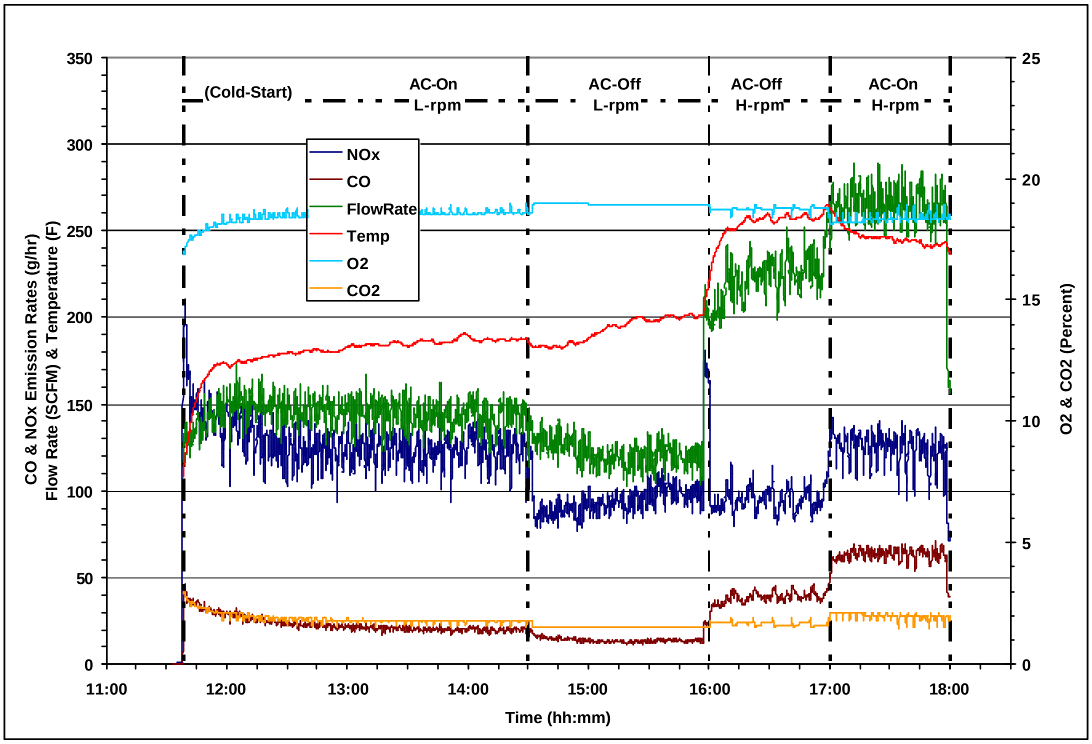


Figure E.8. Emission and flow rate behavior for 2004 Kenworth truck (ID#8).
Notes: L-rpm = 600 and H-rpm = 1000; PM data not available.

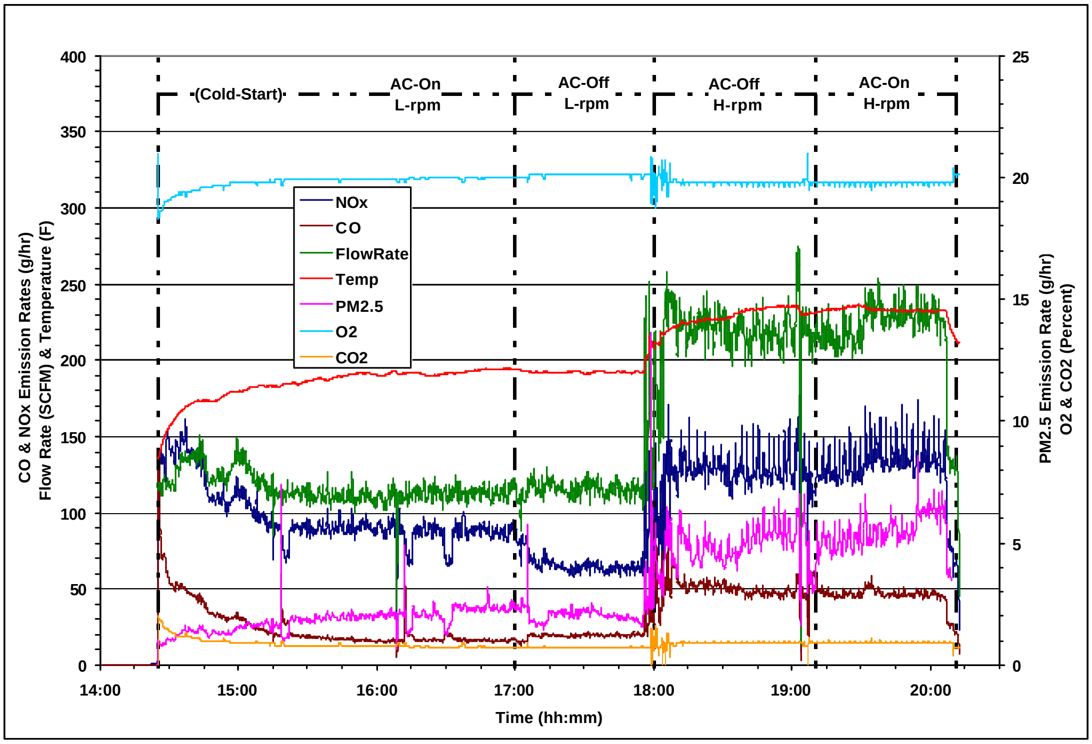


Figure E.9. Emission and flow rate behavior for 2000 Volvo truck (ID#9).
Note: L-rpm = 600 and L-rpm = 1000.

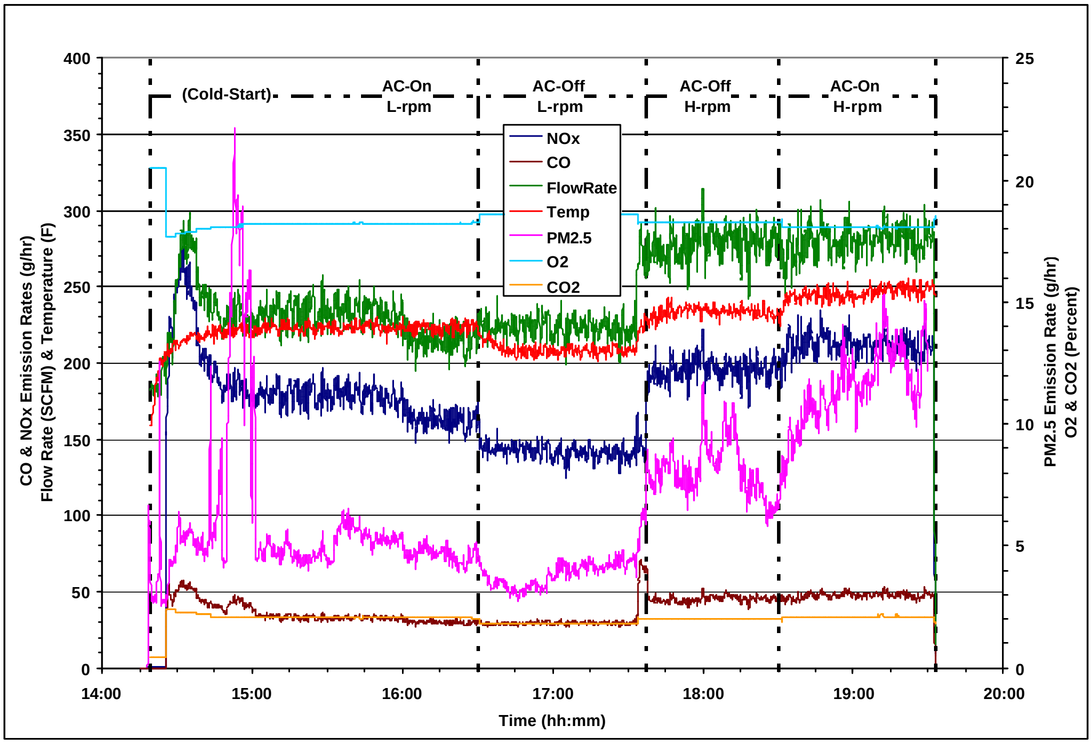


Figure E.10. Emission and flow rate behavior for 1998 Freightliner truck (ID#10).
Note: L-rpm = 750 and H-rpm = 1000.

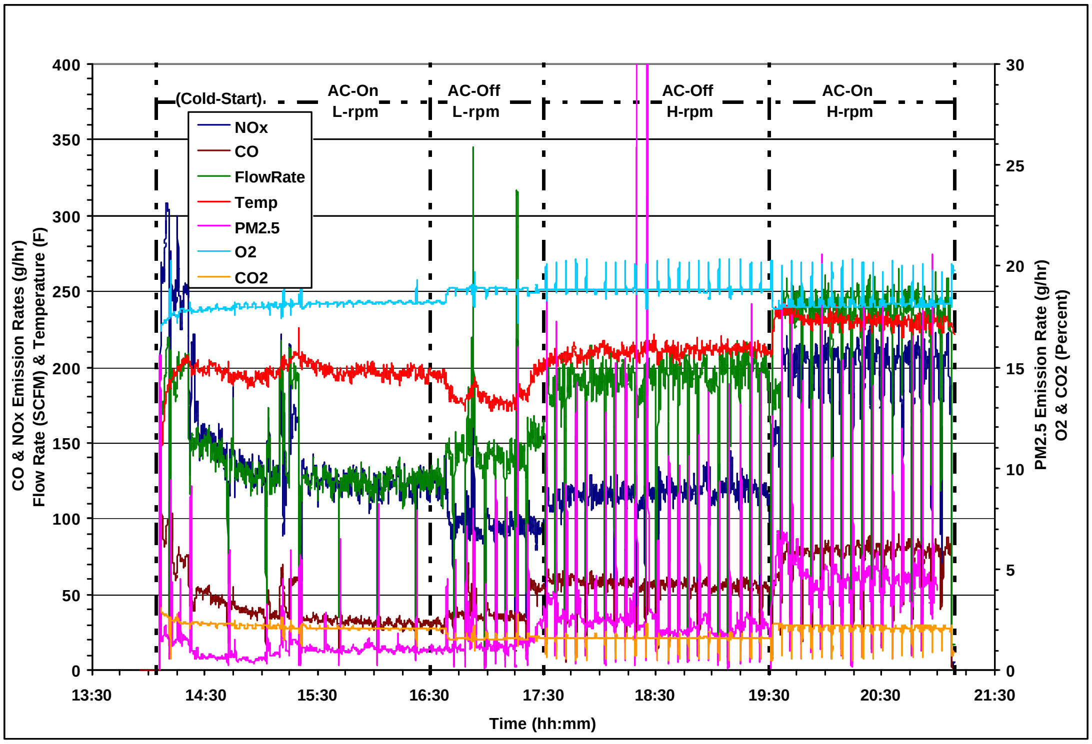


Figure E.11. Emission and flow rate behavior for 2000 Freightliner truck (ID#11).
Notes: L-rpm = 600 and H-rpm = 1000; Constant idling speeds could not be maintained.

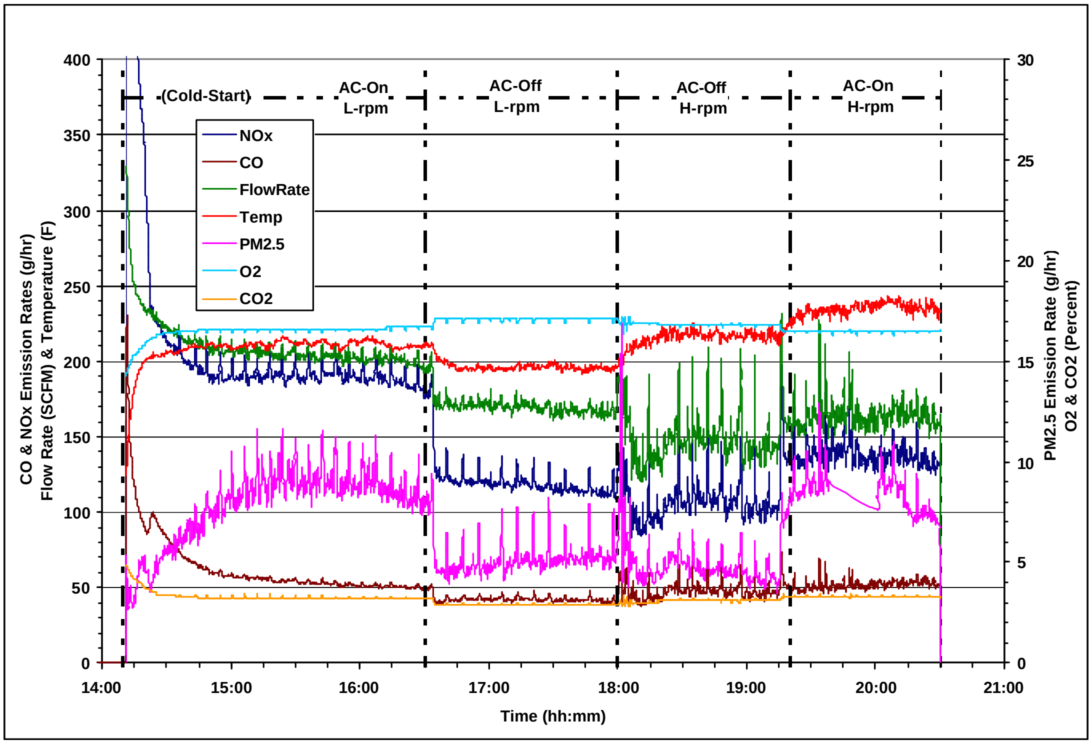


Figure E.12. Emission and flow rate behavior for 1995 International truck (ID#12).
Note: L-rpm = 750 and H-rpm = 1000.

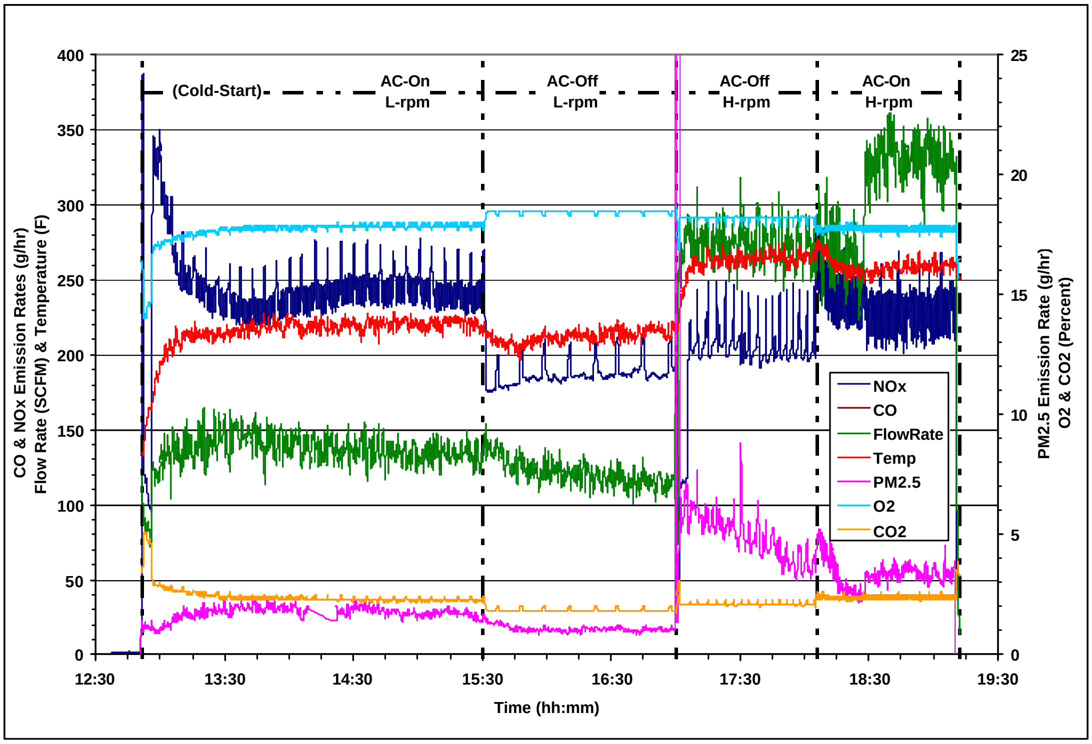


Figure E.13. Emission and flow rate behavior for 2004 International truck (ID#13).
Note: L-rpm = 600 rpm and H-rpm = 1000.

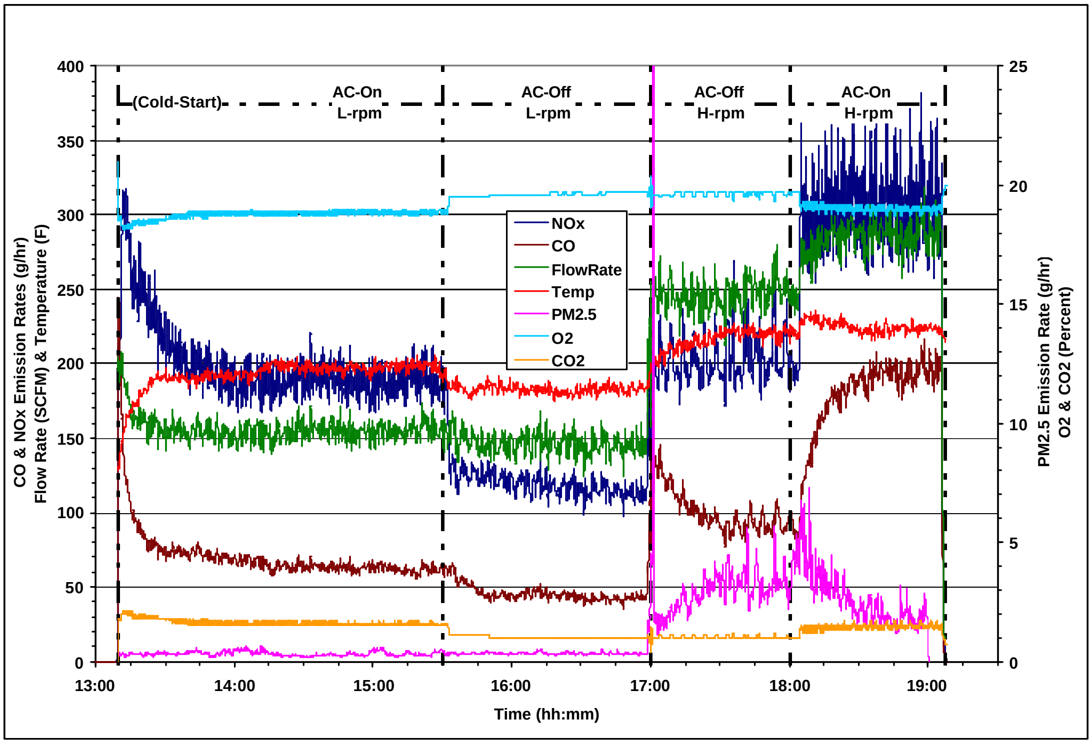


Figure E.14. Emission and flow rate behavior for 1992 Freightliner truck (ID#14).
Note: L-rpm = 600 and H-rpm = 1000.

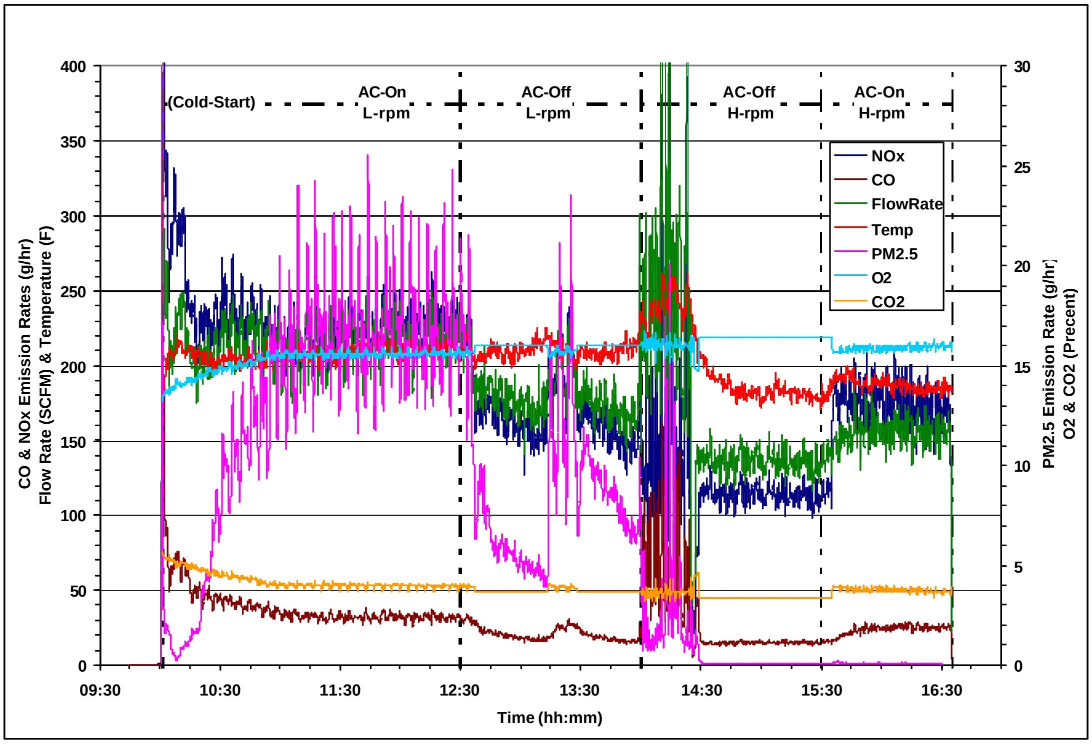


Figure E.15. Emission and flow rate behavior for 2004 Freightliner truck (ID#15).
Note: L-rpm = 600 and H-rpm = 750.

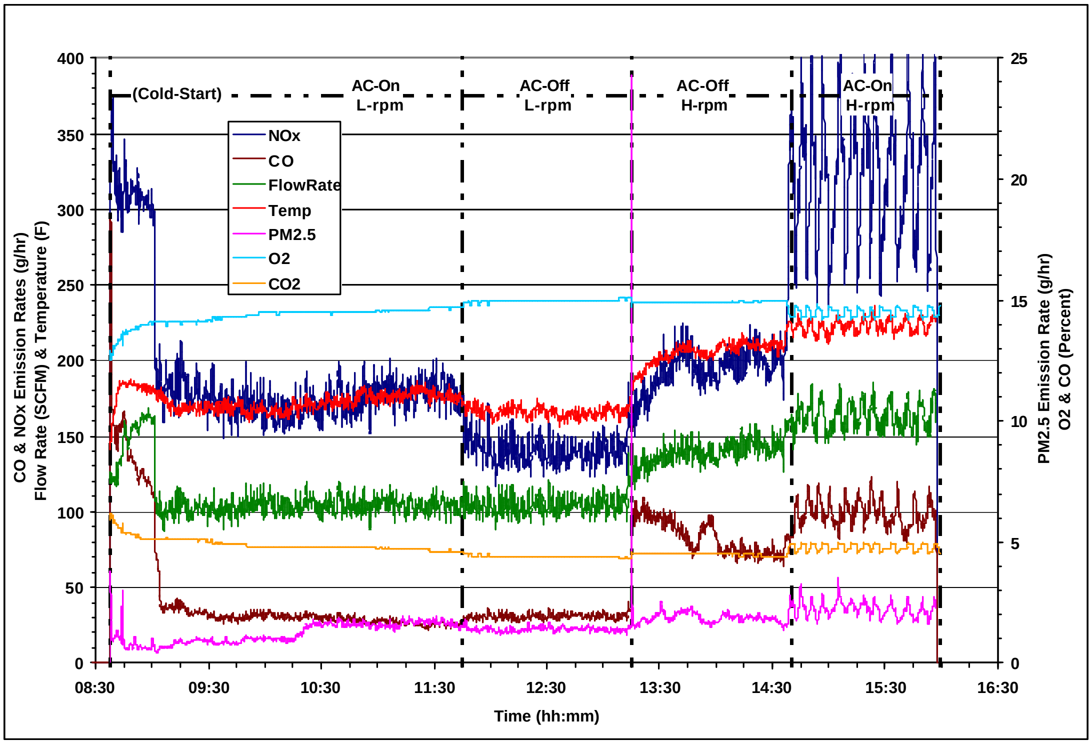


Figure E.16. Emission and flow rate behavior for 1999 Freightliner truck (ID#16).
Note: L-rpm = 600 and H-rpm = 1000.

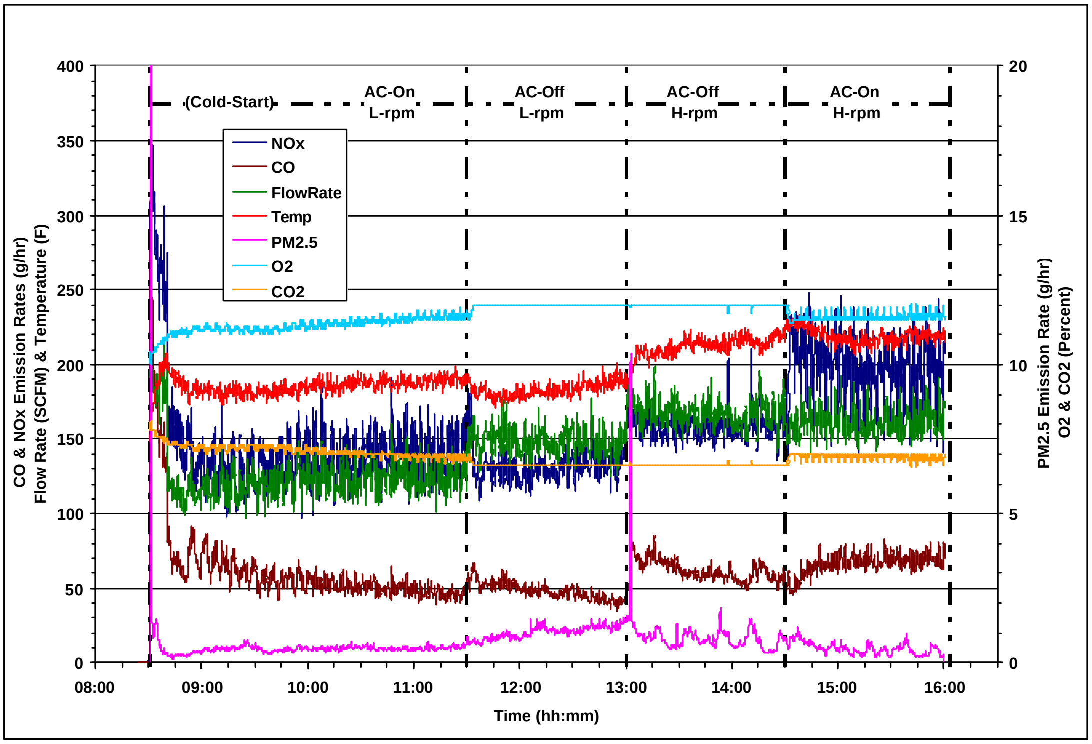


Figure E.17. Emission and flow rate behavior for 2003 Freightliner truck (ID#17).
Note: L-rpm = 700 and H-rpm = 1000.

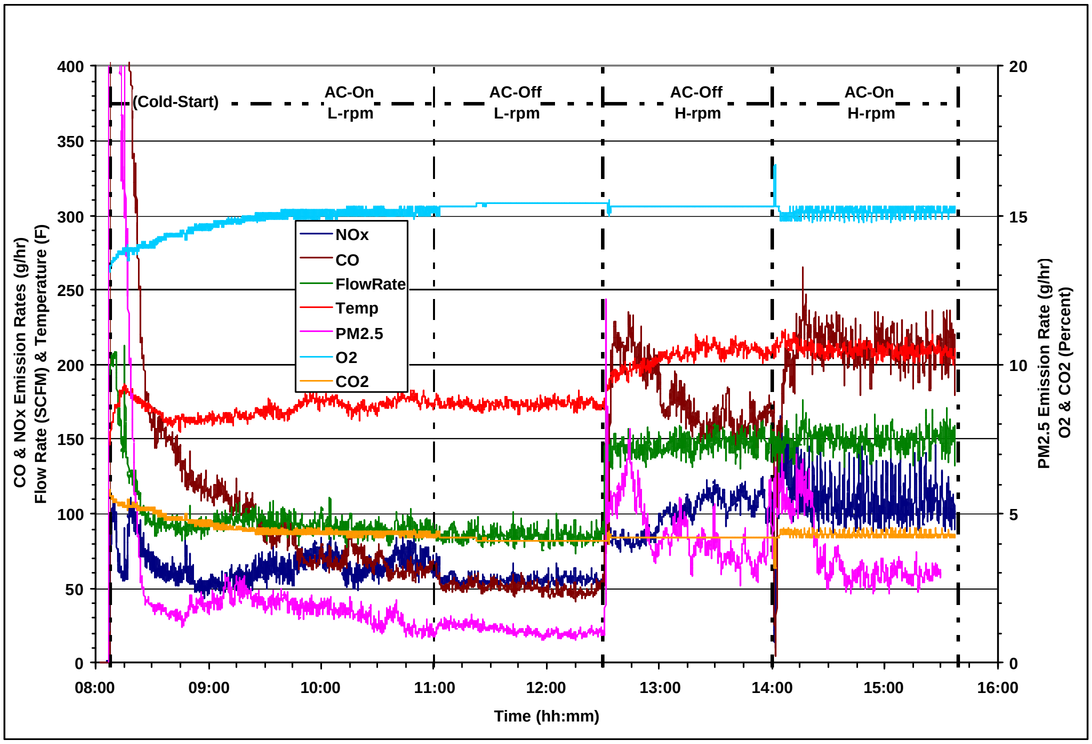


Figure E.18. Emission and flow rate behavior for 1997 Freightliner truck (ID#18).
Note: L-rpm = 600 and H-rpm = 1000.

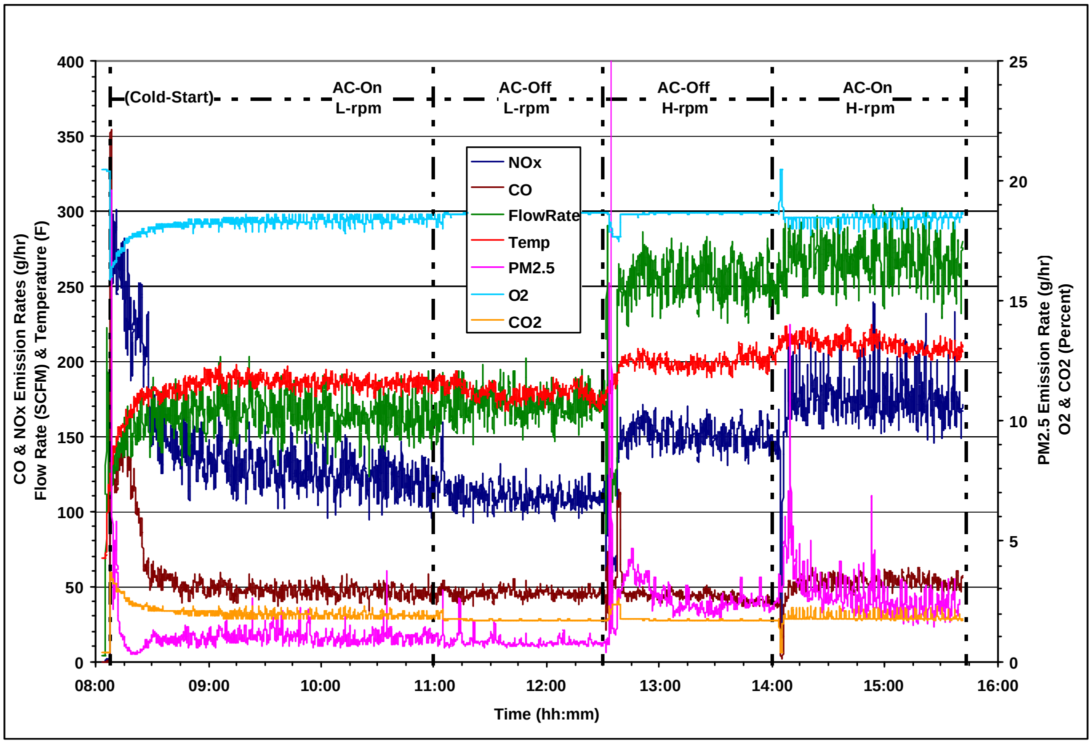


Figure E.19. Emission and flow rate behavior for 2003 Mack truck (ID#19).
Note: L-rpm = 800 and H-rpm = 1000.

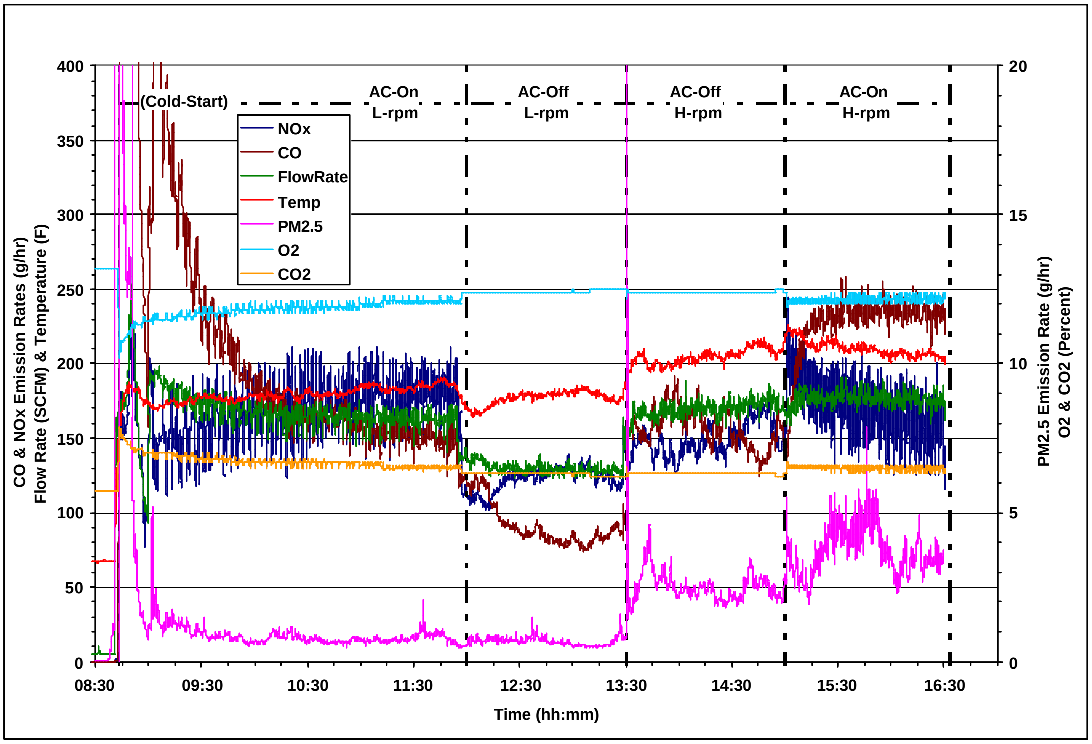


Figure E.20. Emission and flow rate behavior for 1997 Freightliner truck (ID#20).
Note: L-rpm = 750 and H-rpm = 1000.

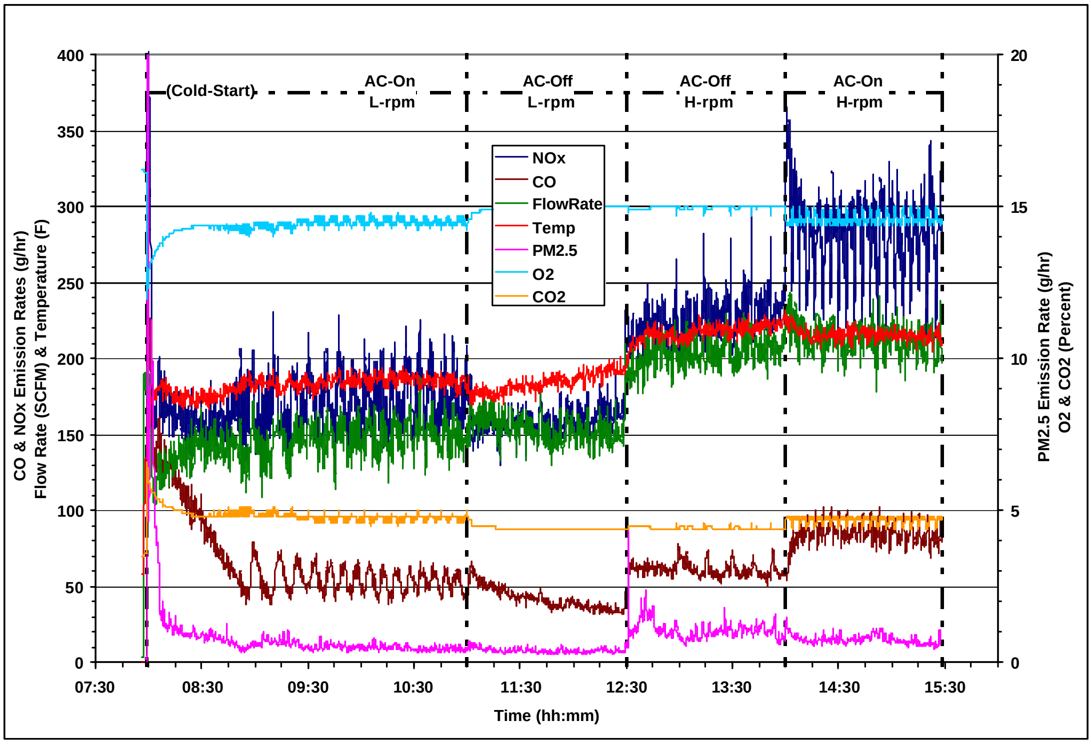


Figure E.21. Emission and flow rate behavior for 2003 Freightliner truck (ID#21).
Note: L-rpm = 700 and H-rpm = 1000.

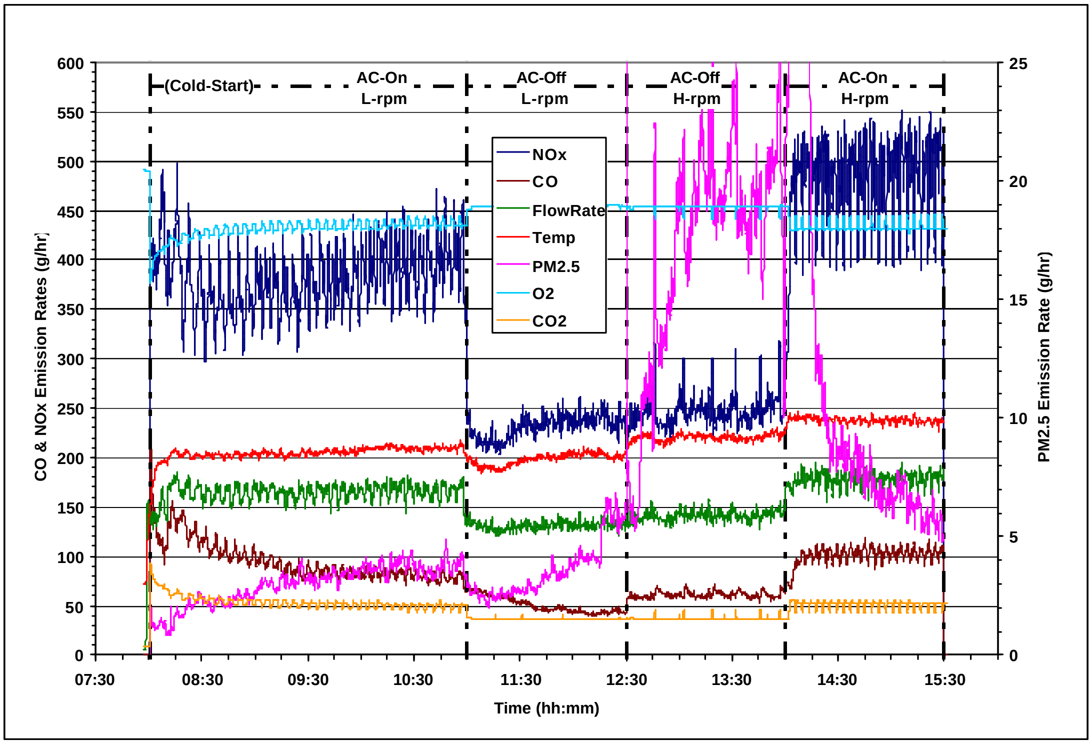


Figure E.22. Emission and flow rate behavior for 1999 Freightliner truck (ID#22).
Note: L-rpm = 800 and H-rpm = 1000.

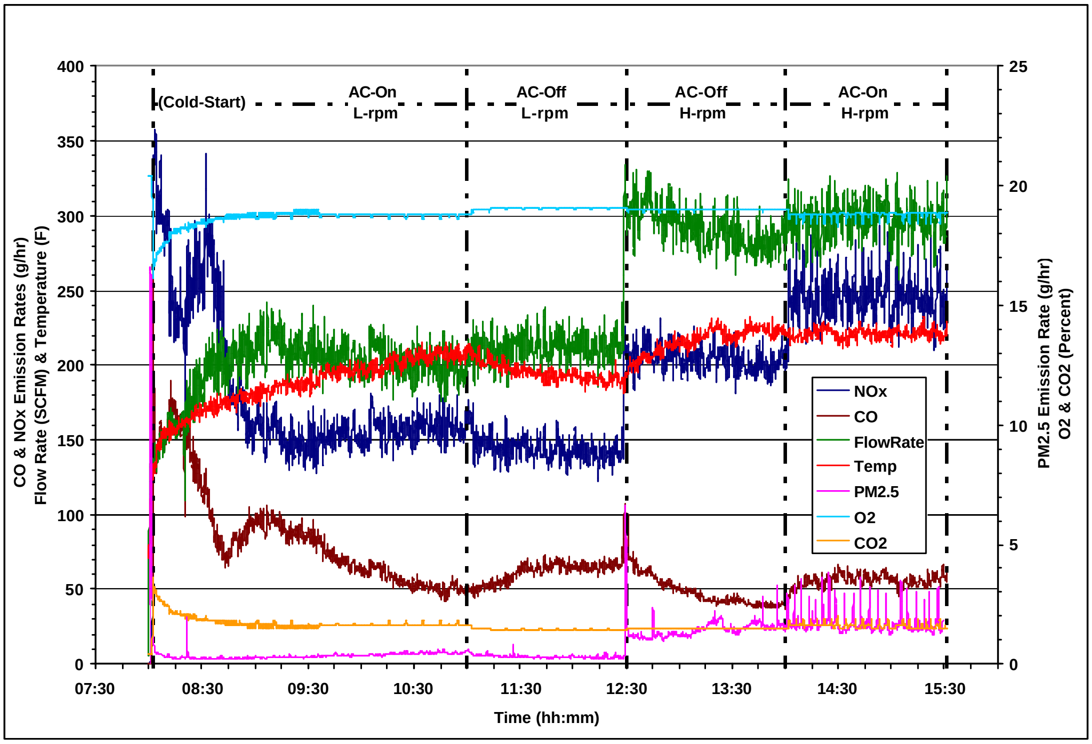


Figure E.23. Emission and flow rate behavior for 2003 Mack truck (ID#23).
Note: L-rpm = 800 and H-rpm = 1000.

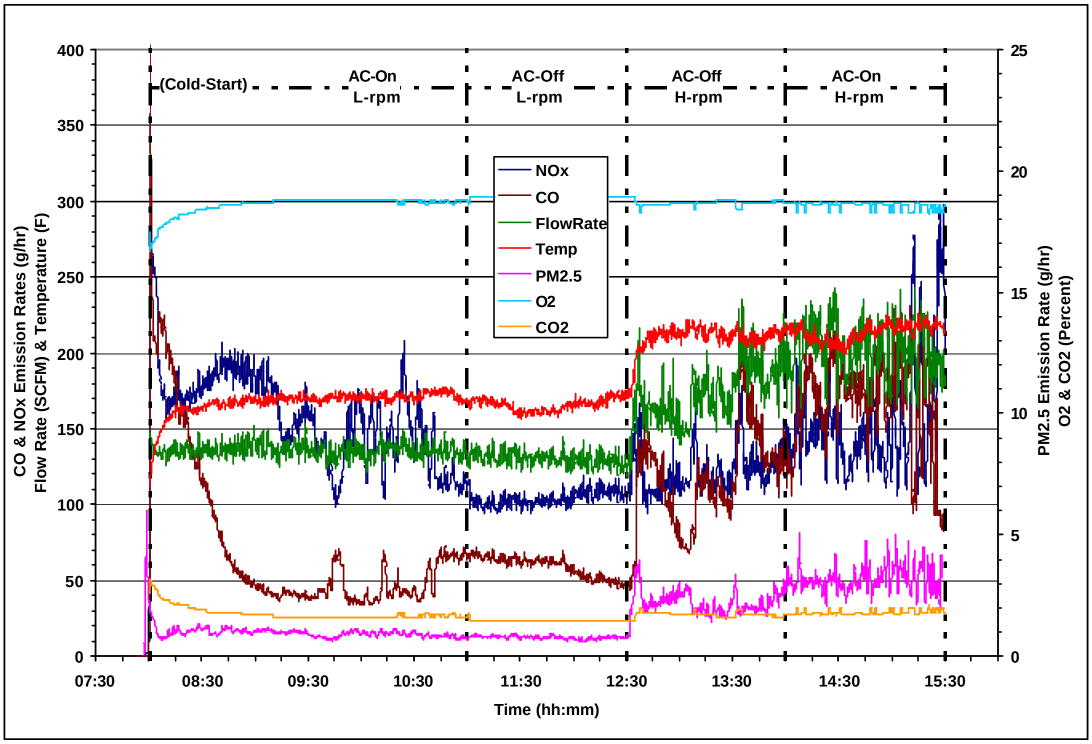


Figure E.24. Emission and flow rate behavior for 2000 Mack truck (ID#24).
Note: L-rpm = 650 and H-rpm = 1000.

Appendix F

Calibration Data for ECOM and DataRAM

Table F.1: Calibration Data for ECOM Analyzer using EPA Protocol Calibration Gases.

Reference #	**88-87025**	**88-86994**	**88-87145**			**88-86967**	**88-86724**								
Balance	**Nitrogen**	**Nitrogen**	**Air**			**Nitrogen**	**Air, CEM Zero Grade**								
Component	**CO**	**NO**	**NOx**	**NO**	**NO_2**	**SO_2**	**CO**	**NOx**	**SO_2**	**CO_2%**	**THC**	**H_2O**	**O_2%**	**N_2**
Analyzed	**100.1**	**493**	**90.6**	**-**	**-**	**99.5**	**0.5**	**0.1**	**0.1**	**1**	**0.1**	**5**	**25.5-21.5**	**Balance**
05/27/2004	100	489	91	6	85	100	0	0	0	1.8	-	-	18.5	-
07/16/2004	100	501	89	5	84	102	0	0	0	1.8	-	-	18.5	-
08/02/2004	100	493	91	2	89	98	0	0	1	1.8	-	-	19.5	-
08/17/2004	101	503	90	6	84	95	0	1	0	1.8	-	-	18.6	-
09/09/2004	100	496	89	7	82	98	0	1	0	2.6	-	-	17.5	-
11/15/2004	100	503	89	9	80	100	5	3	0	0.3	-	-	20.6	-
11/23/2004	99	506	89	3	86	89	0	1	0	0.3	-	-	20.7	-
12/09/2004	101	496	95	1	94	103	0	1	0	0.3	-	-	20.7	-
Average	**100.1**	**498.4**	**90.4**	**4.9**	**85.5**	**98.1**	**0.6**	**0.9**	**0.1**	**1.3**	**-**	**-**	**19.3**	**-**
Stdev	**0.64**	**5.80**	**2.07**	**2.70**	**4.34**	**4.45**	**1.77**	**0.99**	**0.35**	**0.90**	**-**	**-**	**1.23**	**-**
%RSD	**0.64**	**1.16**	**2.29**	**55.3**	**5.08**	**4.54**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Avg % Difference from Standard	-0.02	-1.09	0.25	-	-	1.38	-	-	-	-	-	-	-	-

Note: All units are in parts-per-million (ppm) except where the percent (%) sign is shown.

Table F.2: Gravimetric Calibration Data for DataRAM Analyzer.

Filter Color	Filter Code	Date	Truck ID	Cal Factor	$PM_{2.5}$	PM>2.5	Total PM	Sampling Time (min)	Ratio 2.5/Total
NA	NA	23-Jun	1	0.152	2.2	NA	NA	211.9	NA
NA	NA		1	0.148	4.1	NA	NA	260.8	NA
Gray	1A	21-Aug	10	3.409	1.4	0.8	2.2	155.8	0.64
Black	1B		10	1.710	1.4	0.4	1.8	214.5	0.78
Black	2A	22-Aug	9	1.221	1.7	0.5	2.2	349.8	0.77
Black	2B	23-Aug	10	1.621	2.2	0.4	2.6	314.8	0.85
Gray	3A	24-Aug	11	3.616	1.6	0.6	2.2	422.5	0.73
Gray	3B	25-Aug	12	1.126	1.4	0.7	2.1	118.0	0.67
Gray	4A	26-Aug	12	1.115	3.4	0.8	4.2	359.5	0.81
Gray	4B	27-Aug	13	5.028	1.2	0.4	1.6	368.5	0.75
Beige	5A	10-Sep	14	5.322	0.5	0.6	1.1	361.0	0.45
LtBrown	6A	11-Sep	14	4.391	4.1	1.1	5.2	605.7	0.79
Brown	6B	12-Sep	14	5.198	2.0	0.9	2.9	610.2	0.69
Black	5B	22-Sep	1	0.465	3.8	0.9	4.7	380.8	0.81
Black	7A	06-Nov	15	1.232	3.7	0.3	4.0	394.8	0.93
Gray	7B	09-Nov	16	1.179	1.5	0.2	1.7	441.8	0.88
LtBrown	8A	10-Nov	17	2.690	0.6	0.5	1.1	451.8	0.55
Brown	8B	11-Nov	18	2.684	4.1	0.8	4.9	451.8	0.84
Gray	9A	12-Nov	19	1.713	0.5	0.5	1.0	459.8	0.50
Gray	9B	13-Nov	19	3.230	1.1	0.3	1.4	454.8	0.79
Brown	10A	14-Nov	20	2.277	2.5	0.1	2.6	504.7	0.98
Beige	10B	16-Nov	21	6.791	0.8	0.4	1.2	451.8	0.67
Black	11A	17-Nov	22	0.638	6.1	1.8	7.9	451.5	0.77
Gray	11B	18-Nov	23	2.539	0.4	0.6	1.0	451.8	0.40
LtBrown	12A	19-Nov	24	3.972	1.2	0.4	1.6	453.0	0.75
			Average=	**2.539**				**Average=**	**0.729**
			Stdev =	**1.802**				**Stdev =**	**0.145**
			%RSD =	**71.0**				**%RSD =**	**19.9**
			n =	**25**				**n =**	**23**

Notes: Units for $PM_{2.5}$ and total PM are in milligrams (mg).

Appendix G

DataRAM Sample Filter Spectra

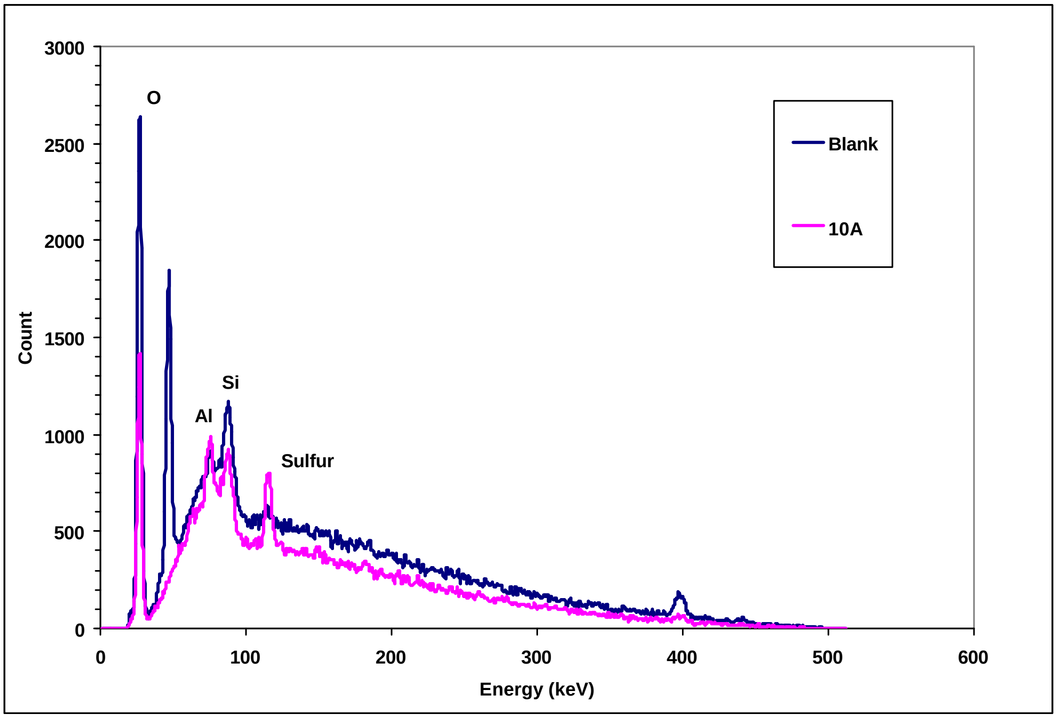


Figure G.1. Composite spectrum for 1997 Freightliner truck (ID#20).

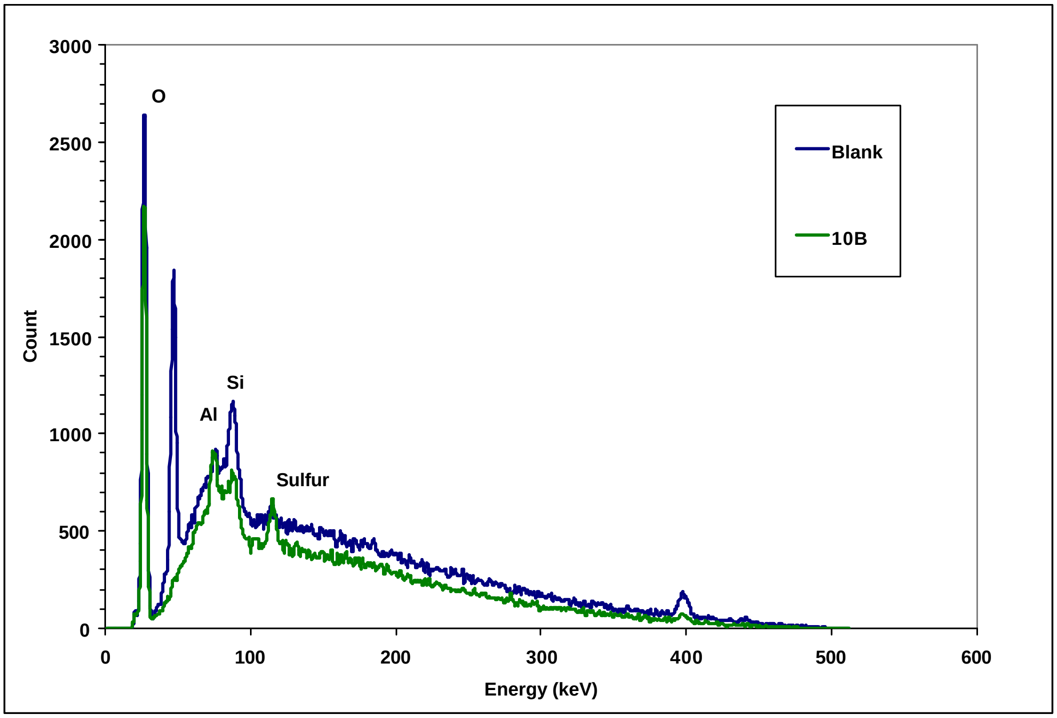


Figure G.2. Composite spectrum for 2003 Freightliner truck (ID#21).

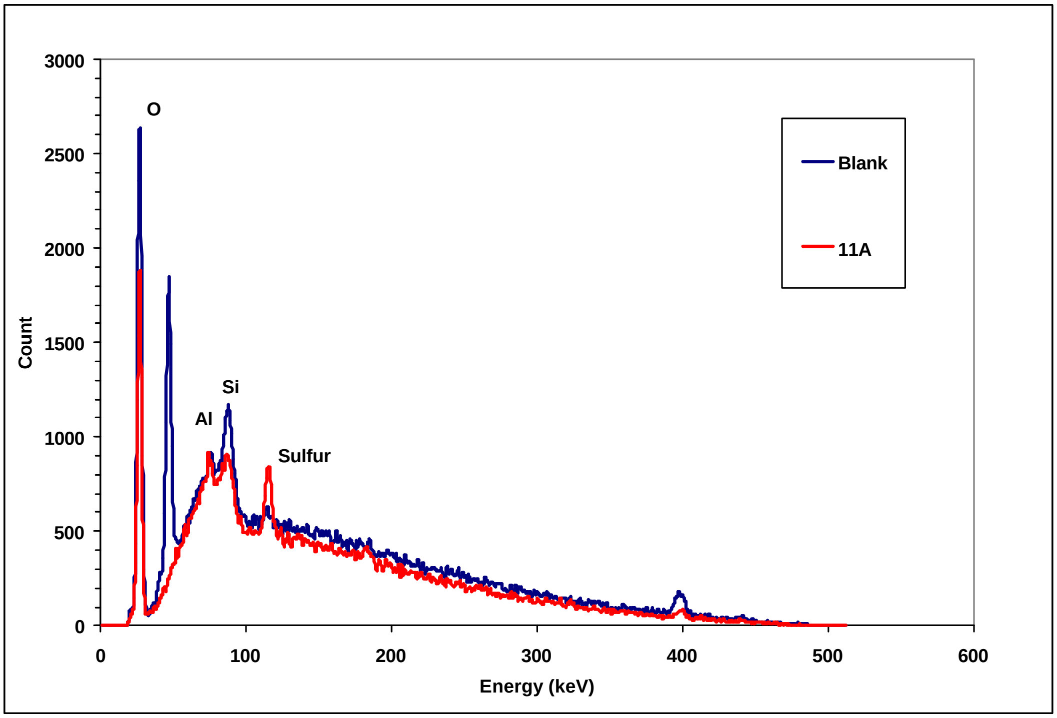


Figure G.3. Composite spectrum for 1999 Freightliner truck (ID#22).

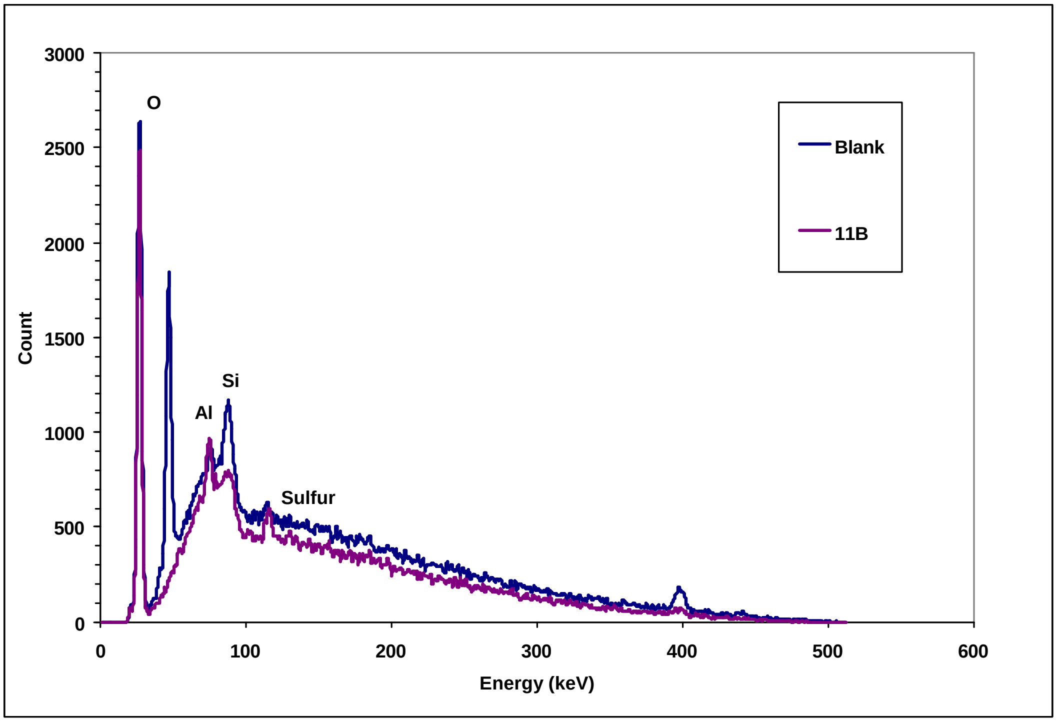


Figure G.4. Composite spectrum for 2003 Mack truck (ID#23).

VITA

James A. Calcagno, III received the Bachelor of Science in Mechanical Engineering from the University of New Orleans in Louisiana during 1988. He moved to Huntsville, Alabama to accept a position at Coyne Cylinder Company in Quality Control, where he worked as part of the engineering design team in the improvement and implementation of manufacturing processes. Promoted to Project Engineer, he was responsible for guiding facility compliance with safety and environmental regulations, and he also developed a proficiency in air and water pollution control equipment and permitting. In May 2001, he received the Masters of Science in Environmental Engineering from the University of Tennessee. Currently he is working as a Graduate Research Assistant at the University of Tennessee. In December 2005, he will receive the Doctor of Philosophy degree in Civil Engineering with a concentration in Environmental Engineering (Air Quality).