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Evaluating Real-World Idle Emissions from Heavy-Duty Diesel Vehicles

ABM Siddiqur Rahman Khan

Thesis submitted to the
College of Engineering and Mineral Resources
At West Virginia University
In Partial Fulfillment of the Requirements
For the degree of

Master of Science
In
Mechanical Engineering

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Morgantown, West Virginia
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ABSTRACT

Evaluating Real-World Idle Emissions from Heavy-Duty Diesel Vehicles

ABM S. Khan

Long haul trucks in the USA idle for extended periods at truck stops and at pickup and drop-off points. The idling consumes fuel, contributes to engine wear and reduces atmospheric quality, but it cannot simply be proscribed because in many cases cab heat or air-conditioning provides essential driver comfort. As an example, there are nearly 1.5 million interstate trucks that operate in California, where climate control is essential. A comprehensive tailpipe emissions database to describe idling impacts is not available at present, although studies have been conducted to quantify idle emissions and to project the advantages of idle reduction technologies based on a few vehicles. This thesis presents one of the most complete data set available that may be used to quantify the impact of future idle reduction programs, and incorporates results from the West Virginia University transient test cell, the E-55/59 Study and the Gasoline-Diesel PM Split Study. The data have covered over sixty heavy-duty engines and trucks, with model years ranging from 1975 to 2004. Idle emissions data for regulated pollutants (CO, HC, NOx, and PM) have been compiled and reported in grams per hour (g/hr). Idle CO_2 emissions allowed the projection of fuel consumed, in units of gal/hr. These data were compared with existing data in the literature, while also researching the model year effects.

For the E-55/59 and the PM Split data, test-to-test variation was observed for repeat idle tests on the same vehicle, due to measurement variation, auxiliary loads, and ambient conditions. Idle emissions showed trends with engine model year, but substantial vehicle-to-vehicle variation for vehicles with similar model years was also evident. For post-1990 vehicles, idle CO and PM emissions were found to decrease with increasing engine model year. The idle NOx emissions were, on average, higher after 1990 than before, which would correspond to the advent of electronic engine management and the advancing of timing to improve idle combustion. Vehicles with post 1990 engine model years were found to emit approximately 23 g/hr of CO, 9 g/hr of HC, 83 g/hr of NOx, 1.4 g/hr of PM, and 4600 g/hr of CO_2 during idle, whereas vehicles with 1975 to 1990 model years were found to have on average 31 g/hr of CO, 21 g/hr of HC, 48 g/hr of NOx, 4 g/hr of PM, and 4500 g/hr of CO_2 idle emissions. No significant model year variations were observed for idle fuel consumption. Idle fuel consumption from the 1975-1990 model year and post 1990 model year vehicles was 0.46 gal/hr and 0.47 gal/hr respectively. Effects of air conditioning and elevated engine speed on idle emissions were also observed. Use of air conditioning increases emissions and fuel consumption by

25% on average. However, CO_2 and NOx emissions and fuel consumption increased by more than 150% except for PM and HC emissions, which increased by about 100% and 70% respectively when the engine speed was elevated from 600 rpm to 1100 rpm. Two 2-stroke diesel buses of MY 1982 and MY 1992 were tested during the PM Split Study and another bus (MY 2000) was recently tested during the Transit Vehicle Exhaust Emissions Evaluation Study. All emissions from the two 2-stroke diesel buses were higher than the MY 2000 bus except NOx, which was high for the MY 2000 bus.

In addition, idle emissions from the Transient mode of the Heavy Heavy-Duty Truck (HHDDT) Schedule were calculated and compared with the values obtained from idle cycles. Over the whole database, idle emissions from the Transient mode were higher than the emissions from the idle cycles except NOx, which was less than the NOx emissions obtained from the idle cycles. The high idle values of CO, HC, and CO_2 from the Transient mode has been partly due to the effect of some accessory loadings such as fan and the compressors and partly due to the possible inclusion of emissions at initial acceleration while evaluating emissions from the continuous data. NOx emissions from the Transient mode were less than the NOx emissions obtained from the idle cycles, which could be attributed to the advance injection timing intentionally employed during idle.

Model years 1991, 1992, 1995, and 2000 DDC Series 60 engines in a test cell were found to consume fuel at only 70% of the level found in the PM Split and E-55/59 data. This is because fan and compressor loads were absent in the test cell. The test cell engines did exhibit CO and NOx emissions similar to the post-1990 vehicles, but emitted PM at about half of the level of the post-1990 vehicles.

ACKNOWLEDGEMENT

I would like to take this unique opportunity to thank and salute my friend, philosopher and guide, Dr. Nigel Clark, George B. Berry Chair of Engineering and Professor, Department of Mechanical and Aerospace Engineering. I left behind my homeland, my job in Bangladesh Army, and all of my relatives, including my wife and my beloved daughter with an aim to pursue higher education in the United States, the Mecca of higher education and research. Since then I have been under his charming, caring, and friendly wings. I would also like to convey my special thanks to all professors of the Department of Mechanical and Aerospace Engineering including my advisors Dr. Andrei Smirnov and Dr. Scott Wayne and Graduate Program Director, Dr Jacky Prucz.

I take this opportunity to specially thank the sponsors of the projects E-55/59 and PM Split Study, namely; U.S. Department of Energy Office of FreedomCAR and Vehicle Technologies through the National Renewable Energy Laboratory, Coordinating Research Council Inc., California Air Resources Board, U.S. Environmental Protection Agency, the South Coast Air Quality Management District and the Engine Manufacturers Association. I am also grateful to all engineers and staffs of the Transportable Laboratories (Translab), who despite their busy schedule gave their valuable time to teach me every bits and bites on the operation of the Translab and its analyzers. Tom, Ryan, Andy, Byron, Tedd, and Curtis, thank you all. Finally, I would like to pay special tribute to my father, brothers, sisters, father-in-law, my wife and my little mum, Mariam. I am honored to dedicate this work to my mother, who always prayed the best for me. May Allah, the Almighty bless her departed soul.

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LIST OF ABBREVIATIONS AND SYMBOLS

A/C	air conditioning
APU	auxiliary power unit
ANL	Argonne National Laboratory
ATC	Aberdeen Test Center
ATCM	Airborne Toxic Control Measure
CAFEE	Center for Alternative Fuels, Engines, and Emissions
CARB	California Air Resources Board
CFR	Code of Federal Regulations
CFV-CVS	critical flow venturi – constant volume sampling
CN	Cetane Number
CNG	Compressed Natural Gas
CO	carbon monoxide
CO_2	carbon dioxide
COV	coefficient of variance
CRC	Coordinating Research Council
DDC	Detroit Diesel Corporation
DFH	Direct-Fired Heater
DOE	Department of Energy
DOT	Department of Transportation
EMFAC	Emissions Facts
FTP	Federal Test Procedure
^0F	degrees of Fahrenheit
GVW	Gross Vehicle Weight
g/gal	grams per gallon
g/hr	grams per hour
HDDV	Heavy-Duty Diesel Vehicles
HFID	heated flame ionization detector
HHDDT	Heavy Heavy-Duty Diesel Truck
HC	hydrocarbons

hp	horsepower
Hz	hertz
I&M	Inspection and Maintenance
lbs	pounds
MY	model year
NOx	oxides of nitrogen
NREL	National Renewable Energy Laboratory
NDIR	non-dispersive infrared
ORNL	Oak Ridge National Laboratory
PM	particulate matter
%	percentage
rpm	revolutions per minute
TEOM	Tapered Element Oscillating Microbalance
THC	total hydrocarbons
USEPA	United States Environmental Protection Agency
VMT	vehicle miles traveled
VOC	volatile organic compounds
vs.	Versus
WVU	West Virginia University

INTRODUCTION

National Energy Policy, 2001, while reiterating the importance of 'wise energy use', emphasized the need for reducing emissions and fuel consumption from long haul trucks at truck stops by implementing alternatives to idling [1]. Long haul trucks refer to Class 8 trucks with more than 33,000 pounds (lbs) Gross Vehicle Weight (GVW). The majorities of these trucks carry essentials across the country and stay overnight. Drivers of these trucks idle their engines for extended time during rest periods to ensure necessary cab heating or cooling, which cannot be proscribed because of the annual high and low temperature profile across the country that demands the use of heating and cooling for essential comfort. Figure 1 and Figure 2 show the average high and low temperature profile of ten major cities across the USA, which has been compiled from www.weather.com. Figures show that the average annual high temperature of these cities remains above 70^0F from April to September except Seattle, while the average low temperature remains below 45^0F from January to March and from October to December except Houston, Los Angeles, and Miami. Drivers also idle their engines in order to keep the engine warm, and to maintain battery voltage. Other reasons cited by the drivers include safety and habit [2].

There exists limited data on the extent and duration of idling from heavy-duty diesel vehicles (HDDV). Brodrick et al. [3] of the Institute of Transportation Studies, University of California, Davis, conducted a pilot survey on 233 line haul trucks in northern California but could not provide a conclusive figure on the extent of idling. The two extreme scenarios of idling duration from Class 7 and Class 8 vehicles ranged from 1000 hours per year to 5000 hours per year with 1830 hours per year considered a base case [4]. Another report estimates annual idling from long haul trucks could be between 1500 to 2400 hours [2]. This broad range implies seasonal effect, weather, and operation pattern of these vehicles.

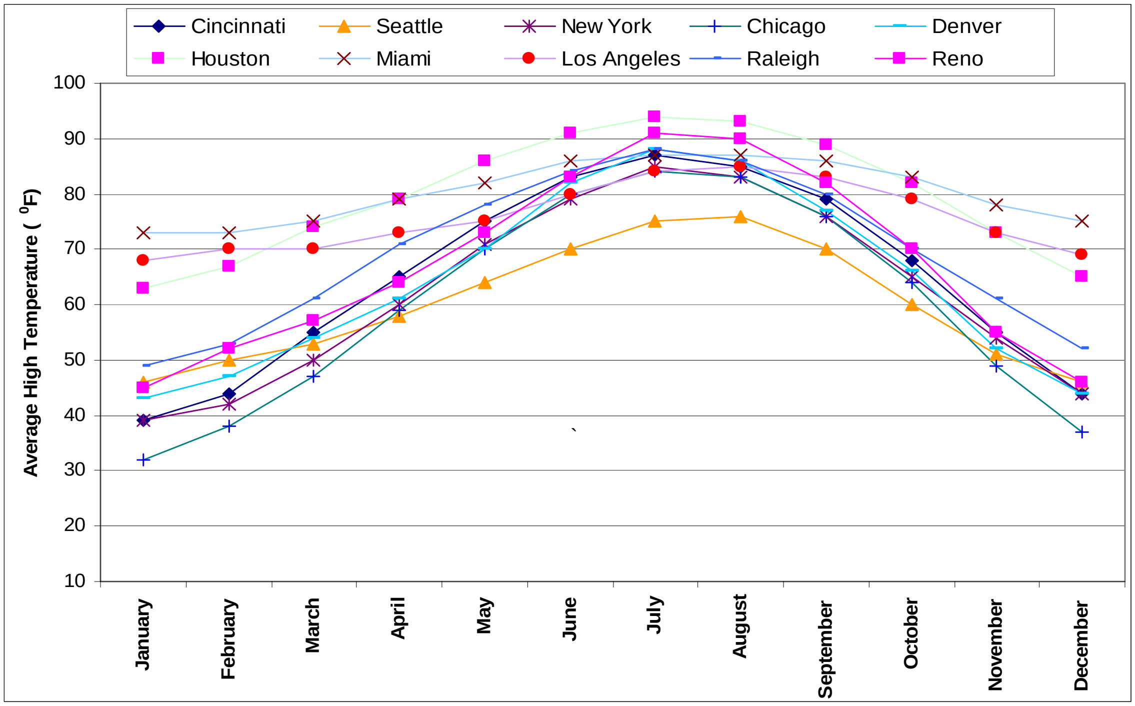

Figure 1: Average annual high temperature of ten major cities across the USA

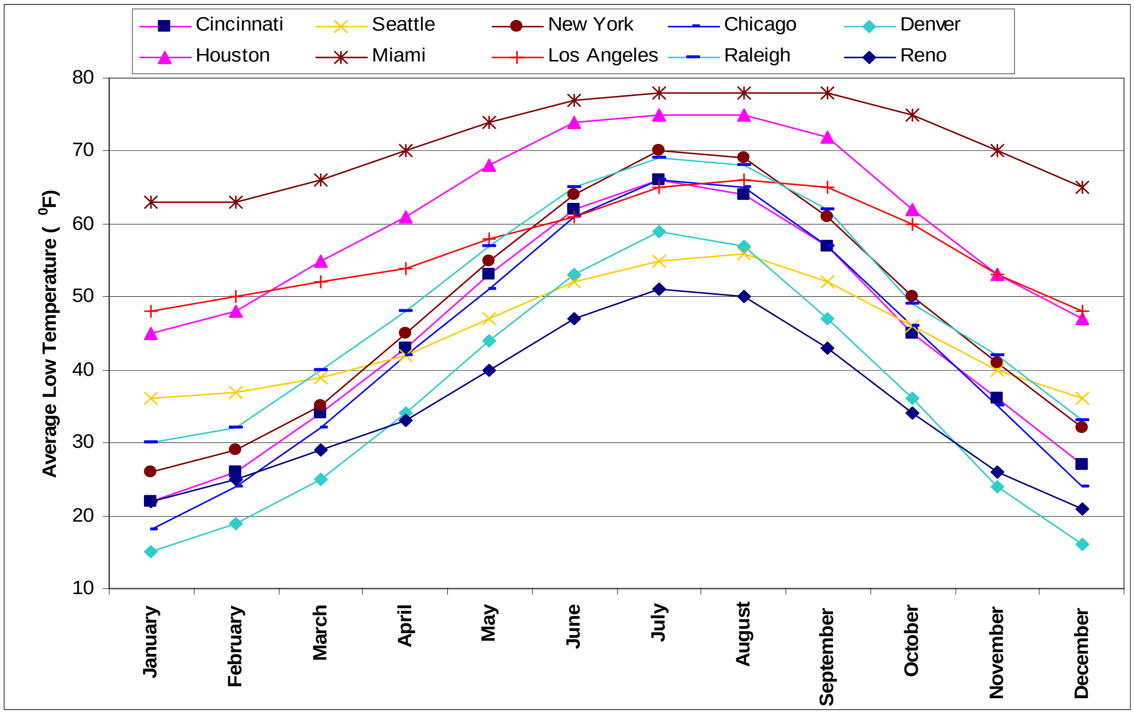

Figure 2: Average annual low temperature of ten major cities across the USA

Extended idling from heavy-duty diesel trucks have economic, environmental, and health effects. These effects range from fuel wastage to significantly adding criteria pollutants to the ambient emissions inventory. It also increases annual repair and maintenance costs by generating more wear and tear on the engines. It would be unwise not to mention the noise pollution generated by idling of long haul trucks throughout the night. Taking into consideration the Argonne National Laboratory's (ANL) data [4] of 1.0-gallon diesel consumption per hour and considering the base case of annual idle duration, 1,500,000 long haul trucks in California consumed 2745 million gallons of diesel annually. This fuel wastage accounts for about 55 billion United States dollars (US$) at present market price. In the same way it could be calculated that these long-haul trucks annually contribute about 28.5 million tons of carbon dioxide (CO_2), 155,000 tons of oxides of nitrogen (NOx), 12,000 tons of hydrocarbons (HC), 260,000 tons of carbon monoxide (CO) and 7000 tons of particulate matter (PM) in California alone. In reality, these amounts could be larger because "calculations presented above" were made in a conservative framework considering the long haul trucks only. All these pollutants together contribute to global warming, formation of ozone smog and pose adverse health effects especially to children, elderly people and people with existing heart or respiratory diseases.

Realizing the extraordinary quantity of idling emissions and their adverse impacts, especially on overall fuel consumption, US federal and state environment organizations have initiated a number of steps in reducing these emissions. 'Anti-Idling Legislation' has been enacted in about 26 states across the United States with some legislation targeting specific urban areas and others with statewide restrictions. This restriction enforces limits on continuous idling from minimum two minutes to maximum fifteen minutes with the majority being five minutes [5]. Long-haul truck operators are also encouraged to use idle reduction technologies that would provide cab heating or cooling. In December 2002, The California Air Resources Board (CARB) adopted its first Anti-idling Airborne Toxic Control Measure (ATCM) that would prohibit school buses and other diesel-fueled vehicles from idling within 100 feet of a school [6]. The CARB has also developed the 'Emissions Factors' (EMFAC) that tabulate idle emissions in grams per hour (g/hr) and grams per minute (g/min) for volatile organic compounds (VOC), CO, and NOx for both summer and winter conditions. Idle emissions of particulate matter (PM_{10}) are tabulated only for HDDV (8501+ lbs GVW) as PM_{10} emissions from gasoline vehicles are considered to be negligible [7]. It is expected that all these steps would primarily reduce idle emissions of NOx, PM, CO, HC, and CO_2, save millions of dollars in fuel and lower maintenance costs by reducing engine wear and tear.

LITERATURE REVIEW

A number of studies have been conducted recently to quantify idle emissions from the HDDV especially from long haul trucks to understand the effect of engine speed and accessory loading on idle emissions from these trucks and to evaluate the performance of idle reduction technologies. McCormick et al. [8] of the Colorado Institute for Fuels and Engines Research, Colorado School of Mines, Colorado performed a comprehensive study on idle emissions from twenty four HDDV (twelve trucks and twelve buses) and four heavy-duty Compressed Natural Gas (CNG) vehicles. Diesel trucks included ten Class 8 and Class 7 trucks, and one school bus whereas CNG vehicles included one medium-duty postal van and three transit buses. They considered hot and cold idle together as they did not find a significant difference between them. The study found that diesel trucks, on average, emitted 10.2g/hr of total hydrocarbons (THC), 70.98g/hr of CO, 84.96g/hr of NOx, and 1.8g/hr of PM of idle emissions, whereas CNG vehicles' idle emissions averaged 86.1g/hr of THC, 67.14g/hr of CO, 16.02g/hr of NOx, and 0.18g/hr of PM. The study could not portray altitude effect on idle emissions. However, the study revealed an increasing trend in idle NOx emissions with increasing engine model years (MY). Idle PM emissions exhibited a weaker trend with respect to engine MY and no significant MY trends were observed for CO or THC idle emissions. The study emphasized the need for additional data on a broader range of engine MY and vehicle types in order to explicitly observe MY trends on idling emissions.

Brodrick et al. [9] examined the effect of engine speed and accessory loading on heavy-duty diesel truck's idle emissions. The study used U.S. Environmental Protection

Agency's (USEPA) emission measurement trailers to quantify idle emissions from a 1999 model year Freightliner [450 horse power (hp) engine] in five idling modes namely idling after cruising, idling after transient cycle, low speed idling and high speed idling with air conditioning (A/C) on in both modes and long high speed idling with A/C on. For all modes the idle emissions of CO, HC, NOx, and CO_2 ranged from 14.6 to 189.7 g/hr, 1.4 to 86.4 g/hr, 103 to 225 g/hr and 4034 to 9743 g/hr respectively. They also measured idle fuel consumption, which ranged from 0.36 to 0.93 gal/hr. The study, however, did not measure idle PM emissions. The study revealed that engine speed and accessory loading significantly affected idle emissions. Increasing the engine speed from 600 rpm to 1050 rpm (with A/C on in both cases) resulted corresponding increase in idle CO, NOx, and CO_2 emissions by approximately 460%, 53% and 90% respectively. It also affected the fuel economy by almost 70%.

Storey et al. [10] of the Oak Ridge National Laboratory (ORNL) examined CO, HC, NOx, CO_2, PM, Aldehyde and Ketone emissions from heavy-duty trucks' exhausts at idle mode. Experimental testing on five Class 8 trucks were performed at the U.S. Army's Aberdeen Test Center (ATC)'s climate controlled chamber between June 2001 and May 2002. Trucks' model years ranged from 1992 to 2001. Out of these five trucks, one was equipped with auxiliary power unit (APU) and another was fitted with a diesel direct-fired heater (DFH). Trucks were tested at both high and low idle speeds in three following climate conditions: 90^0 F with cabin air conditioning on, 0^0F with cabin heater on, and 65^0F with no accessories on. The approximate extreme values of idle emissions were found to be 50 to 350 g/hr of NOx, 10 to 80 g/hr of HC, 0.8 to 20 g/hr of PM, and 22 to 295 g/hr of CO. They also calculated fuel consumption, which ranged from 0.5 to 1.8 gal/hr. The study found that emissions of these species increased with increasing idle speed. It also observed that ambient temperature affected PM emission and data showed that PM increased with increasing ambient temperature. Pekula et al. [11] of the Rowan University, College of Engineering, used the same data set to observe the effect of ambient temperature, humidity, and engine speed on idling emissions from heavy-duty diesel trucks. The study found that emissions rates were a function of both inlet temperature and engine load. Idle NOx and CO_2 emissions for low and high idle speed were 97 g/hr and 5170 g/hr and 181.4 g/hr and 11948 g/hr respectively.

Some additional studies [4, 12] have also been conducted to analyze the potentials of various available and forthcoming idle reduction technologies in reducing idle emissions and saving fuel. These studies also focused on the market compatibility and cost benefit analysis of these technologies. The term "idle reduction technologies" refers to the technologies that allow engine operators to refrain from long-duration idling of the main propulsion engine by using alternative power sources [13]. The alternative power sources provide either heating or cooling or both to the drivers' cabin. Some of them also help in charging batteries and maintaining engine oil, coolant and fluids at the proper temperature for smooth starting of the engine. These technologies are classified into two broad categories: Mobile or on-road technology and stationary or off-road technology. Stationary or off-road technology has further been divided into two sub-groups basing on the requirements of components to operate them. The first category, Electrified Parking Spaces – Single System does not need any supporting system to be fitted on the trucks. Trucks will go to the parking spaces, fit the delivery module onto the cabin and enjoy heating, ventilation and air-conditioning. The second category, Electrified Parking Spaces – Dual System requires technology both on the truck and on the ground. Mobile or on-road technologies on the other hand are fitted on the vehicles or in-built on the engines and include automatic shut down/start up system, battery powered thermal control units, DFH, APU, generator sets etc. Mobile systems require greater financial commitment than stationary systems on the part of the truckers or the employers who buy those [14].

OBJECTIVES OF THE RESEARCH

This thesis aims to present a more generalized picture of idle emissions from a wide range of heavy-duty diesel trucks and buses in terms of model years and engine rated power. In addition to quantifying regulated emissions, CO_2, and idle fuel consumption, this thesis would also observe the trends in idle emissions from vehicles with model years (MY) from 1975 to 2004. This thesis considers idle emissions data from forty-eight heavy-duty diesel trucks from the E-55/59 Study [15] and eighteen heavy-duty diesel vehicles including two diesel-driven transit buses from the Gasoline-Diesel PM Split Study [16]. E-55/59 Study was sponsored by the Coordinating Research Council (CRC), California Air Resources Board (CARB), U.S. Environmental Protection Agency (USEPA), U.S. Department of Energy (DOE) Office of FreedomCAR and Vehicle Technologies through the National Renewable Energy Laboratory (NREL), South Coast Air Quality Management District, and the Engine Manufacturers Association. This project had the major objective of acquiring regulated and non-regulated emissions from in-use trucks in Southern California. The Gasoline-Diesel PM Split Study was sponsored by the U.S. Department of Energy (DOE) Office of FreedomCAR and Vehicle Technologies through the NREL. The objective of this study was to collect reliable regulated PM data from broad spectrum of heavy-duty vehicles in Southern California. Idle emissions of regulated gases and CO_2 and fuel consumption from all these vehicles were examined and reported in g/hr and gal/hr respectively. In addition, emissions from the idle segments of the continuous data on the 'Transient mode' of the Heavy Heavy-Duty Diesel Truck (HHDDT) Schedule were evaluated for all trucks tested during the E-55/59 study and compared with emissions from idle cycles. The thesis also examines the effect of elevated engine speed and accessory loadings including fan and the A/C on idle emissions. In addition, idle emissions data from six Detroit Diesel Corporation (DDC) Series 60 engines of MY 1991, 1992, 1995, and 2000 tested for the fuel certification has also been considered for comparison. Finally a comparison of vehicle idle emissions obtained by the West Virginia University (WVU) and idle data available in the literature has been presented. Vehicle emissions data were collected by the WVU Transportable Emissions Measurement Laboratory (Translab) located at Riverside, California, whereas the engine emissions data were taken from the engine test cell of the Center for Alternative Fuels, Engines, and Emissions (CAFEE) of WVU located in Morgantown, West Virginia.

VEHICLES AND ENGINES MATRICES

For this study data were procured from previous studies that examined emissions from sixty-six HDDV. Table 1 provides information on the actual vehicles recruited. Out of these vehicles, first forty-eight heavy-duty diesel vehicles' data were procured from the E-55/59 Study, in which the author participated. They included twelve DDC engines, thirteen Caterpillar, and twenty three Cummins engines. MY of these engines ranged from 1975 to 2004. However, for the first twenty-five trucks, vehicle MY has been taken as engine MY since engine MY of these trucks were not recorded when they were procured for emissions testing. The next eighteen heavy-duty trucks and buses' data were procured from the PM Split Study, where a total of thirty-two tractor/box trucks and two diesel buses were tested. This thesis takes into consideration the idle emissions of sixteen 'Class 8' trucks and two 'Class 7' trucks with GVW more than 32,000 lbs. They included one Volvo, three Cummins, five DDC, and seven Caterpillar engines. Two buses had DDC 6V92 model 2-stroke diesel engines. MY of all the engines from the PM Split Study ranged from 1982 to 2001. Interesting to note that three trucks in the E-55/59 Study (CRC-1, CRC-2, and CRC-3) were also procured for the PM Split study. These three trucks were designated as PM-33, PM-26, and PM-16 respectively. This repetition provided the opportunity to observe the repeatability of data generation from the same vehicle in two different studies.

Table 1: Vehicles Tested for Acquiring Idle Data

Identification	**Vehicle Model Year**	**Vehicle Manufacturer**	**Engine Model Year**	**Engine Model**	**Engine Power (hp)**	**Engine Manufacturer**
E55CRC-1	1994	Freightliner	1994	Series 60	470	Detroit
E55CRC-2	1995	Freightliner	1995	CAT3406 B	375	Caterpillar
E55CRC-3	1985	International	1985	NTCC	300	Cummins
E55CRC-4	2000	Navistar	2000	CAT C-10	270	Caterpillar
E55CRC-5	2000	Freightliner	2000	N14-435E1	435	Cummins

E55CRC-6	1995	Freightliner	1995	Cummins	370	Cummins
E55CRC-7	1990	Peterbilt	1990	Series 60	450	Detroit
E55CRC-8	1996	Kenworth	1996	M11-300	370	Cummins
E55CRC-9	1998	Peterbilt	1998	C 12	410	Caterpillar
E55CRC-10	1998	Sterling	1998	Series 60	470	Detroit
E55CRC-11	2000	Freightliner	2000	ISM	330	Cummins
E55CRC-12	1986	International	1986	Cummins	300	Cummins
E55CRC-13	1978	Freightliner	1978	Cummins	350	Cummins
E55CRC-14	1986	International	1985	LTA10	270	Cummins
E55CRC-15	1973	Kenworth	1986	NTC	350	Cummins
E55CRC-16	1979	White	1979	CAT 3208	200	Caterpillar
E55CRC-17	1993	Freightliner	1993	L-10	330	Cummins
E55CRC-18	1991	Ford	1991	L-10	300	Cummins
E55CRC-19	1987	International	1987	L-10	300	Cummins
E55CRC-20	1992	Peterbilt	1992	Series 60	450	Detroit
E55CRC-21	1990	Freightliner	1990	3406 B	400	Caterpillar
E55CRC-22	1993	Ford	1993	L-10	280	Cummins
E55CRC-23	1983	Peterbilt	1983	Cummins	N/A	Cummins
E55CRC-24	1975	Kenworth	1975	NTCC	350	Cummins
E55CRC-25	1983	Freightliner	1983	Cummins	N/A	Cummins
E55CRC-26	1999	Freightliner	1998	C-10	270	Caterpillar
E55CRC-27	2000	Freightliner	1999	Series 60	500	Detroit
E55CRC-28	1999	Freightliner	1998	Series 60	500	Detroit
E55CRC-29	2000	Volvo	1999	ISX475ST2	450	Cummins
E55CRC-30	1999	Freightliner	1998	Series 60	500	Detroit
E55CRC-31	1998	Kenworth	1997	N14-460E+	460	Cummins
E55CRC-32	1992	Volvo	1991	3406B	280	Caterpillar
E55CRC-33	1985	Freightliner	1984	3406	310	Caterpillar
E55CRC-34	2004	Freightliner	2003	Series 60	500	Detroit
E55CRC-35	2001	Sterling	2000	Series 60	470	Detroit
E55CRC-36	2001	Peterbilt	2001	C-15	475	Caterpillar
E55CRC-37	2004	Volvo	2004	ISX	500	Cummins
E55CRC-38	2003	Volvo	2004	ISX	530	Cummins
E55CRC-39	2004	Volvo	2003	ISX	530	Cummins
E55CRC-40	2004	Freightliner	2003	Series 60	500	Detroit
E55CRC-42	2000	Freightliner	1999	3406	435	Caterpillar

E55CRC-43	1995	Peterbilt	1994	Series 60	470	Detroit
E55CRC-44	1989	Volvo GM	1989	3406	N/A	Caterpillar
E55CRC-45	1993	Volvo GM	1993	L10-280	280	Cummins
E55CRC-46	1989	Freightliner	1989	3176	N/A	Caterpillar
E55CRC-47	1986	Ford	1986	6V92	350	Detroit
E55CRC-48	1998	Freightliner	1998	N14 Plus	447	Cummins
E55CRC-49	1994	International	1993	N/A	N/A	Caterpillar
PM-31*	1982	GMC	1982	6V92/8067-3421	340	Detroit
PM-17	1985	Freightliner	1985	3406 B	350	Caterpillar
PM-16	1985	International	1985	NTCC-300	300	Cummins
PM-18	1992	Ford	1992	3406 B	280	Caterpillar
PM-20	1992	Volvo	1992	3406 B	280	Caterpillar
PM-32*	1992	Transportation Manufacturer	1992	6V92/8067-3K21	270	Detroit
PM-19	1993	Freightliner	1993	Series 60C	350	Detroit
PM-21	1994	Freightliner	1994	M11-330B	330	Cummins
PM-25	1994	Freightliner	1994	L14101	365	Detroit
PM-33	1994	Freightliner	1994	Series 60	470	Detroit
PM-26	1995	Freightliner	1995	3406 B	375	Caterpillar
PM-22	1996	Volvo	1996	VE-D12	425	Volvo
PM-24	1997	Ford	1997	Series 60	365	Detroit
PM-23	1997	Volvo	1997	CAT 3406	435	Caterpillar
PM-30	1998	Sterling	1998	Series 60	470	Detroit
PM-27	1999	Sterling	1999	CAT C-12	425	Caterpillar
PM-29	2000	Sterling	2000	CAT C-12	425	Caterpillar
PM-28	2001	Volvo	2001	2N14-370	370	Cummins

* Transit bus

While observing the trend in idle emissions with respect to MY, selection of vehicles over the period and number of vehicles in each MY year plays an important role. In the E-55/59 Study, efforts were made to procure vehicles for every MY to have an even distribution of vehicles over the MY. MY distributions of the vehicles from the E-55/59 and the PM Split Study are shown in Figure 3. The test matrices included only the heaviest class of on-road diesel vehicles of GVW 30,000 lbs and above as higher emissions rates are associated with heavy class of vehicles [17].

Emissions data obtained from the above vehicles were then compared with the engine idle emissions, which have been obtained by the CAFEE. A total of six DDC Series 60 engines of MY 1991, 1992, 1995, and 2000 were tested. Idle emissions data from these engines were collected and presented in g/hr. These engines were operated with Type 2-D diesel, Shell diesel, and CARB specified diesel. These engines were operated on the Federal Test procedure (FTP) cycle as per the test requirement from which the idle segments have been considered only in order to quantify idle emissions.

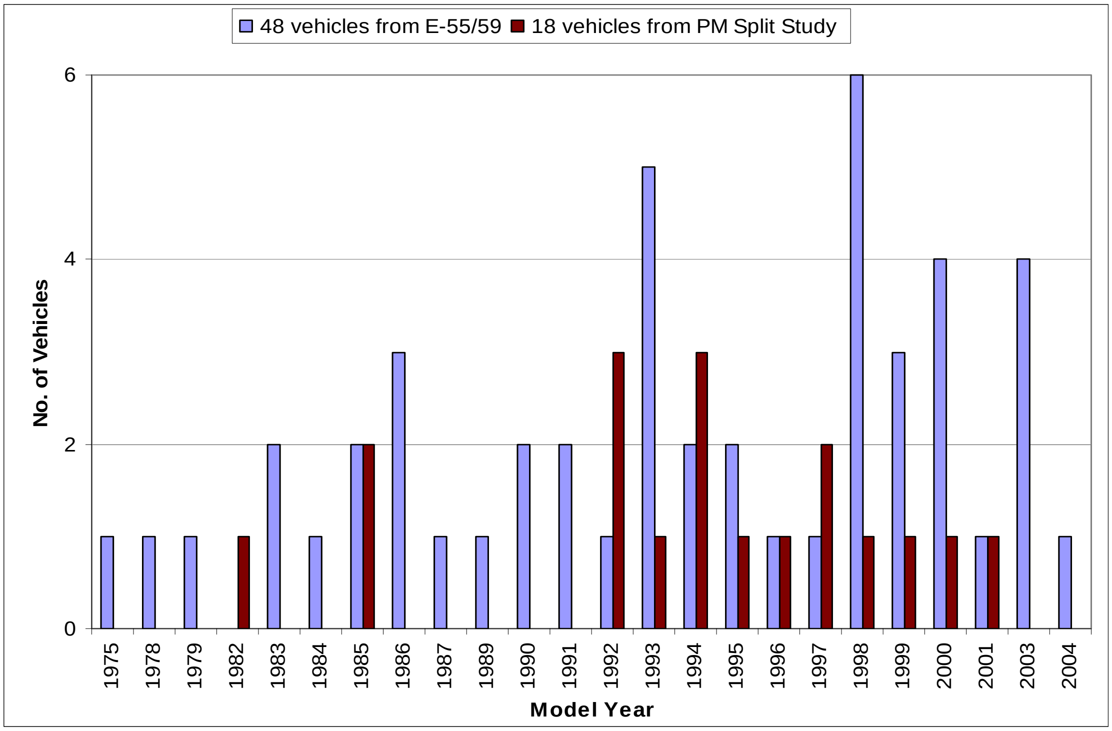

Figure 3: Model year distribution of engines

TEST SITE, LABORATORY, AND SAMPLING ANALYSIS

Test Site and Test Duration

WVU Translab, while located on the West Coast (Riverside, California) was assigned to conduct emissions characterization from the vehicles listed in Table 1. Data for both the studies were collected over a long period from July 2001 to March 2004. Because of this long duration, some vehicles were tested during summer time when ambient temperatures were in the 90s degree Fahrenheit (^{0}F), whereas, some were tested during the winter time when ambient temperatures dropped to the lower 40s (^{0}F) (Figure 4). At the same time the relative humidity varied over this long duration, although variation of relative humidity was more profound from morning to afternoon. On average, there was 26% difference in the relative humidity from morning to afternoon (Figure 5). This wide variation in relative humidity and temperature was likely to affect idle emissions, especially NOx. Pekula et al. [11] observed a 15% to 20% decrease in idle NOx concentration when relative humidity increased by a factor of three. They also observed that NOx emissions had increased with increasing ambient temperatures. Figure 4 and Figure 5 show average annual relative humidity and average high and low temperature profiles of Riverside, California [18, 19].

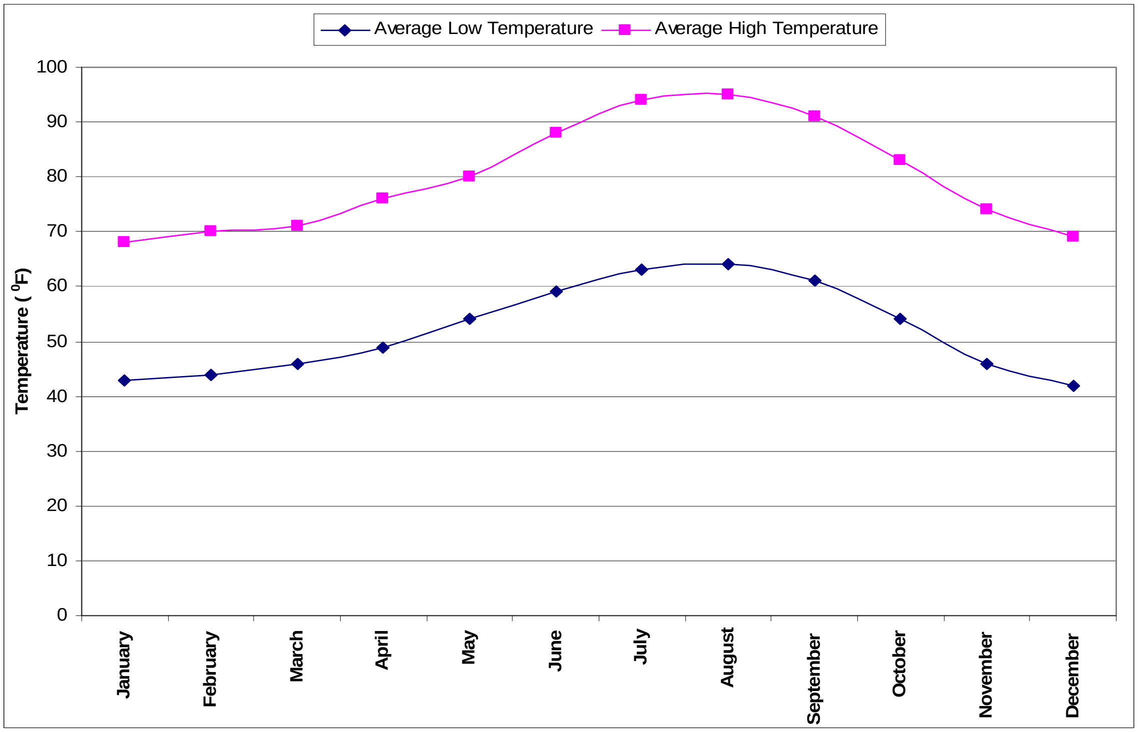

Figure 4: Monthly average high and low temperatures for Riverside, California

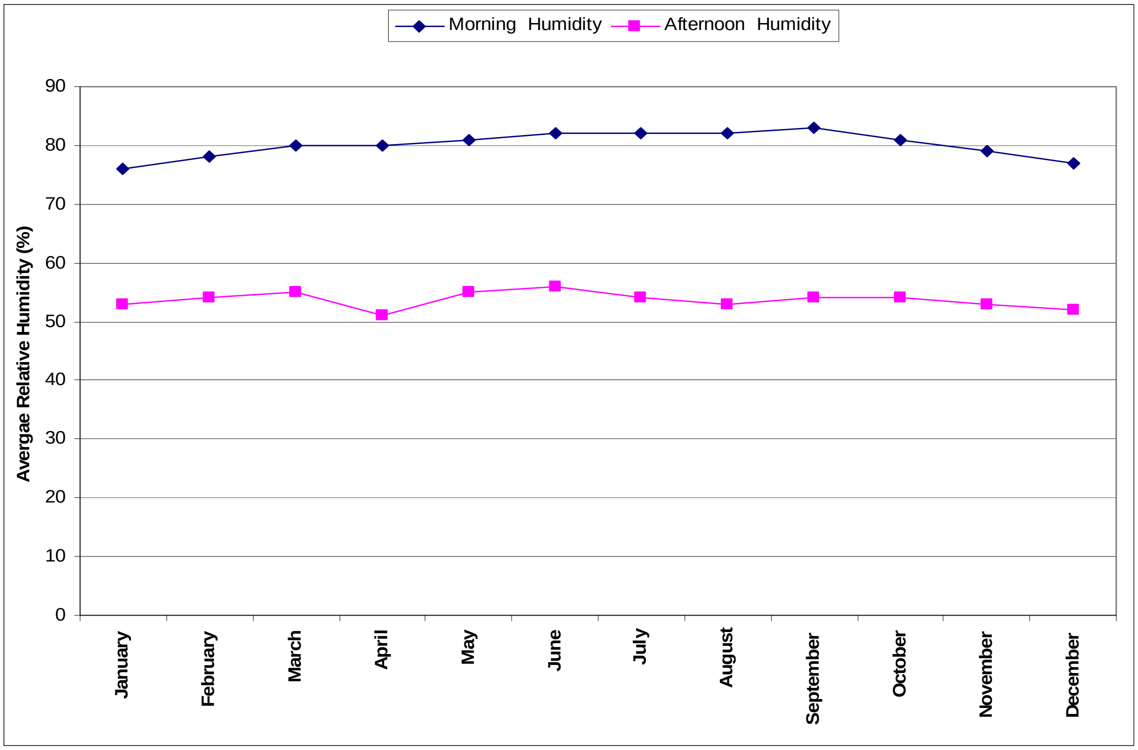

Figure 5: Average annual relative humidity profile for Riverside, California

Test Laboratory and Sampling

All vehicles under the E-55/59 Study and the Gasoline/Diesel PM Split Study have been tested on the WVU Translab, while located at Riverside, California. The Translab was equipped with the state-of-the-art engine test equipment and was capable of testing medium and heavy-duty diesel vehicles. During idle, the vehicle was kept at idle for certain time with the engine speed kept at 600 revolutions per minute (rpm). For the Transient mode of the HHDDT Schedule, the driver operated the vehicle following the prescribed vehicle speed trace presented on a monitor, placed in front of him inside the cabin of the vehicle. The Translab had a full-scale exhaust dilution tunnel capable of measuring heavy-duty vehicles exhaust emissions in accordance with the Code of Federal Regulations (CFR) [20]. Idle exhaust was ducted to the dilution tunnel based on the critical flow venturi – constant volume sampling (CFV-CVS) concept. Microprocessor controlled heated probes and sampling lines were used to draw gaseous samples into the gas analyzers. Background samples and dynamic blanks were gathered for the correction of measured regulated emissions. Continuous sampling and analysis of the exhaust stream were accomplished by the non-dispersive infrared (NDIR) analyzers for CO and CO_2; wet chemiluminescent analyzers for NOx; and a heated flame ionization detector (HFID) for HC. Data from the dynamometer, emissions measurement equipment and test engines were acquired and archived at a frequency of 5 hertz (Hz). PM was sampled using two parallel filter-sampling trains. Continuous PM was measured using a Tapered Element Oscillating Microbalance (TEOM) and cycle-averaged PM was measured using filtration of diluted exhaust on two 70-mm fluorocarbon coated glass fiber filters. These filters were weighed before and after each test following proper conditioning. A detailed description of the WVU Translab can be found in two papers [21, 22]. Point to note that since the instruments were ranged for driving cycles, some accuracy might have been sacrificed at light load (idle).

TEST FUELS

During the E-55/59 Study and the PM Split studies, vehicles tested for the idle emissions were operated with CARB specified diesel, which specifies a minimum 48 Cetane Number (CN) and 0.05% sulfur (maximum) by weight. During the project period, some samples of CARB diesel were analyzed and detailed specifications were obtained. Table 2 compares laboratory analyzed average values of some salient properties and the prescribed properties for the CARB specified diesel [23].

Table 2: Comparison of Specified and Evaluated Properties of the CARB Specified Diesel

Fuel Property	Unit	CARB Specifications	CARB Measured Value
Cetane Number		48 (min)	52.9-54.4
Sulfur	% (weight)	0.05 (max)	0.0060-0.0148
Aromatics	% (volume)	10 (max)	19.82-21.49, Total Aromatics (by wt %)
Polycyclic Aromatics	% (weight)	1.4 (max)	2.92-3.44
API Gravity		33-39	37.6-38.7
Kinematic Viscosity @40^0C	mm^2/s	2.0-4.1	2.42-2.781
Flashpoint	^{0}F	130 (min)	132-154
Distillation Range	^{0}F		
10% point		340-420	386.1-415.5
50% point		400-490	492.1-517.7
90% point		470-560	611.2-626.9

TEST SCHEDULE AND PROCEDURE

As there cannot be any prescribed idle drive cycle, vehicles were idled for certain duration (seconds) to collect emissions data. These data has been analyzed and converted into g/hr. In the E-55/59 Study, vehicles were kept on idle for either 900 (Idle 3) or 1800

(Idle 32) or 2700 (Idle 33) seconds, whereas in the PM Split Study, vehicles were idled for 1180 seconds, except one vehicle, which stopped idling after 1080 seconds. Average emissions from the short idle and long idle tests of CRC-2 truck (MY 1995 Freightliner) are presented in Figure 6. Y-error bars represent ±1 standard deviation for each pollutant. Difference in test schedule duration that is, the short idle (Idle 3) and long idle (idle 32) had mixed effect on emissions rates. CO, HC, NOx, and CO_2 varied little but PM showed greater variation. Therefore, average emissions from all idle tests were compiled for all vehicles over the entire database. Every vehicle and engine was tested at least two times on idle in order to get good repeatability of the test results. In case of variable repeatability the vehicle was tested again to get the repeatability within acceptable limit. All vehicles, except CRC-38 truck of the E-55/59 have been operated at constant engine speed of approximately 600 rpm without any accessory loading. CRC-38 truck, in addition to two test runs at 600 rpm engine speed was operated with 1100 rpm engine speed and A/C to observe the effect of elevated speed and A/C on emissions and fuel consumption.

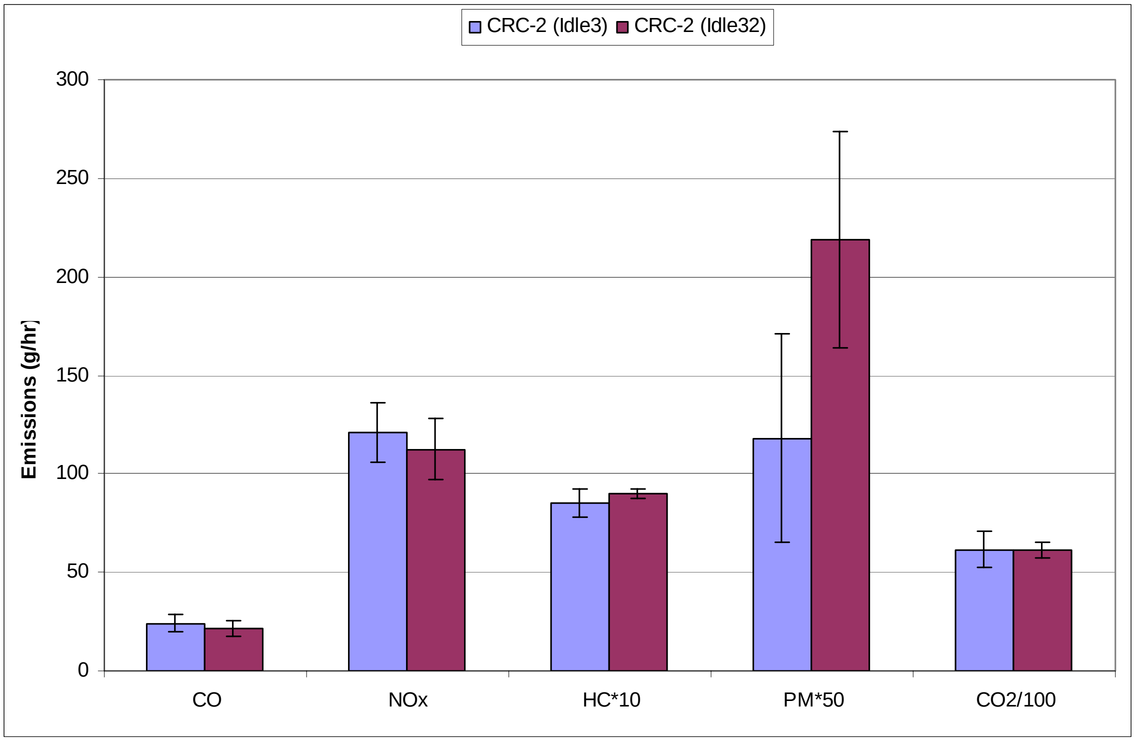

Figure 6: Effect of idle duration on emissions

RESULTS AND DISCUSSION – CHASSIS DATA

This section begins with a discussion on test-to-test variations from all vehicles tested during the E-55/59 Study and the PM Split Study and their graphical presentation followed by a detailed discussion on the improvement in engine technology from 70s to late 90s. MY effects on idle emissions were observed in two broad groups: MY 1975 to 1990 and MY 1991 to 2004, because of the difference in engine technology during these periods, which has been discussed in MY Split section. Idle CO, HC, NOx, and PM emissions measured from tested vehicles are presented in the following sections. CO_2 emissions, although not regulated by the USEPA have also been evaluated and presented in this study. In addition, idle fuel consumption inferred from the CO_2 emissions for these vehicles was measured and presented in gal/hr. This section also makes an endeavor to observe the effect of air conditioning and elevated engine speed on idle emissions. Transit bus idle emissions are always of special interest because of their direct exposure to the community and therefore, have been presented in separate section.

Test-To-Test Variation

In order to observe the test-to-test variations during the testing, emissions data from three trucks E-55/59 CRC-7, CRC-19, and CRC-28 of MY 1990, 1987, and 1998 respectively have been presented. These three vehicles were tested five times on idle mode. Average emissions data with ±1 standard deviations and coefficient of variance (COV) are presented in Table 3. These data are also graphically presented in Figure 7 with Y-error bars showing the ±1 standard deviations. Higher standard deviations from these test results could be attributed to varying ambient conditions, differences in engine technology, and driver's driving pattern in maintaining idle speed of 600rpm and different engine components such as the cooling fan, alternator, and air brake compressor [24]. NOx emissions on idle can also vary when electronic injection is used because the manufacturer may advance the timing at light load to maintain combustion stability and reduce PM containing high soluble organic fraction. Variability in the PM measurement could be attributed partly to the difficulty in measuring PM with filters lightly loaded, partly to the background corrections, and partly to the true variation between trucks because both injection timing and the condition of the injection system would affect the formation of PM. High variations in idle CO emissions could also be attributed to the variations in air-fuel ratio [17].

Table 3: Test-to-Test Variations in Emissions from CRC-7, CRC-19, and CRC-28 Trucks of the E-55/59 Study

Vehicle	Pollutants	Test 1	Test 2	Test 3	Test4	Test 5	Test 6	Average	σ	COV
CRC - 7 MY ’90	***CO (g/hr)***	***9.16***	***7.32***	***6.16***	***6.76***	***4.04***	***8***	***6.9***	***1.75***	***25.30***
	NOx (g/hr)/10	***8.2***	***7.14***	***7.16***	***6.64***	***9.56***	***9.84***	***8.09***	***1.35***	***16.68***
	THC (g/hr)	***3.64***	***2.22***	***2.12***	***1.48***	***3.24***	***3.8***	***2.75***	***0.94***	***34.21***
	PM (g/hr)*10	***0***	***0***	***0.4***	***1.6***	***4***	***2***	***1.33***	***1.55***	***116.74***
	CO_2 (g/hr)/100	***40***	***31.38***	***32***	***28.8***	***39.08***	***41.04***	***35.38***	***5.25***	***14.84***
CRC -19 MY ’87	CO (g/hr)	30.4	40.4	34	33.2	59.6	59.2	42.8	13.27	31.00
	NOx (g/hr)/10	2.92	2.68	0.8	1.92	1.52	1.52	1.89	0.79	41.98
	THC (g/hr)	29.2	34.4	16.8	27.2	41.2	30	29.8	8.09	27.15
	PM (g/hr)*10	51.2	56.8	68.4	55.2	84.8	91.2	67.93	16.69	24.56
	CO_2 (g/hr)/100	43.92	44.4	28.92	37.44	38.88	35.88	38.24	5.72	14.96
CRC - 28 MY ’98	***CO (g/hr)***	***35***	***35.4***	***23.4***	***30.4***	***28.6***	***26.2***	***29.83***	***4.78***	***16.02***
	NOx (g/hr)/10	***8.68***	***8.2***	***9.14***	***13.56***	***15.76***	***12.36***	***11.28***	***3.07***	***27.26***
	THC (g/hr)	***3.8***	***2.42***	***2.42***	***1.06***	***2.18***	***0***	***1.98***	***1.30***	***65.88***
	PM (g/hr)*10	***6.8***	***5.8***	***6***	***3.8***	***5.2***	***4.6***	***5.37***	***1.07***	***19.91***
	CO_2 (g/hr)/100	***38.88***	***35.22***	***34.4***	***42.08***	***47.6***	***44.46***	***40.44***	***5.22***	***12.91***

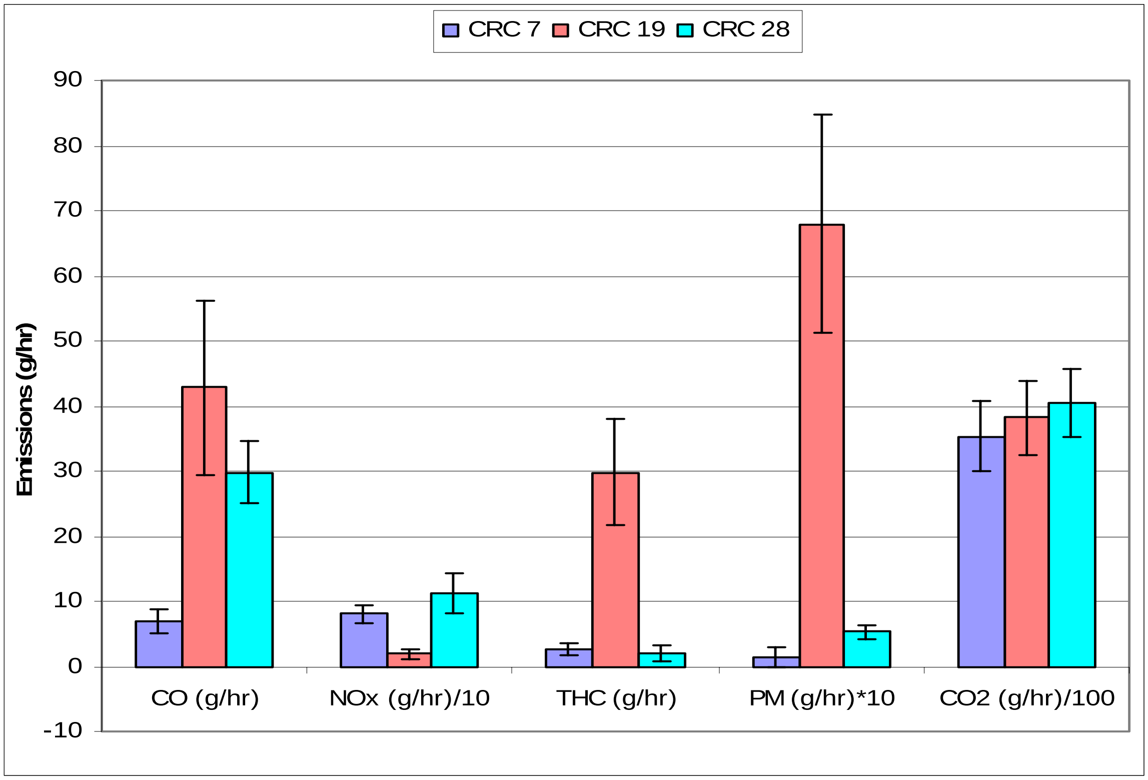

Figure 7: Average Idle emissions from CRC-7, CRC-19, and CRC-28 trucks of the E-55/59 Study with Y-error bars showing ± 1 standard deviations

Repeatability of Idle Data

Three vehicles from the E-55/59 Study had also been tested on idle on the PM Split Study. CRC-1, CRC-2, and CRC-3 trucks from the E-55/59 refer to PM-33, PM-26, and PM-16 trucks of the PM Split Study respectively. During the E-55/59 Study, these trucks were tested on idle for a number of runs while they were tested for one idle test run under the PM Split Study. Average idle emissions from the E-55/59 have been compared to the idle values obtained from the PM Split Study and presented in Figure 8. The first two trucks showed little variation in CO, NOx, and HC emissions. On the second truck CO_2 decreased by about 20% while PM increased by about 50% when the truck was tested for the E-55/59. On the third truck PM decreased by about 30% while CO_2 decreased by 55% when tested during the E-55/59 Study.

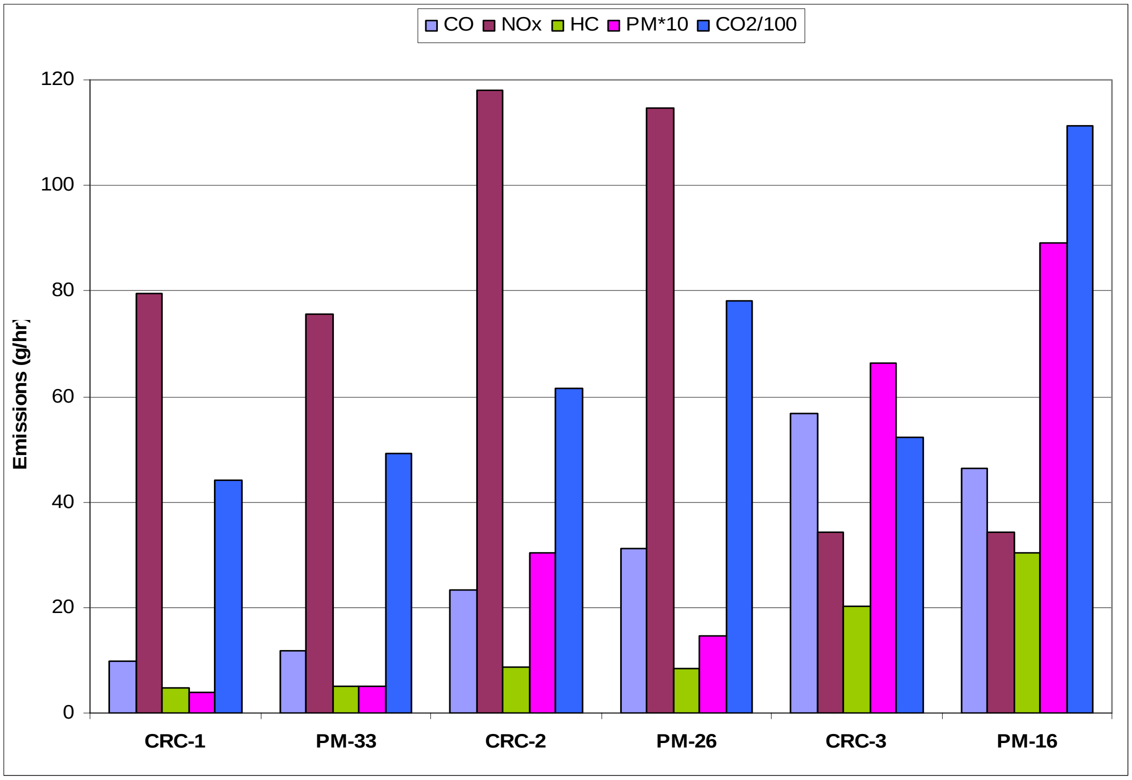

Figure 8: Repeatability of idle data. CRC-1, CRC-2, and CRC-3 truck of the E-55/59 Study were also tested during the PM Split Study as PM-33, PM-26 and PM-16 respectively

Model Year Split

Idle emissions trends were observed by observing emissions into two distinct groups: vehicles with MY 1975-1990 and MY 1991-2004 because, the automobile industry has gone through many remarkable changes during the 90s partly due to the enforcement of stricter emissions regulations and partly due to the outstanding advancements in this field. These changes together contributed to lower emissions of some of the criteria pollutants, more engine power, and improved fuel economy because of efficient combustion and electronic fuel injection. It has been observed that the majority of the vehicles with MY 1975-1990 had mechanically managed engines, whereas the majority of the vehicles with MY 1991-2004 had electronically managed engines. Electronically managed engines have advanced timing at low loads to avoid ‘white smoking’. Advanced timing increases the cylinder temperature and more NOx is generated [25]. It would be unwise not to mention the contribution of other developments such as injection rate shaping, low sac cooling, charge motion, superior fuel atomization, and reduced engine oil consumption. Superior fuel atomization and air management, charge motion, reduced engine oil consumption decreases PM production for later MY vehicles. Therefore, observing the trends in emissions in pre 1990 (1975-1990) MY and post 1990 MY will provide effective comparison in emissions characteristics from these groups of vehicles.

NOx/CO_2 Ratio

In order to observe the immediate difference between pre 1990 (1975-1990) and post 1990 MY, NOx/CO_2 ratios from both the Transient mode of the HHDDT Schedule and idle cycles were observed. NOx/CO_2 ratio is an indicator of advance injection timing, which has been employed by the engine manufacturers in the 90s in order to ensure complete and stable combustion. It is also an indicator of how much emissions are released per unit of fuel consumption since fuel consumption is calculated from CO_2 emissions**.** Table 4 compiles the summery of idle NOx/CO_2 ratio from the E-55/59 and the PM Split Study and the Transient NOx/CO_2 ratio from the Transient mode of the E-55/59 only.

Table 4: Idle NOx/CO_2 Ratio from the E-55/59, PM Split Study and the NOx/CO_2 Ratio from the Transient Mode

NOx/CO_2 Ratio	MY 1975-1990	MY 1991-2004
E-55/59 Study	0.0104	0.0182
PM Split Study	0.0154	0.0179
Transient (From E-55/59)	0.0087	0.0089
Idle (E-55/59)/Transient Ratio	1.1954	2.0449

For the E-55/59 program NOx/CO_2 ratio for the post 1990 MY vehicles was 75% higher than the NOx/CO_2 ratio of the MY 1975-1990 MY vehicles, whereas for the PM Split Study this ratio was 26% higher for the later MY vehicles. However, the PM split Study only had three vehicles with MY 1975-1990. NOx/CO_2 ratio in the Transient mode from the same vehicles of the E-55/59 program showed a different picture. NOx/CO_2 ratio from the Transient mode was lower than the idle NOx/CO_2 ratio and varied little for the later MY vehicles. High NOx/CO_2 ratio for the later MY vehicles indicated advanced injection timing on them. Engine manufacturers have been doing this intentionally in order to reduce white smoke and to ensure combustion stability at light loads (during idle). Figure 9 shows the NOx/CO_2 from the idle mode and the Transient mode.

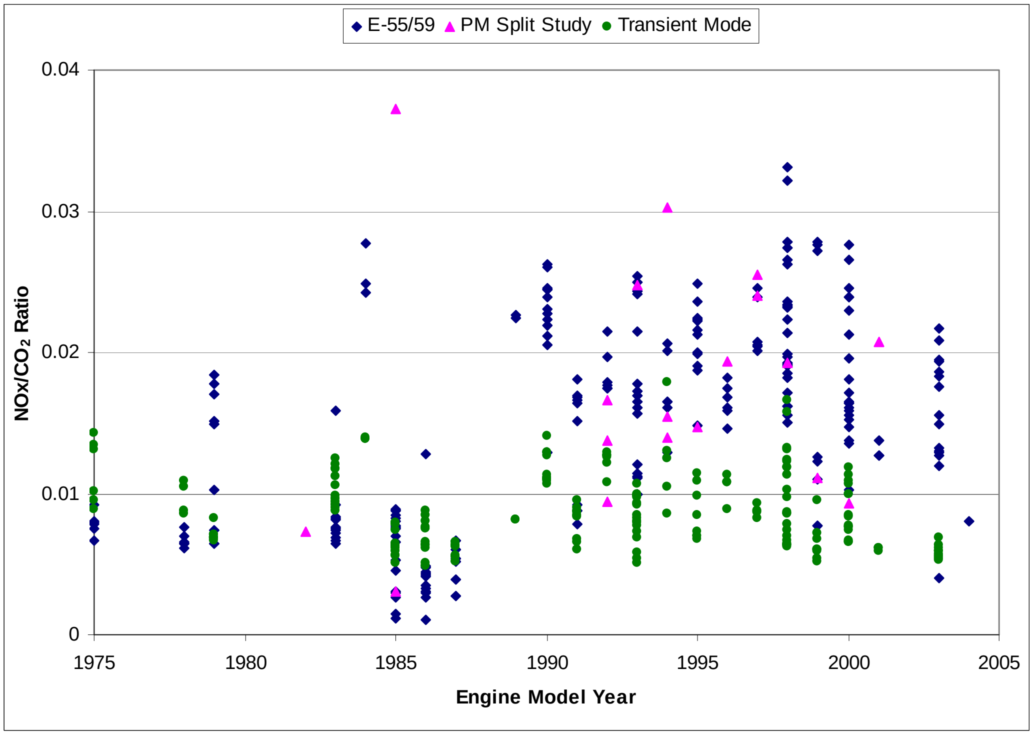

Figure 9: Comparison of idle and transient NOx/CO_2 ratio

Regulated Emissions

Carbon Monoxide (CO)

CO emissions from heavy-duty diesel vehicles are generally low during normal operation and reduced further during idling. Idle CO emissions data of sixty-six vehicles have been collected and arranged according to increasing MY in Figure 10. Data showed a decreasing linear trend from 1975 to 2004 although the trend was not that conclusive (R^2=0.08). These data also showed two divisions from MY 1975-1990 and MY 1991-2004. Idle CO emissions from the maximum vehicles with MY 1975-1990 averaged approximately 31 g/hr whereas the post 1990 MY vehicles averaged 23 g/hr. In this data set CRC-3, CRC-12 and CRC-4 trucks of the E-55/59 Study had exhibited more than 80 g/hr of CO emissions in some idle test runs. There were equipment malfunction while testing CRC-4 (first run), and it was not considered in the modified data. CRC-3 was repaired and re-tested. Modified data included idle emissions after the repair. CRC-16 and CRC-45 was malfunctioning vehicle and was identified as inspection and maintenance [I&M] candidates, for which they were excluded from the modified data. CRC-38 was tested with A/C and at elevated speed, which were not included in the modified data. Therefore, Eliminating CRC-3 (MY 1985) and CRC-4 (MY 2000) vehicles' idle emissions from the data group provided a more conclusive decreasing trend with increasing engine MY as seen in Figure 11.

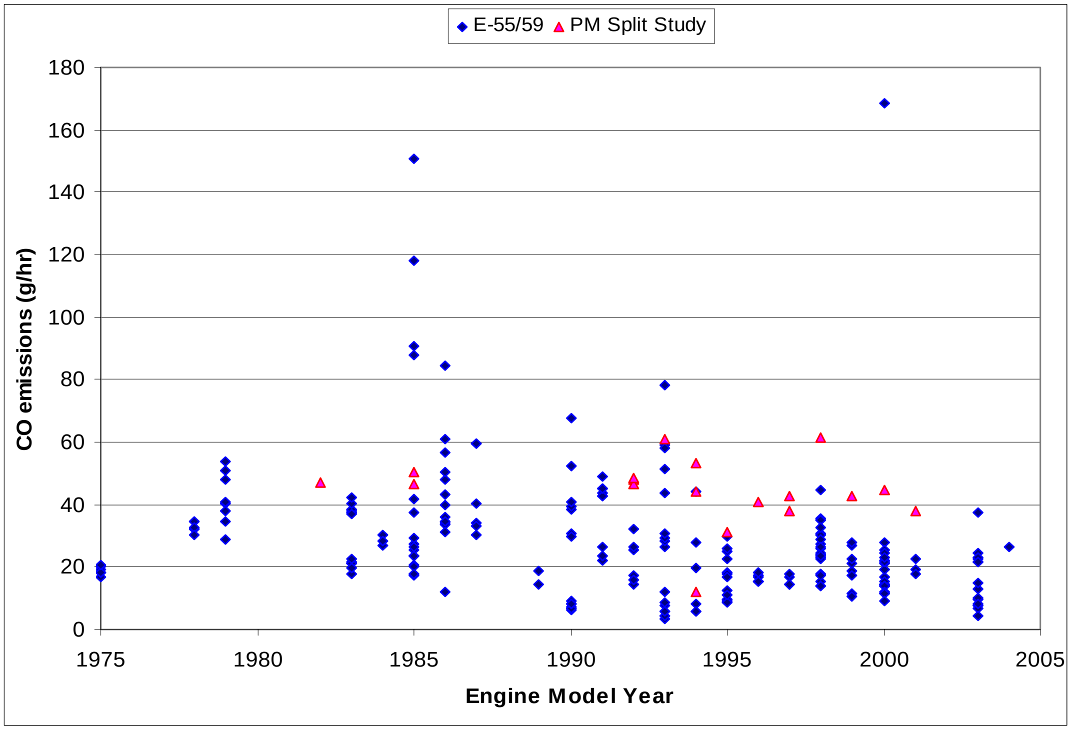

Figure 10: Idle CO emissions

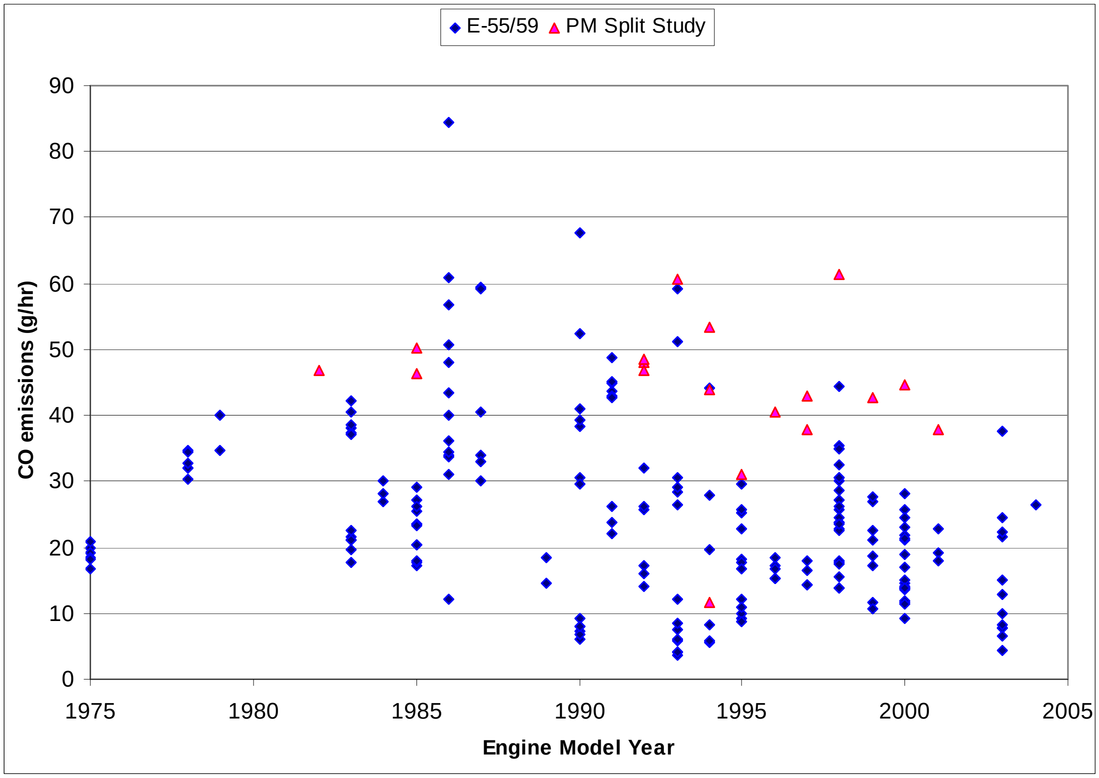

Figure 11: Idle CO emissions, excluding emissions from CRC-16, CRC-38, and CRC-45 trucks. Scale differs from Figure 10

Hydrocarbons (HC)

Idle HC emissions, like idle CO emissions, from diesel engines are usually very low in comparison to their gasoline counterpart, because of high combustion efficiency. More so, accurate data are difficult to obtain because they may be comparable to ambient background levels. Figure 12 presents the idle HC emissions with increasing engine MY, which showed an apparent downward trend. Idle HC emissions from vehicles with MY 1975-1990 averaged approximately 21 g/hr whereas vehicles with post 1990 MY averaged 9 g/hr. Almost all vehicles from 1975 to 2004 MY had HC emissions less than 50 g/hr except CRC-15, CRC-22, and CRC-45 of the E-55/59 Study. HC emissions from CRC-15 truck ranged from 34 g/hr to 95 g/hr averaging 62 g/hr, while HC emissions from CRC-22 ranged from 52 g/hr to 65 g/hr. CRC-45 emitted the highest HC emissions, which ranged from 200 g/hr to 315 g/hr. These vehicles also emitted very high CO and PM emissions on these test-runs. CRC-45 (MY 1993), was an Inspection and Maintenance [I&M] candidate with a number of maintenance problems. On the other hand, in some cases idle HC emissions were too low and could not even be detected accurately. For example, one test-run each from E-55/59 CRC-12, CRC-28, CRC-30 and CRC-40 trucks and PM-19 truck emitted almost zero or below detectable idle HC emissions. Modified HC emissions, which did not include emissions from CRC-3 (before repair), CRC-16, CRC-38, and CRC-45 trucks, showed a downward trend with increasing MY (Figure 13). These findings were contrary to the findings of McCormick et al. [8] who did not observe any trend for idle HC emissions with engine MY.

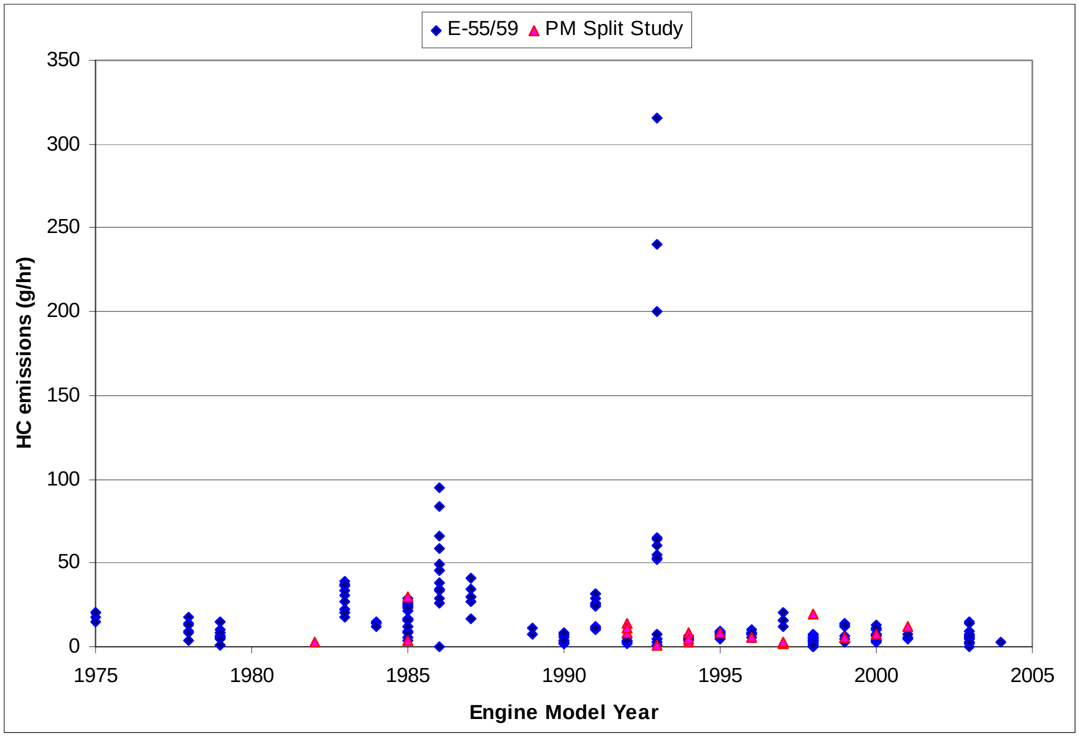

Figure 12: Idle HC emissions

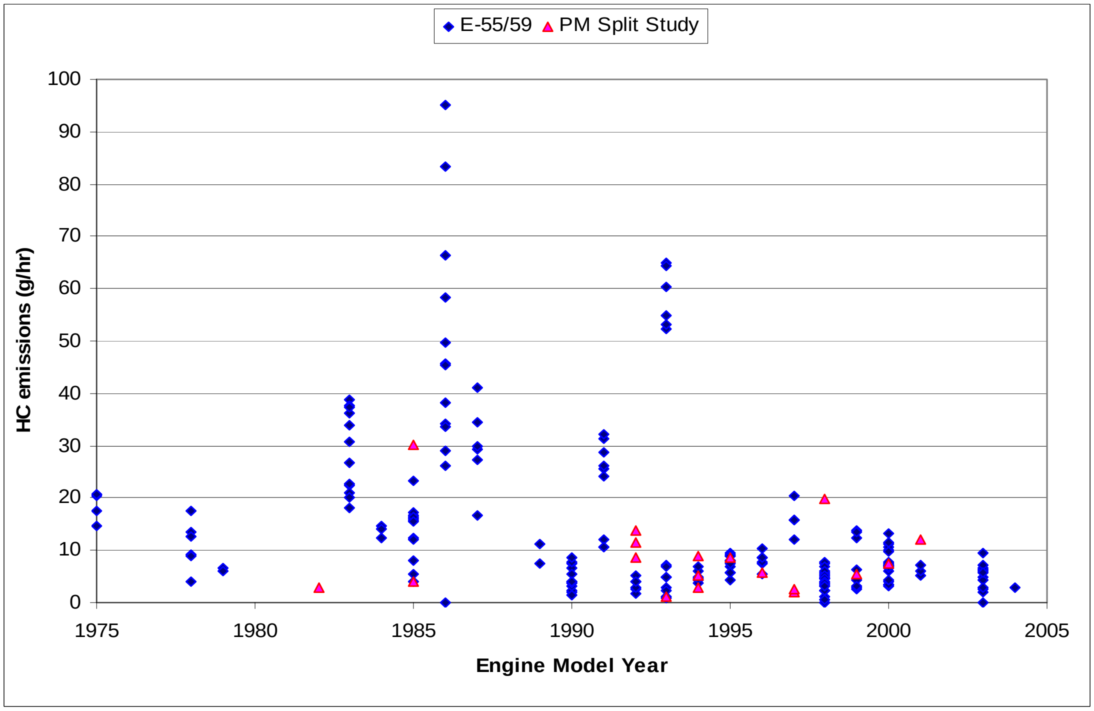

Figure 13: Idle HC emissions excluding emissions from CRC-16, CRC-38, and CRC-45 trucks. Scale differs from Figure 12

Oxides of Nitrogen (NOx)

Idle NOx emissions exhibited a total contrast to the idle CO and HC emissions. It showed an upward trend with increasing engine MY (Figure 14), which was also demonstrated while observing the NOx/CO_2 ratio. MY 1975-1990 vehicles averaged approximately 46 g/hr of idle NOx emissions, whereas vehicles with post 1990 MY emitted approximately 85 g/hr of idle NOx emissions. Overall, the idle NOx data varied from approximately 3 g/hr to 242 g/hr. Out of all the vehicles tested CRC-38 truck (MY 2003) of the E-55/59 emitted extremely high NOx emissions, which had been tested with A/C and elevated engine speed. Two test-runs on this truck with elevated speed with and without A/C had 242 and 207 g/hr of idle NOx emissions respectively. Therefore, emissions from these test-runs were excluded in the modified data. The modified NOx emissions also do not include emissions from the CRC-16, CRC-45 trucks. Figure 15 shows modified NOx emissions, which showed an increasing trend with MY. MY 1975-1990 vehicles emitted approximately 48 g/hr of NOx while the post 1990 vehicles emitted about 83 g/hr of NOx. The increasing trend of NOx emissions with engine MY also confirmed the findings of McCormick et al [8].

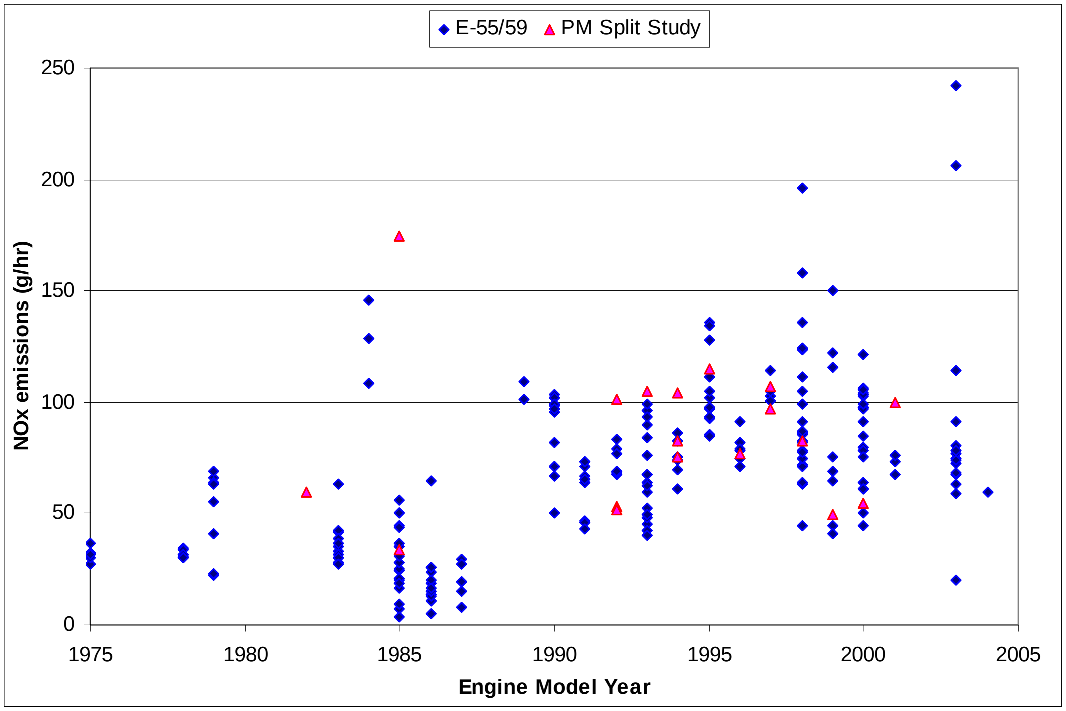

Figure 14: Idle NOx Emissions

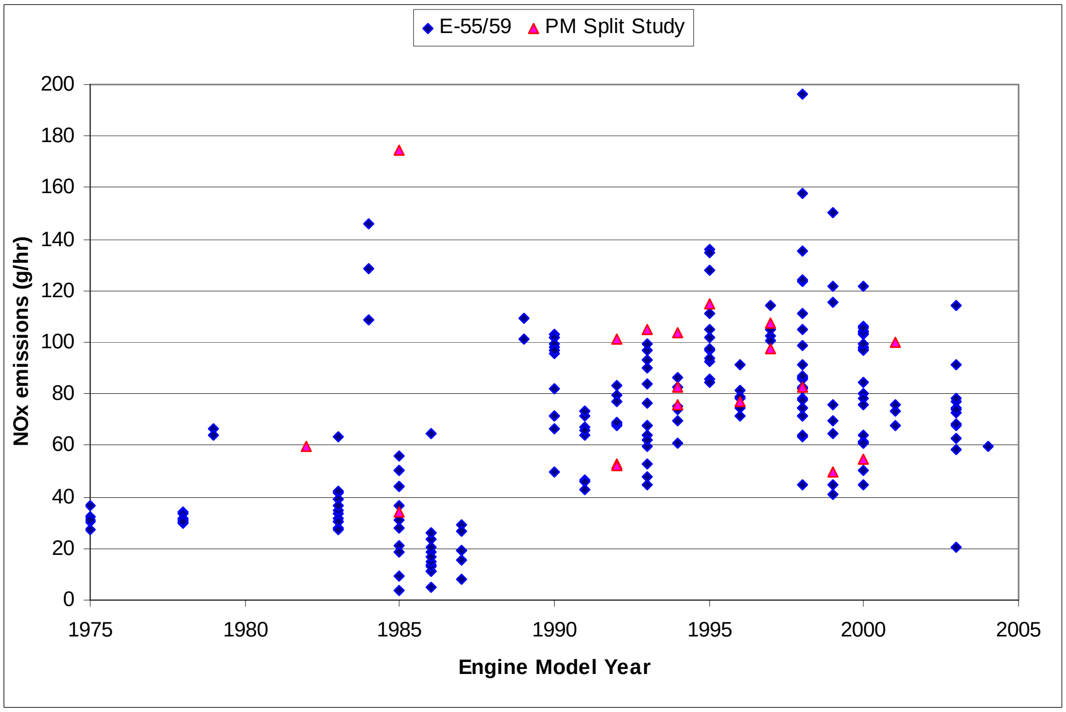

Figure 15: Idle NOx emissions excluding emissions from CRC-16, CRC-38 and CRC-45 trucks. Scale differs from Figure 14

Particulate Matter (PM)

Idle particulate emissions are shown in Figure 16. Overall idle PM emissions from these vehicles were very low and in many cases were non-detectable. A downward trend in idle PM emissions with increasing engine MY have been observed for almost all vehicles. CRC-45 vehicle, which emitted exceptionally high idle HC emissions, also emitted exceptionally high PM. Problems associated with that vehicles have already been discussed while discussing HC emissions. It has also been observed that CRC-3 and CRC-15 vehicles emitted high PM. CRC-3 truck, before repair emitted 10 g/hr of PM on average, while after repair it dropped to approximately 5 g/hr. CRC-15, on the other hand, out of six test-runs emitted more than 10 g/hr during three test-runs out of six test-runs. No problems were experienced during the testing of these vehicles. Exclusion of PM data from CRC-3, CRC-16, CRC-38 and CRC-45 trucks provided a decreasing trend in PM emissions with increasing engine MY. Figure 17 shows the modified idle PM emissions, which did not include PM emissions from CRC-16, CRC-38, and CRC-45 trucks. MY 1975-1990 vehicles averaged approximately 4.0 g/hr of PM whereas MY 1991-2004 averaged approximately 1.4 g/hr. PM emissions were almost negligible (0.62 g/hr) from vehicles with MY 2000 and beyond. It was interesting to note that some vehicles that were found to emit high NOx were, in contrast, emitted low PM, establishing the 'NOx-PM trade off', although this phenomenon has not been observed over the entire database.

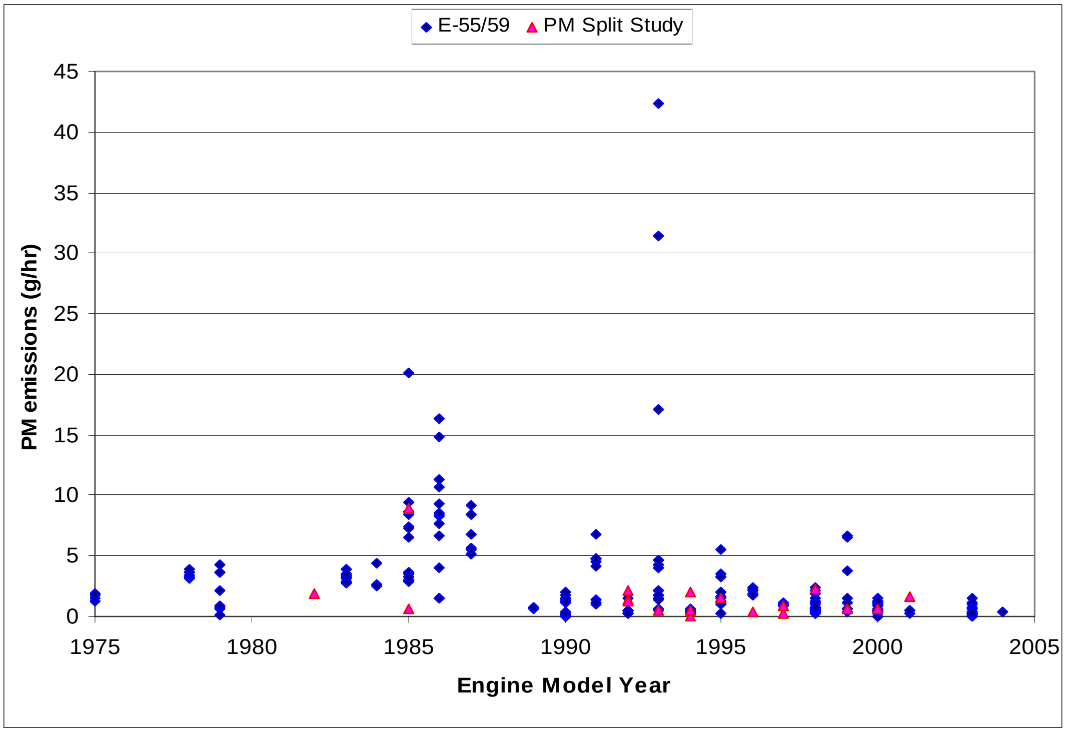

Figure 16: Idle PM emissions

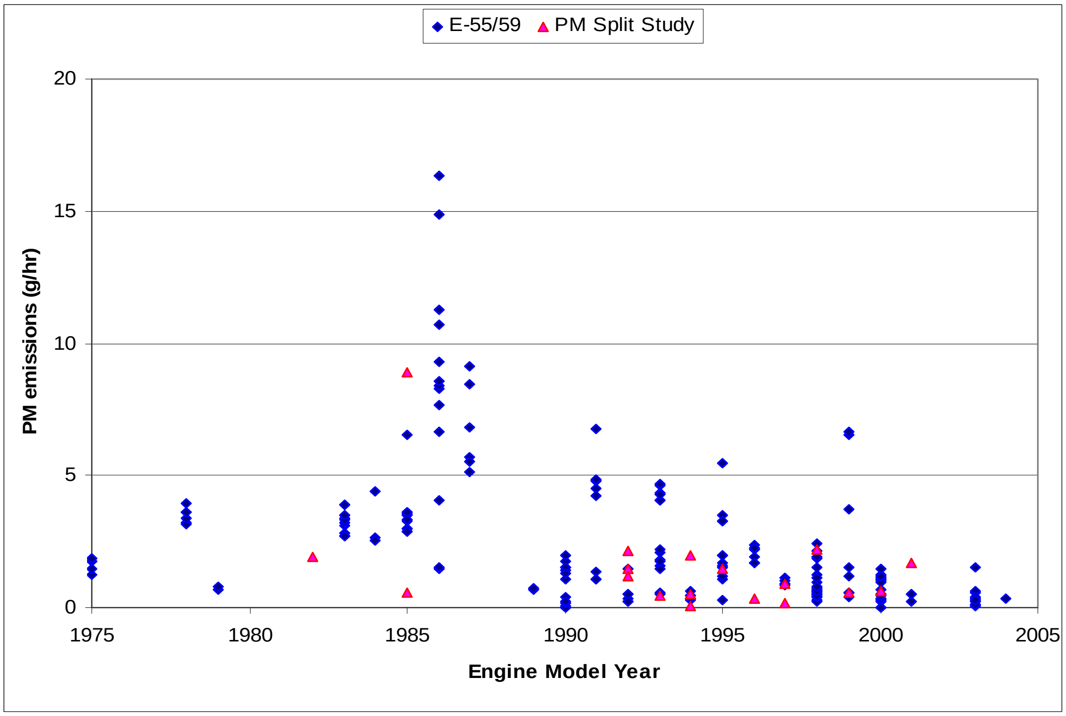

Figure 17: Modified idle PM emissions excluding emissions from CRC-16, CRC-38 and CRC-45 trucks. Scale differs from Figure 16

CO_2 Emissions

Carbon dioxide (CO_2) is a major green house gas (GHG) produced during complete or incomplete combustion. The USEPA at present does not regulate CO_2 emissions. With increased focus on climate change and global warming it is expected that CO_2 emissions will be regulated in future [26]. Figure 18 shows that CO_2 emissions maintained a uniform trend for almost all vehicles considered in this study except CRC-4 and CRC-38 trucks of the E-55/59 Study, and PM-31 and PM-16 vehicles of the PM Split Study, which emitted more than 8,000 g/hr of CO_2 emissions. It has already been mentioned that CRC-38 was tested at high idle engine speed and with air conditioning, which in turn was responsible for high CO_2 emissions. CRC-4 truck emitted approximately 9000 g/hr of CO_2 in the first test-run, in which it had equipment malfunction problem, although the average CO_2 from this truck was approximately 5500 g/hr. PM-31, a 2-stroke diesel bus emitted about 11,000 g/hr of CO_2 emissions, which is natural as 2-stroke vehicles consumed more fuel because of inefficient combustion. No problems were reported for other test-runs having more than 8,000 g/hr of CO_2 emissions. Modified CO_2 emissions are presented in Figure 19, which did not take into account the high CO_2 emissions from CRC-16, CRC-38 and CRC-45 trucks. The modified data demonstrated a more static trend. No distinct division could be drawn for vehicle groups with MY 1975-1990 and the post 1990 MY. However, the average CO_2 emissions from these two groups were approximately 4614 g/hr and 4504 g/hr respectively.

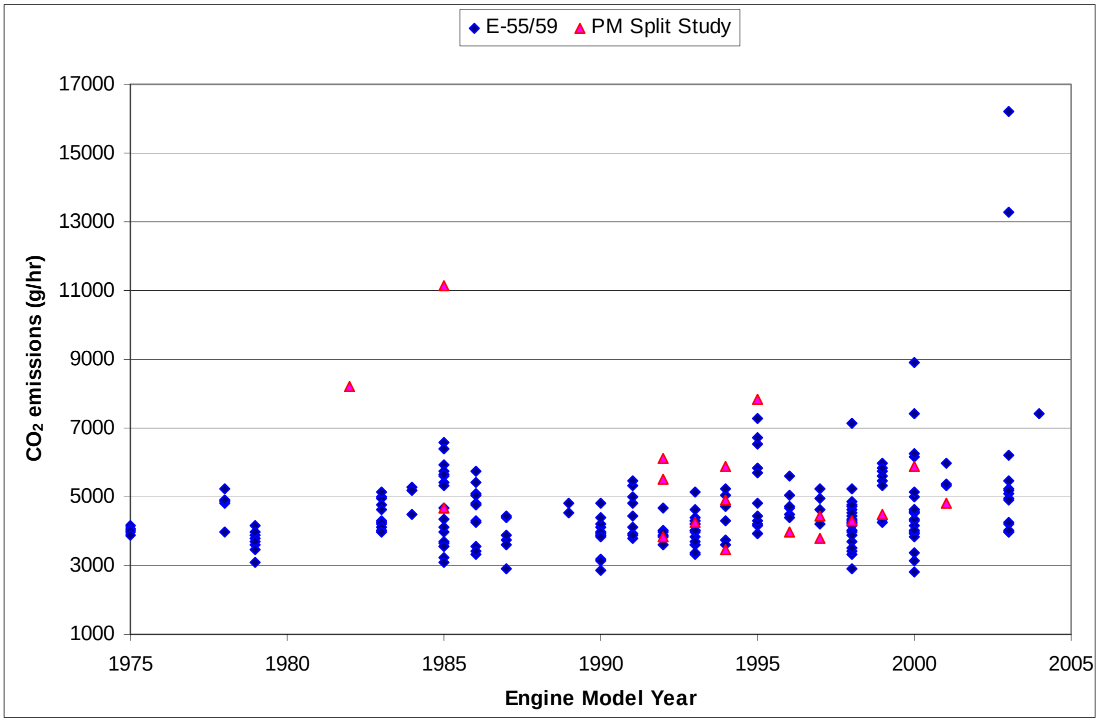

Figure 18: Idle CO_2 emissions

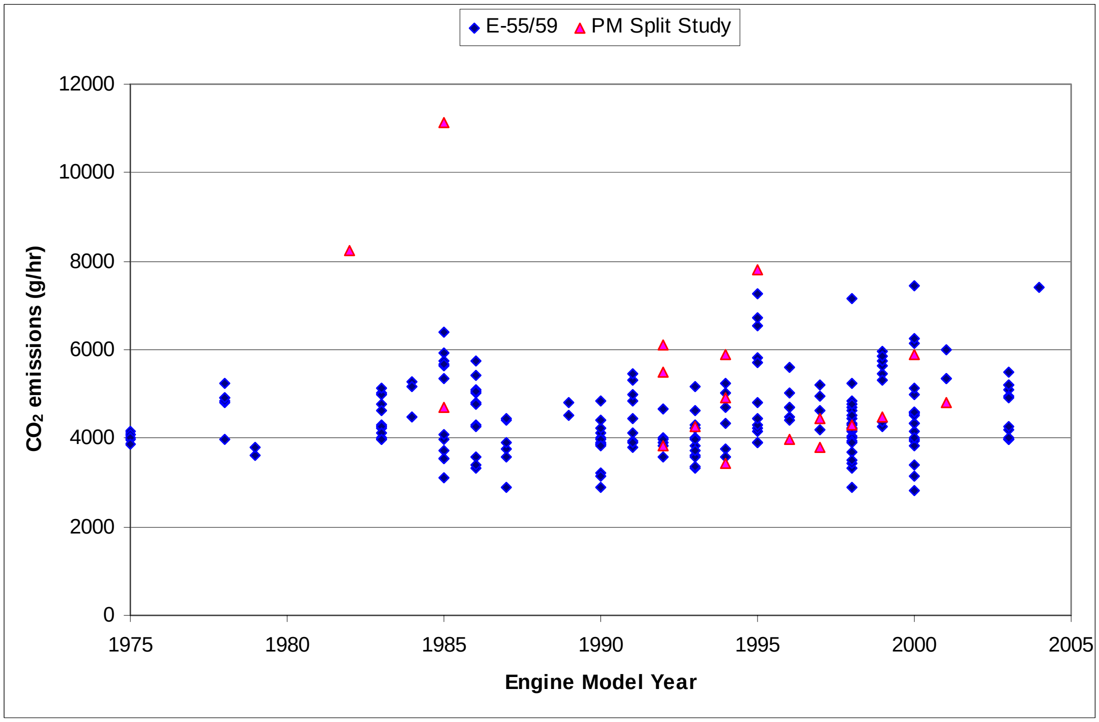

Figure 19: Idle CO_2 emissions excluding emissions from CRC-16, CRC-38 and CRC-45 trucks. Scale differs from Figure 18

Idle Fuel Consumption

Like regulated emission, no conclusive figure has been available for idle fuel consumption in literature. This value ranged from 0.3 gallons per hour (gal/hr) to 1.0 gal per hour in the literature. In order to present a comprehensive data base, idle fuel consumption has been evaluated from all trucks from the E-55/59 Study and the PM Split Study, which are presented in Figure 20. Overall these data maintained a constant trend, which was expected as fuel consumption has been inferred from CO_2 emissions by carbon balance. Fuel consumption from these vehicles varied from 0.31 gal/hr to 1.62 gal/hr. On average, vehicles with MY 1975-1990 and post 1990 MY consumed fuel at an hourly rate of 0.46 and 0.47 gallons respectively. A number of vehicles were found to consume more than 1.0 gal/hr in both the E-55/59 and the PM Split Study. Out of these vehicles, fuel consumption from the CRC-16, CRC-38 and CRC-45 truck has been excluded because of the reasons mentioned in previous sections. The modified fuel consumption is shown in Figure 21. It is worth mentioning that a comprehensive database on idle fuel consumption from heavy-duty diesel buses and trucks is not available. Wider variations have also been observed in idle fuel consumption from the available literature.

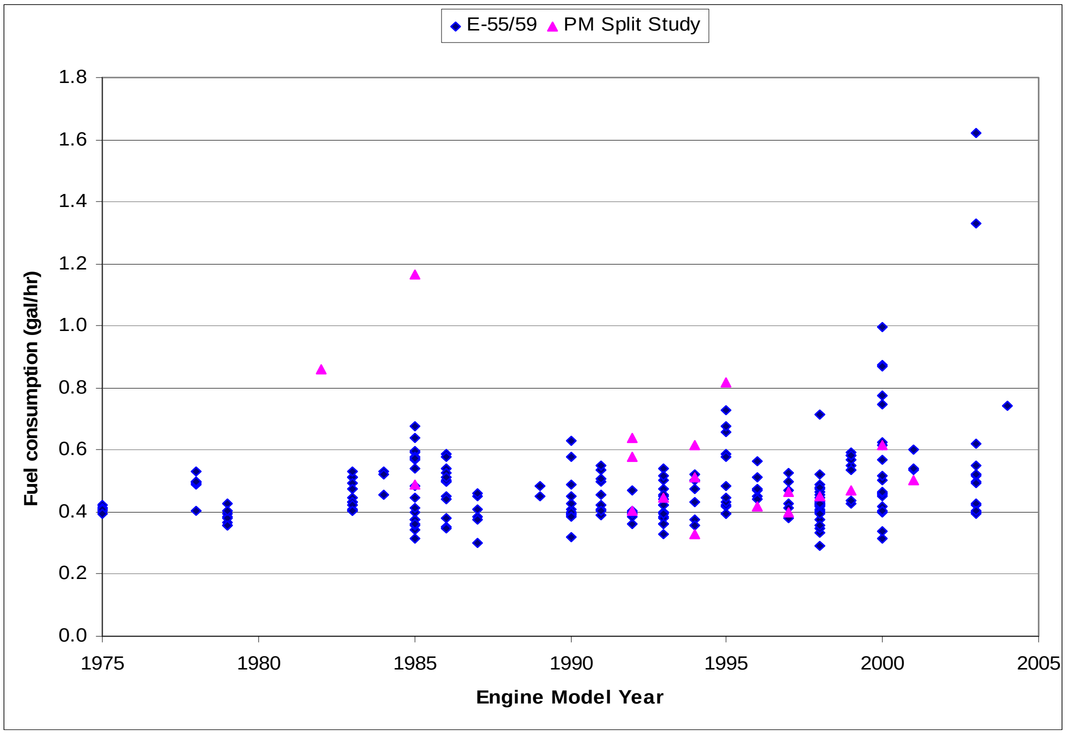

Figure 20: Idle fuel consumption in gallons per hour

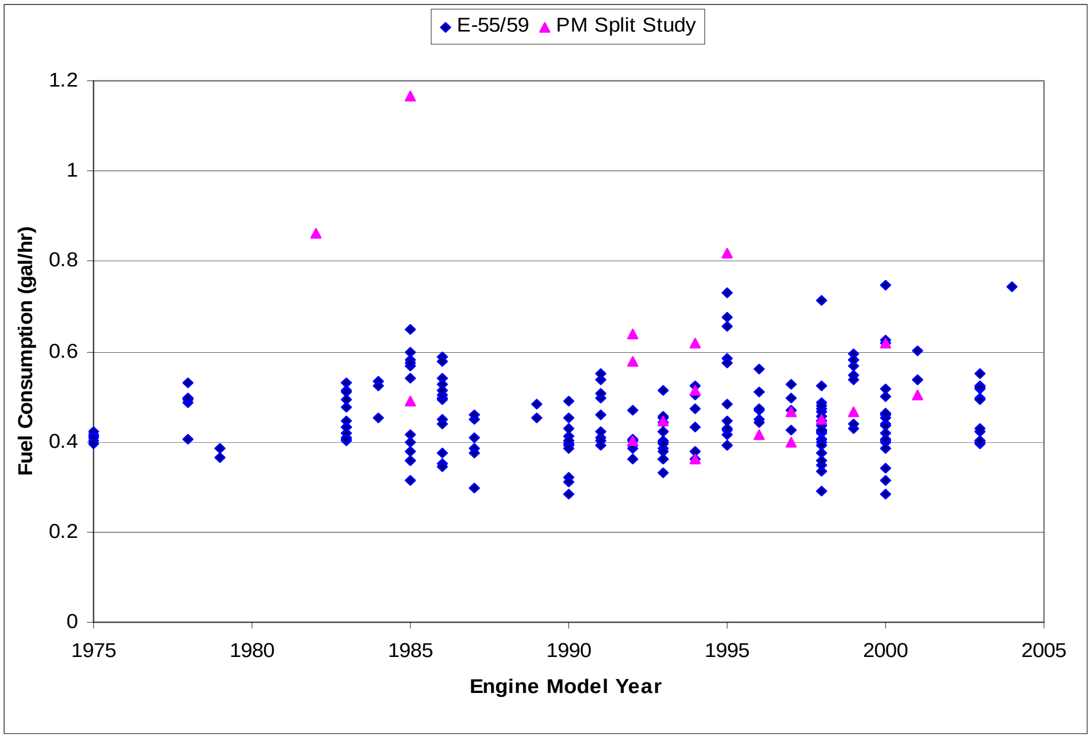

Figure 21: Modified idle fuel consumption excluding CRC-16, CRC-38 and CRC-45 trucks. Scale differs from Figure 20

Effect of Air Conditioning and Idle Speed on Idle Emissions

To observe the effects of engine speed and A/C on idle emissions, CRC-38 (MY 2003) truck was tested on 4 different modes. They are (i) idle at 600 rpm without A/C, (ii) idle at 600 rpm with A/C, (iii) idle at 1100 rpm without A/C, and (iv) idle at 1100 rpm with A/C. Effects of these varying conditions are plotted in Figure 22. It has been observed that CO_2, NOx, PM, and fuel consumption increased by 25%, 30%, 20%, and 27% respectively with the addition of A/C at 600 rpm engine speed. Whereas, elevating the idle engine speed from 600 rpm to 1100 rpm caused an increase in CO_2, NOx, PM, and fuel consumption by 165%, 225%, 76%, and 170% respectively. Pekula et al. [11] also observed the effect of elevated speed on idle NOx and CO_2 emissions and found that NOx increased by about 86% and CO_2 increased by about 132% when the engine speed was elevated from 600 rpm to 1200 rpm. Use of A/C at elevated speed (1100 rpm) increased CO_2, NOx, PM, and fuel consumption by 22%, 17%, 16%, and 22% respectively. It also affected the fuel economy by almost 70%. Elevating the engine speed from 600 rpm to 1100 rpm and keeping the A/C on increased CO_2, NOx, and PM, by 225%, 284% and 100% respectively. Brodrick et al. [9] also observed the effect of engine speed with A/C on idle emissions and found that elevating the engine speed from 600 rpm to 1050 rpm (with A/C on in both cases) resulted corresponding increase in idle CO, NOx, and CO_2 emissions by approximately 460%, 53% and 90% respectively. Point to note that air conditioning load depends on temperature, humidity, and heat load and therefore, may not be repeatable. Clark et al. [24] also examined the effect of A/C and accessory loadings on idle emissions on a Mack tractor and found that switching on all the lights and A/C affected continuous CO_2 and NOx emissions as shown in Figure 23 and Figure 24. CO_2 and NOx on average increased by about 60% and 45% respectively when the lights and A/C switched on. Variation observed on the Mack Tractor was more than the variation observed in CRC-38 truck because CRC-38 truck has been experimented with only the A/C at the same engine speed.

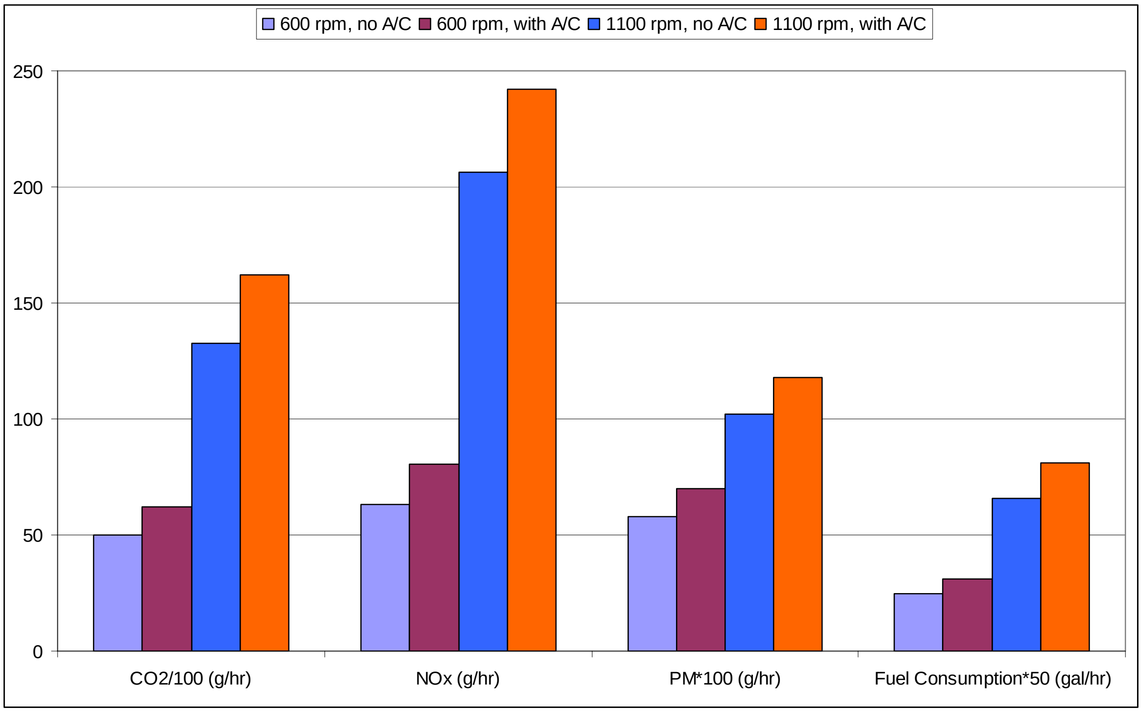

Figure 22: Effects of engine speed and air conditioning on idle emissions and fuel consumption

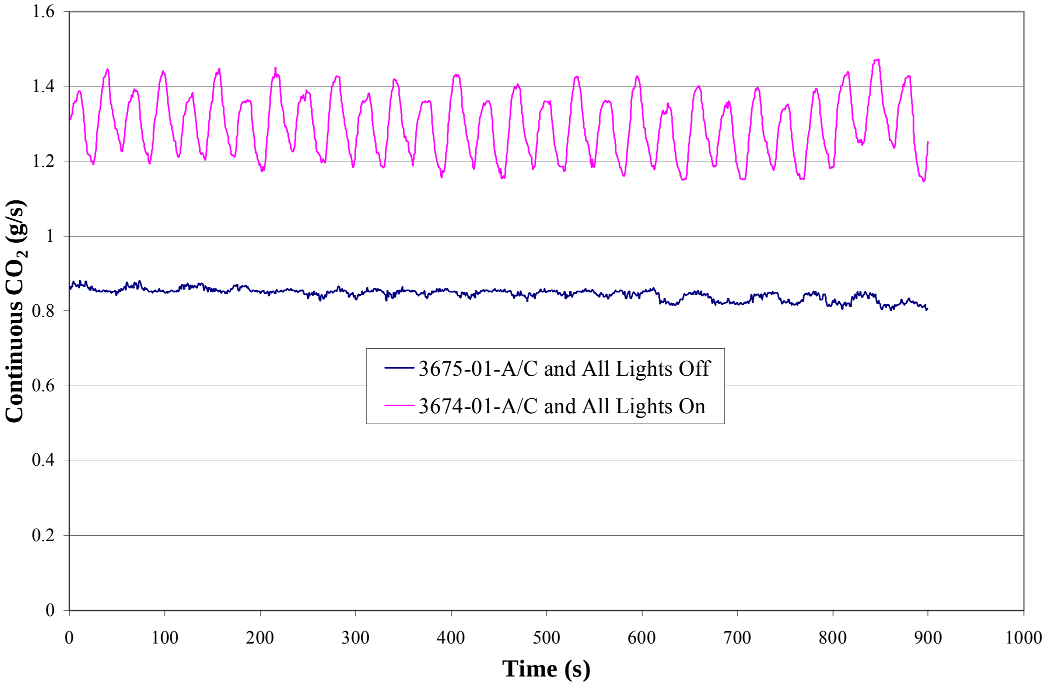

Figure 23: CO_2 concentration over the idle mode with different engine accessories operating, Mack tractor

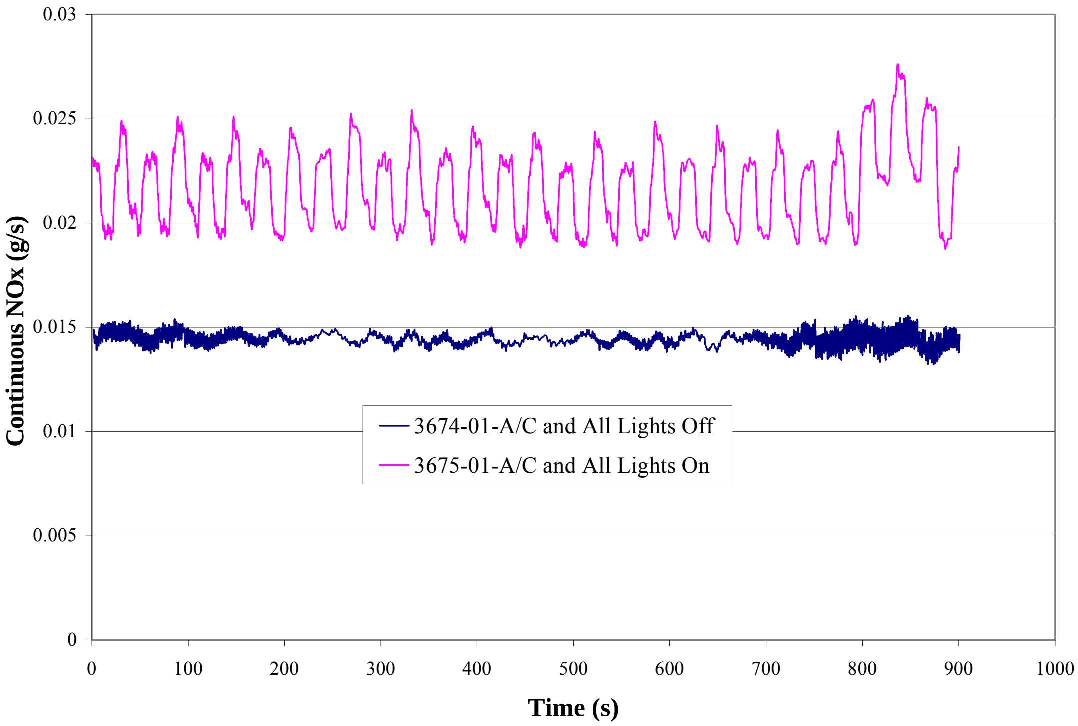

Figure 24: NO_X concentration over the idle mode with different engine accessories operating, Mack tractor

Idle Emissions from Transit Buses

Idle emissions from three transit buses have been presented separately because of their continuous exposure to the people of all ages who wait at the bus depots or various bus stops. Two buses were tested during the PM Split Study and the third bus was recently tested during the Transit Vehicle Exhaust Emissions Evaluation project, which has been sponsored by the U.S. Department of Transportation (DOT), Federal Transit Administration (FTA) [27]. Bus 1 referred to as PM-31, which had a 1982 DDC 6V92/8067-3421 2-stroke diesel engine with mechanical injection system while Bus 2 referred to as PM-32, which had a 1992 DDC 6V92/8067-3 K21 2-stroke diesel engine with electronic fuel injection. Bus 3 was a 2000 MY DDC Series 50 bus with 4-stroke diesel engine equipped with electronic fuel injection. Emissions data from these buses are presented in Figure 25. All emissions except NOx from the two 2-stroke diesel buses were higher than the MY 2000 bus. PM emissions from the Bus 1 was about 600% higher than the PM emissions from Bus 3 while PM emissions from Bus 2 was 400% more than

PM emissions from Bus 3. Bus 1 also emitted high CO_2, because the bus employed mechanical injection. However, 2-stroke diesel buses produced less NOx than Bus3 establishing the NOx-PM tradeoff.

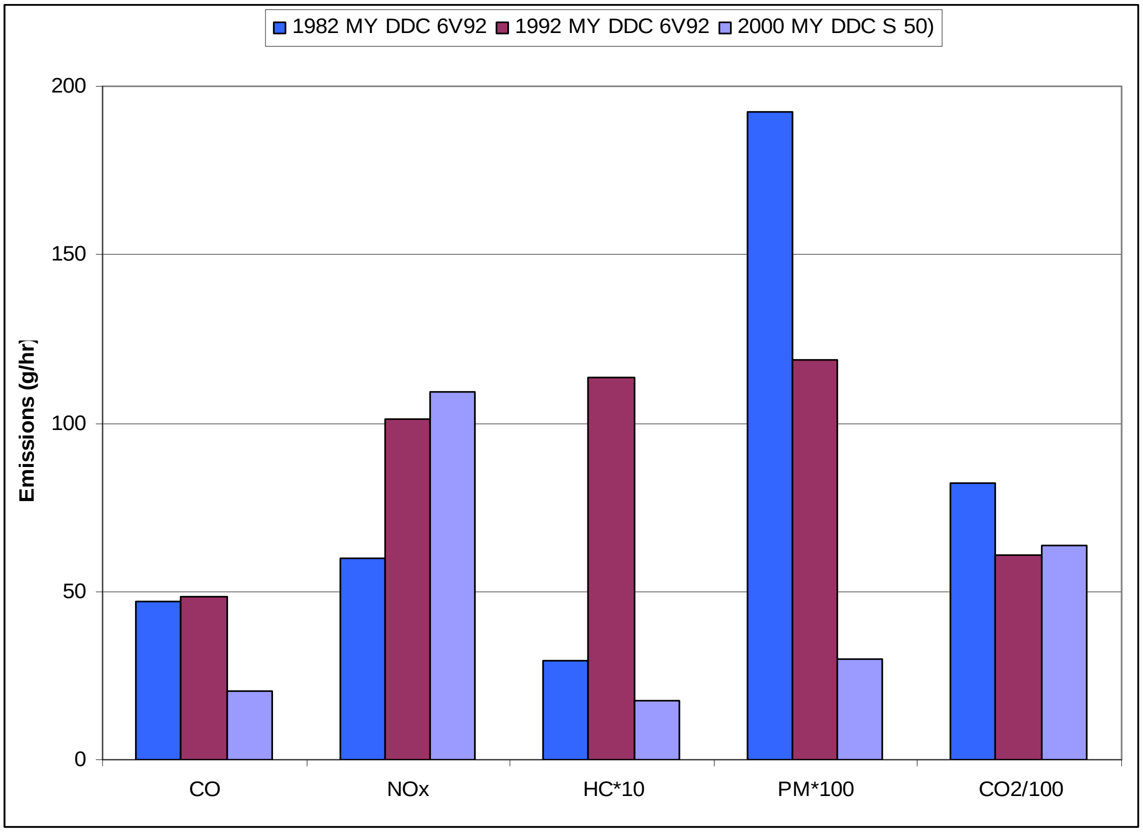

Figure 25: Idle emissions from three transit buses

COMPARISON OF IDLE EMISSIONS FROM THE TRANSIENT MODE AND IDLE CYCLE

Evaluating Idle Emissions from Transient Mode of the HHDDT Schedule

In addition to the direct measurement of emissions on idle cycles, idle emissions can also be obtained from the continuous emissions data of any test schedule, because every test schedule has a certain percentage of idle. It is both time saving and cost effective. However, the reliability of these data could be achieved by comparing these data with idle emissions data gathered from the drive cycles. Almost all heavy-duty trucks during the E-55/59 program, in addition to idle cycles, were tested on Transient and Creep mode of the HHDDT Schedule [28]. The HHDDT schedule consisted of four original modes, namely; Idle, Creep, Transient, and Cruise. In this evaluation, continuous emissions data of the Transient mode has been considered. Figure 26 shows the Transient mode of the HHDDT Schedule. Idle emissions of CO, NOx, HC, and CO_2 from the Transient mode have been obtained from the three idle segments as seen in the figure. Continuous emissions in grams per second has been averaged over the idle duration and presented in g/hr. This could be accomplished in two different ways.

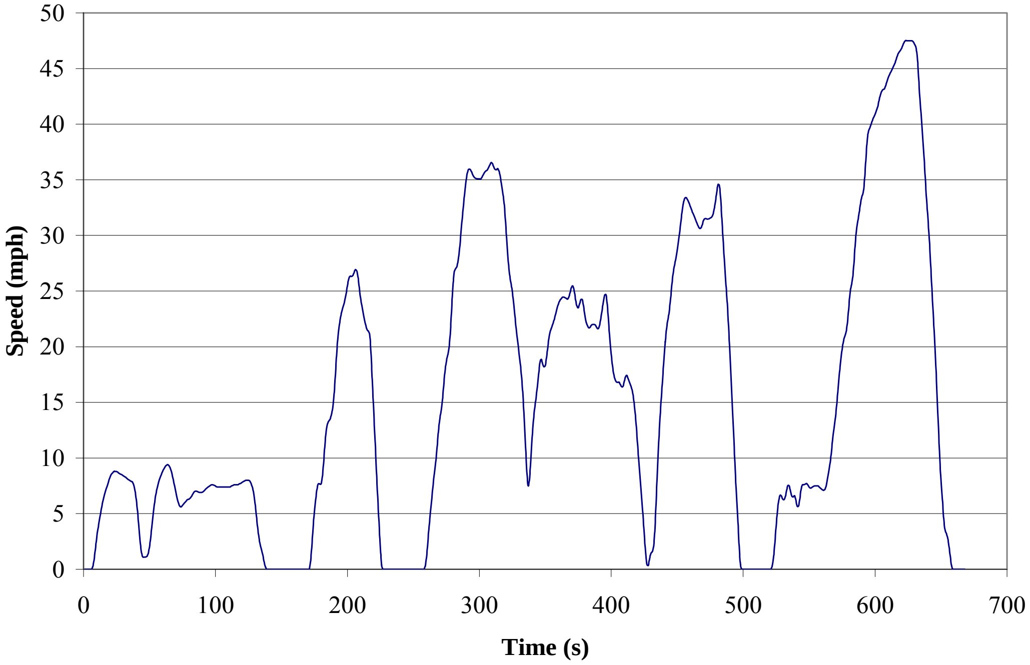

Figure 26: Transient mode of the HHDDT Schedule

For example, continuous NOx emissions trace from CRC-2 truck with respect to hub speed and power are presented in Figure 27 and Figure 28. In the simplest form, idle NOx can be obtained from the following figures considering the equations $y = 3E\text{-}06x^2+0.0006x+0.072$ and $y = 4E\text{-}07x^2+0.0004x+0.0312$ and taking $x = 0$, because the hub power and speed during idle should theoretically be zero. Idle emissions obtained with this method largely depend on the R^2 value. Therefore, these values could have wide variations with the values obtained from idle cycle. For example, idle NOx emissions obtained from Figure 27 and Figure 28 are 262.44 g/hr and 112.32 g/hr respectively, while this value from the idle cycle was 111.2 g/hr. Moreover, neither the hub power nor the hub speed remained absolutely zero during idle as showed in Figure 29 and Figure 30. These figures represent the continuous idle NOx emissions for the same truck with respect to hub power and hub speed respectively, from which it has been observed that hub power varied from -0.002 hp to 0.035 hp and the hub speed varied from – 2.0 rpm to 3.2 rpm. Therefore, in order to accurately obtain the idle values from the continuous emissions, continuous CO, HC, NOx, and CO_2 emissions with hub speed less or equal to 3.0 rpm (<=3.0) has been regarded as idle emissions and presented in Table 5. The table also compiles the idle values from the idle cycle for respective trucks on the corresponding test run.

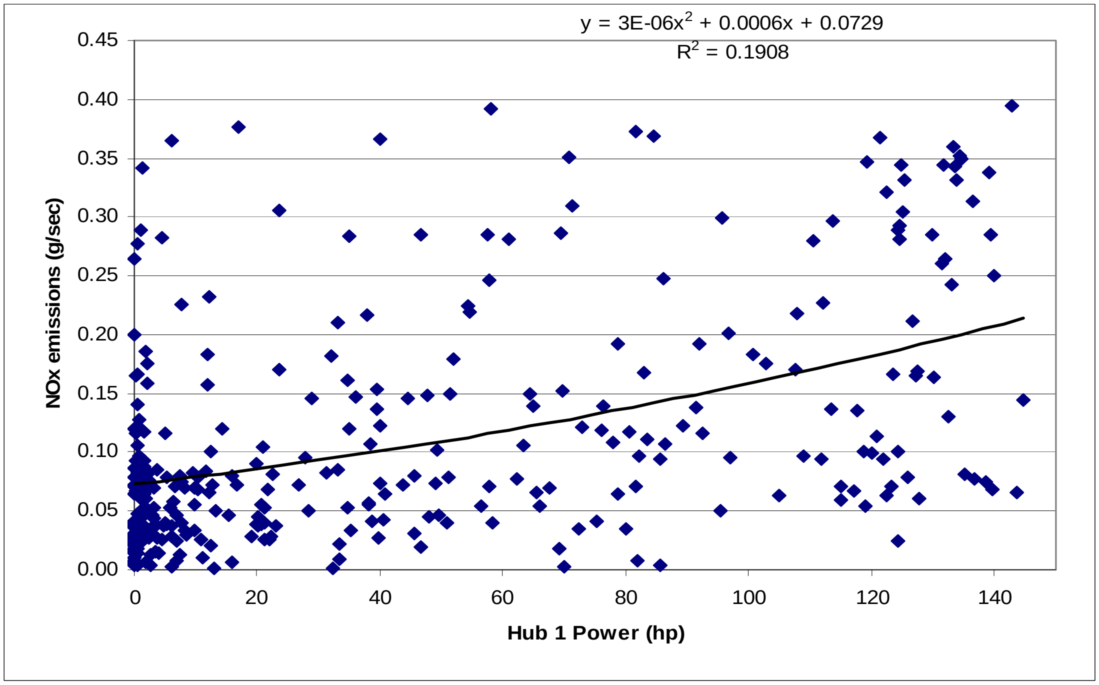

Figure 27: Continuous NOx emissions with respect to hub power (hp) for the E-55/59 CRC-2 truck

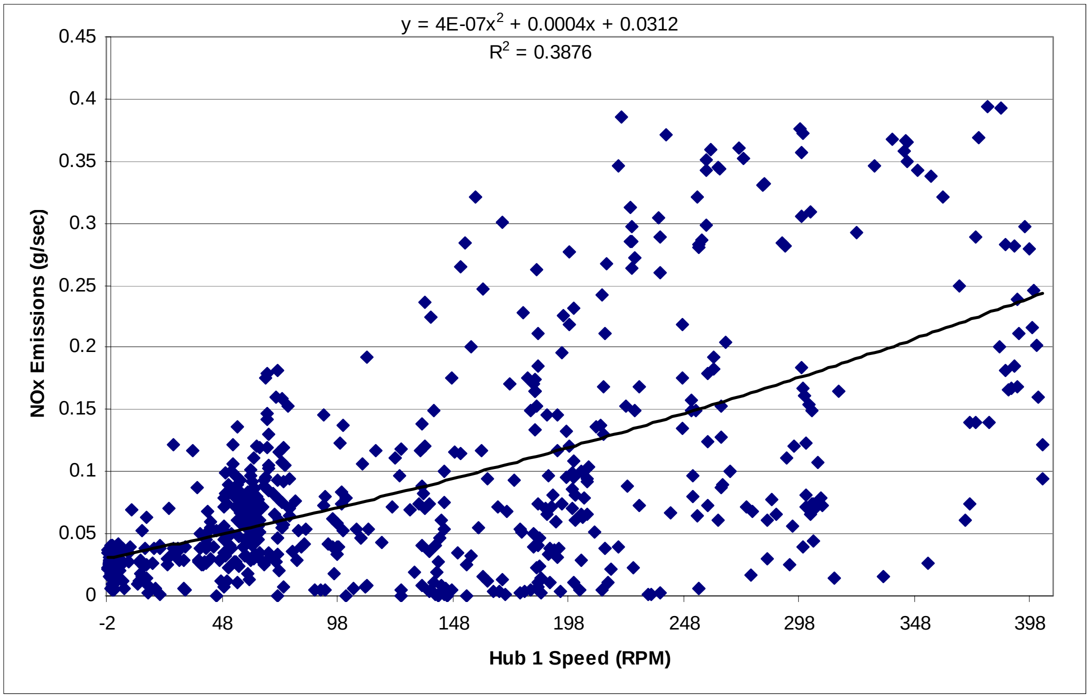

Figure 28: Continuous NOx emissions with respect to hub speed (rpm) for the E-55/59 CRC-2 truck

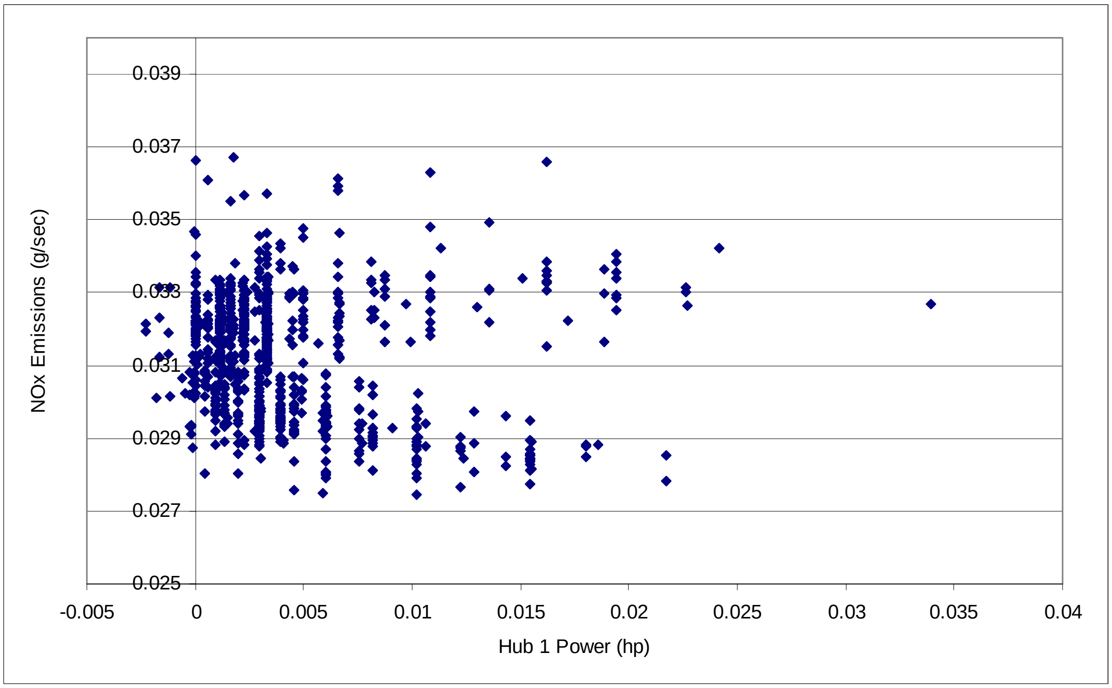

Figure 29: Continuous idle NOx emissions with respect to hub power. Hub power varied from -0.002 hp to 0.035 hp during idling

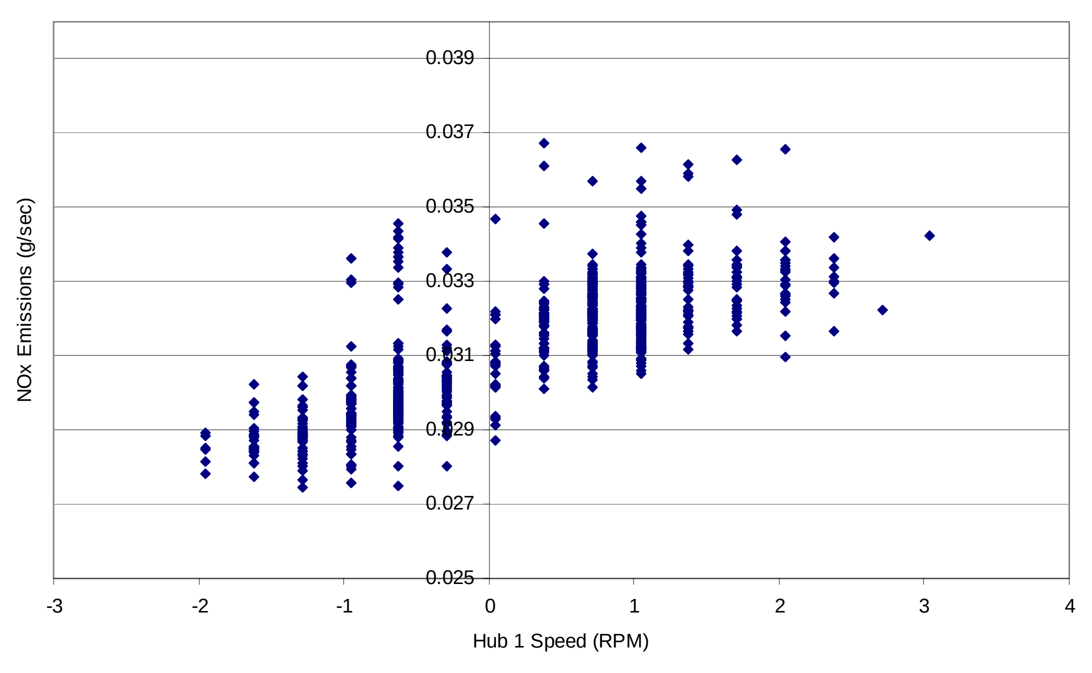

Figure 30: Continuous idle NOx emissions with respect to hub speed. Hub speed varied from -2 rpm to 3.2 rpm during idling

Table 5: Idle CO, HC, NOx, and CO_2 Emissions from the Transient Mode and Idle Cycle

Name of truck	Engine Model Year	Idle CO (g/hr)		Idle HC (g/hr)		Idle NOx (g/hr)		Idle CO_2 (g/hr)	
		Transient	Idle	Transient	Idle	Transient	Idle	Transient	Idle
E55CRC-24	1975	52.76	19.96	27.94	17.68	33.98	36.40	5718	3960
E55CRC-13	1978	94.70	30.60	21.95	12.60	30.93	30.60	29205	3780
E55CRC-16	1979	56.98	40.00	14.00	5.96	53.62	64.40	4062	3780
E55CRC-23	1983	52.10	40.40	38.80	38.68	27.97	42.40	5098	5532
E55CRC-25	1983	34.49	19.60	27.46	22.72	20.55	30.40	4551	4124
E55CRC-33	1984	43.89	27.00	15.95	14.16	104.12	108.40	5154	4480
E55CRC-3	1985	9.49	87.60	30.47	24.36	18.27	24.10	3370	3232
E55CRC-14	1985	70.28	17.40	20.35	5.58	23.97	3.60	17381	3114
E55CRC-12	1985	59.36	33.60	62.68	45.60	23.40	18.40	4275	4316
E55CRC-15	1986	49.36	31.20	60.02	32.40	11.93	26.00	5780	5764
E55CRC-47	1986	21.57	12.12	6.17	29.10	55.76	64.80	5779	5052
E55CRC-19	1987	56.90	40.40	60.71	34.40	12.53	26.80	3913	4440
E55CRC-	1990	15.26	9.16	2.53	3.64	62.93	82.00	4248	4000

7									
E55CRC-21	1990	44.49	38.40	8.83	4.08	100.00	101.00	4656	3884
E55CRC-18	1991	47.86	42.80	26.57	31.28	68.50	73.60	5302	4436
E55CRC-32	1991	25.16	22.16	10.71	12.10	48.58	46.60	4786	5314
E55CRC-20	1992	32.69	17.20	3.06	5.28	69.86	79.20	4455	4024
E55CRC-17	1993	12.85	4.08	5.50	7.20	75.71	48.00	4310	4212
E55CRC-22	1993	66.23	14.18	66.08	32.60	59.11	38.00	5201	2144
E55CRC-45	1993	44.83	57.20	310.00	311.60	57.15	48.60	5323	4362
E55CRC-49	1993	21.23	12.16	5.49	2.40	54.41	62.40	5386	5152
E55CRC-1	1994	44.20	29.58	5.62	4.32	76.53	113.40	6962	5622
E55CRC-43	1994	13.10	27.73	2.36	4.27	49.00	69.20	3774	4291
E55CRC-2	1995	21.94	18.16	14.03	9.44	76.53	111.20	9837	5829
E55CRC-6	1995	13.36	12.40	10.05	5.60	69.84	92.80	5994	4144
E55CRC-8	1996	21.81	17.24	8.08	7.48	57.56	81.60	5734	5604
E55CRC-31	1997	19.83	17.92	22.74	20.28	66.50	114.00	5373	4634
E55CRC-9	1998	23.39	18.00	9.80	4.68	75.99	63.00	4788	3319
E55CRC-10	1998	50.97	25.60	4.49	5.96	73.57	85.60	4684	4704
E55CRC-26	1998	27.92	17.60	6.70	3.96	38.64	60.60	4341	4242
E55CRC-28	1998	0.00	35.40	11.03	2.42	44.27	82.00	4938	3522
E55CRC-30	1998	35.44	44.40	0.00	0.00	103.86	124.20	6251	5254
E55CRC-48	1998	13.14	13.84	17.55	0.66	137.58	196.20	7957	7152
E55CRC-27	1999	44.29	27.80	3.59	2.90	66.70	150.40	5517	5450
E55CRC-29	1999	31.33	17.16	19.93	13.36	44.63	40.80	7041	5322
E55CRC-4	2000	12.47	19.20	5.10	4.20	116.66	97.80	4573	4993
E55CRC-5	2000	13.80	13.72	13.75	11.12	63.88	103.20	4903	6240
E55CRC-11	2000	14.42	13.92	7.86	6.04	43.47	50.60	3387	3128
E55CRC-35	2000	22.96	25.60	9.24	7.64	68.12	80.00	4763	5124
E55CRC-36	2001	23.42	17.94	5.57	5.90	55.71	76.00	5332	5984
E55CRC-34	2003	23.76	21.60	4.80	2.50	26.89	91.00	3952	4198
E55CRC-38	2003	26.89	37.54	9.34	9.36	24.37	20.40	5566	5110
E55CRC-39	2003	10.57	7.72	6.40	6.68	21.31	67.60	5712	5220
E55CRC-40	2003	6.33	8.28	2.73	2.81	33.98	77.87	5010	4027

Comparing Idle Emissions Calculated from the Transient Mode with Measured Idle Emissions

Idle CO, HC, NOx, and CO_2 emissions obtained from the continuous emissions of the Transient mode as mentioned above and the idle CO, HC, NOx, and CO_2 emissions obtained from the idle cycles are graphically presented in Figure 31, Figure 32, Figure 33, and Figure 34 respectively. Emissions values are presented according to the engine MY in order to observe the effect of MY on variations on idle emissions from the Transient mode and idle cycles.

Overall, the idle CO obtained from the Transient mode was higher than the CO emissions from the idle cycle (58% on average). Variations between the two sets of values were higher for the MY 1975-1990 vehicles than the variation observed for the post 1990 MY vehicles. Average increase in idle CO from the Transient mode for the MY 1975-1990 vehicles was about 86%, while this value dropped to 44% for the post 1990 MY vehicles. A similar observation has been found for the CO_2 emissions, where, average variation for the MY 1975-1990 vehicles was about 88% but dropped to 16% for the post 1990 MY vehicles. Overall idle CO_2 obtained from the Transient mode has been higher than the values obtained from the idle cycles (39% on average). High values during the Transient mode could be attributed to some accessory loadings such as fans and compressors and possible inclusion of emissions at the initial acceleration while evaluating emissions from the Transient mode. CRC-13 and CRC-14 trucks showed very high variation between the two values for both the CO and CO_2 emissions. Idle CO_2 and CO emissions from the Transient mode for the CRC-13 truck varied by about 670% and 190% respectively while this variation was about 460% and 290% respectively for CRC-14 truck. A significant variation has been observed on idle CO emissions from the CRC-12 truck, which were found to emit 403% more idle CO in the Transient mode.

Idle HC, like CO and CO_2 from the Transient mode was higher than the values obtained from the idle cycles. However, variations in the 1975-1990 MY vehicles were less than the variations in the post 1990 MY vehicles. Extremely high variation has been observed for the CRC-48 truck. Idle HC from the Transient mode was 17.55 g/hr while it was 0.66 g/hr from the idle cycle. Idle NOx, obtained from the Transient mode, in contrast to CO, HC, and CO_2 emissions were less than the NOx emissions obtained from the idle cycles. Idle NOx obtained from the Transient mode was less than the NOx from the idle cycles for almost all trucks with 1975-1990 MY except CRC-12, CRC-13, and CRC-14 trucks. Out of these three trucks, idle NOx obtained from the Transient mode was 565% higher than the NOx from the idle cycles for CRC-4 truck. NOx obtained from the Transient mode for the post 1990 MY trucks, on average, was less than the NOx obtained from the idle cycles. High values of NOx from the idle cycles could be attributed to the advance injection timing employed at idle.

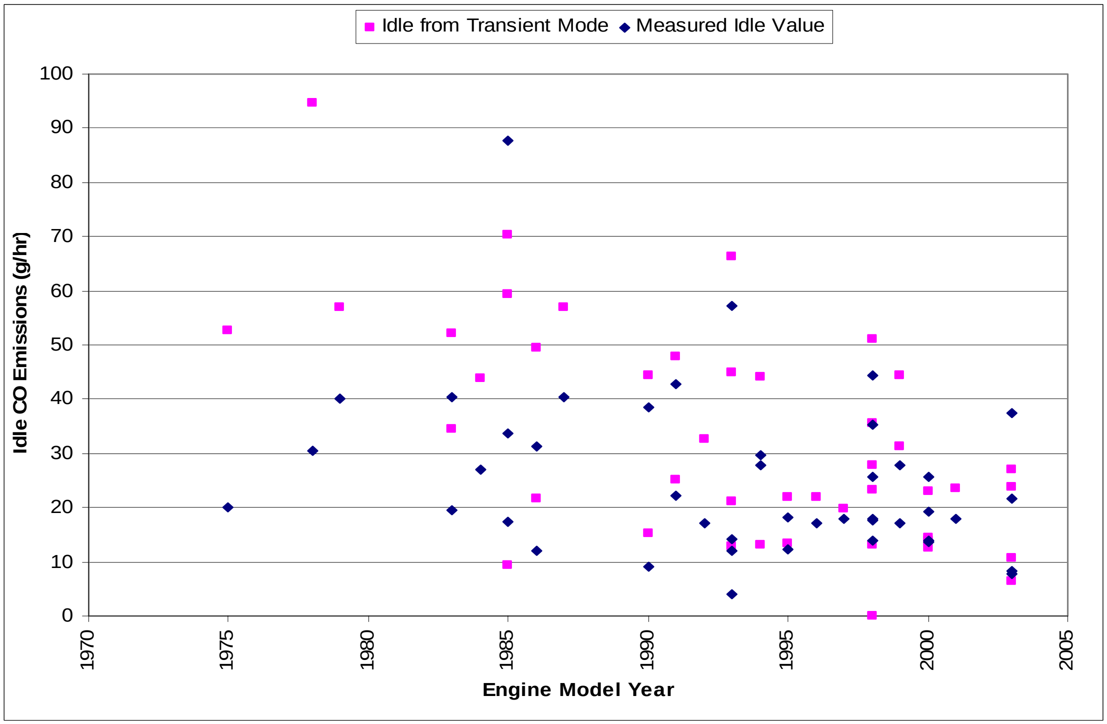

Figure 31: Variation of idle CO obtained from the Transient mode and values from the idle cycles with Engine MY

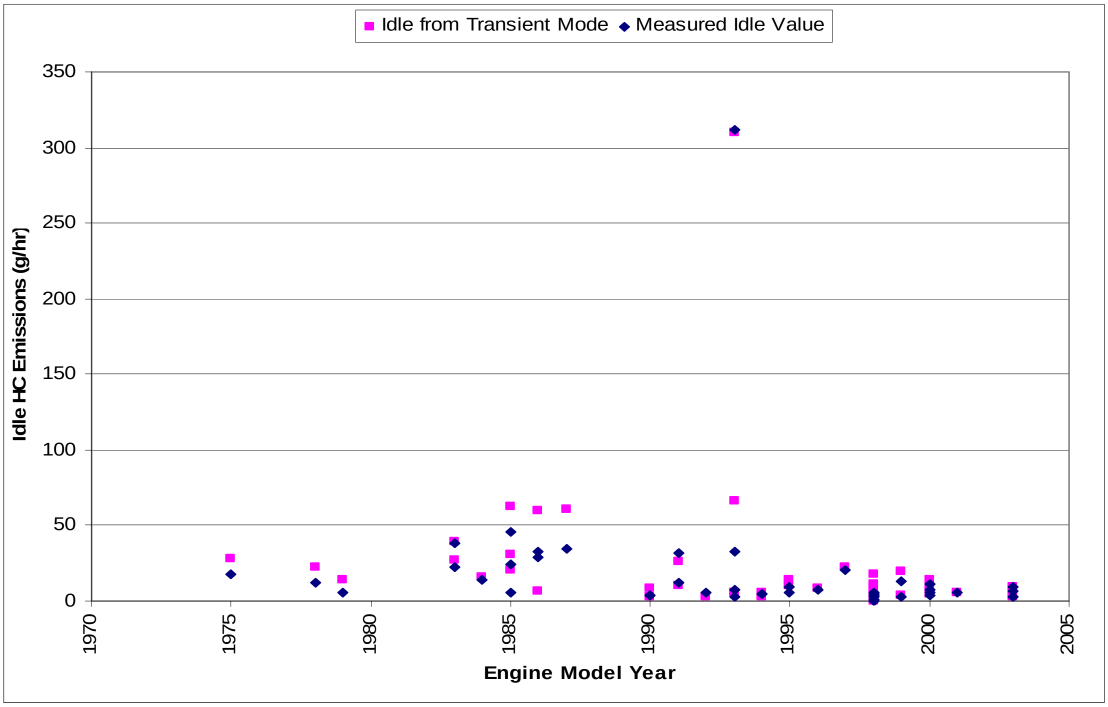

Figure 32: Variation of idle HC obtained from the Transient mode and values from the idle cycles with Engine MY

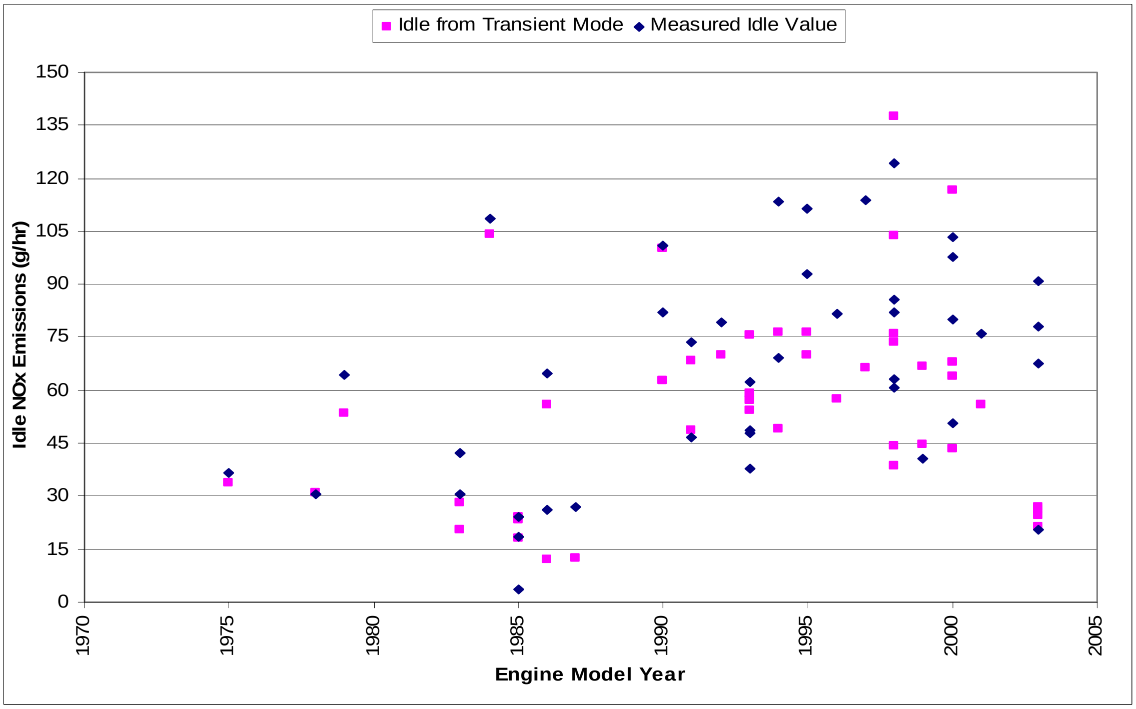

Figure 33: Variation of idle NOx obtained from the Transient mode and values from the idle cycles with Engine MY

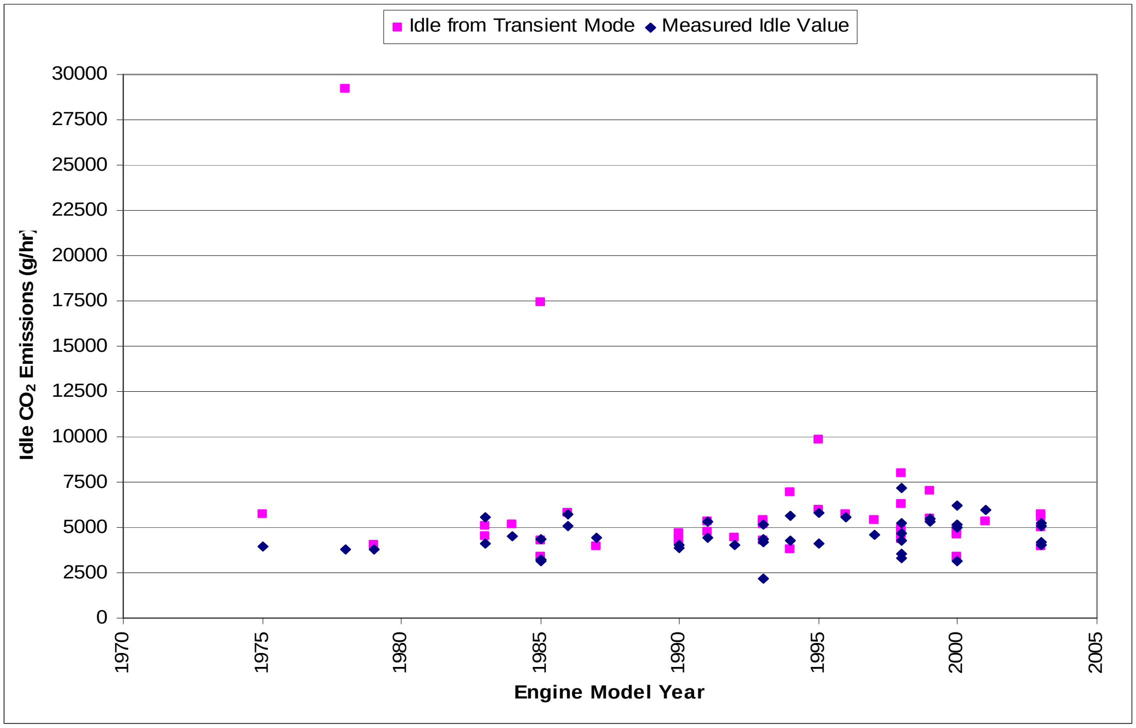

Figure 34: Variation of idle CO_2 obtained from the Transient mode and values from the idle cycles with Engine MY

ENGINE IDLE EMISSIONS

Perhaps this study would not have achieved completeness unless idle emissions obtained from chassis dynamometer testing had been compared and contrasted with idle data obtained from engine certification testing. Engines have been tested in the test cell of WVU Center for Alternative Fuels, Engines, and Emissions (CAFEE). This test cell is equipped with the state-of-the-art engine test equipment and was capable of measuring heavy-duty engines exhaust emissions in accordance with the Code of Federal Regulations (CFR) [20].

Two sets of data were procured from two different engine certification tests. In the first set, idle emissions from six engines tested on the FTP cycle has been compiled. Details of the tested engines are presented in Table 6.

Table 6: Type, Model Year, and Displacement of the Tested Engines

Engine Name	Model Year (MY)	Engine Type	Displacement (Liter)
Engine 1	1992	DDC Series 60	12.7
Engine 2	Engine 1 with rebuilt head and new set of injectors		
Engine 3	1991	DDC Series 60	11.1
Engine 4	1991	DDC Series 60	12.7
Engine 5	2000	DDC Series 60	12.7
Engine 6	1995	DDC Series 60	12.7

Idle emissions were extracted from three idle segments of the FTP cycle, at the beginning (0-20 seconds), from 280-300 seconds, and 905-925 seconds of the FTP cycle. Engine 1 was tested with Type 2-D diesel, Engine 2, Engine 4, Engine 5, and Engine 6 were tested with CARB specified diesel, whereas, Engine 3 was tested with Shell diesel. First four engines were tested for hot idle while Engine 5 and Engine 6 were tested for warm idle. Average idle emissions of CO, NOx, HC, and CO_2 from each engine are presented in Figure 35. Error bars represent ±1 standard deviations between idle emissions measured in three different idle segments of the FTP test. PM emissions could not be evaluated from these sets of engines. CO emissions ranged from 12 g/hr to 68 g/hr when tested for hot idle, averaging 29 g/hr from all engines. Hot idle HC emissions varied from 1.7 g/hr to 8.3 g/hr. The average HC emissions from first four engines were found to be 4.8 g/hr. Idle NOx and CO_2 emissions from the engines for hot idle varied from 49.3 g/hr to 95.5 g/hr and 2680 g/hr to 3426 g/hr respectively and the average NOx and CO_2 were found to be 72.5 g/hr and 3095 g/hr respectively. Engine 5 and Engine 6 emitted high NOx (90 g/hr and 126 g/hr respectively) and CO_2 (4896 g/hr and 8100 g/hr respectively) at the start of the FTP cycle. These values sharply reduced during the 280-300 seconds segment but increased during the 905-925 seconds segment. This pattern has not been observed for the first four engines, which were tested for hot idle. Therefore, emissions data from

Engine 5 and Engine 6 have been excluded when average engine idle emissions are presented.

In the second set, Engine 2 of the first test set was tested on the FTP cycle and idle emissions data of CO, HC, NOx, PM and CO_2 for the first 240 seconds were collected and reported in g/hr. This engine was tested with CARB specified diesel. Average emissions of CO, NOx, HC, PM, and CO_2 were found to be 31.13 g/hr, 84.27 g/hr, 4.92 g/hr, 0.84 g/hr, and 4117.9 g/hr respectively. Figure 36 shows the idle emissions from Engine 2.

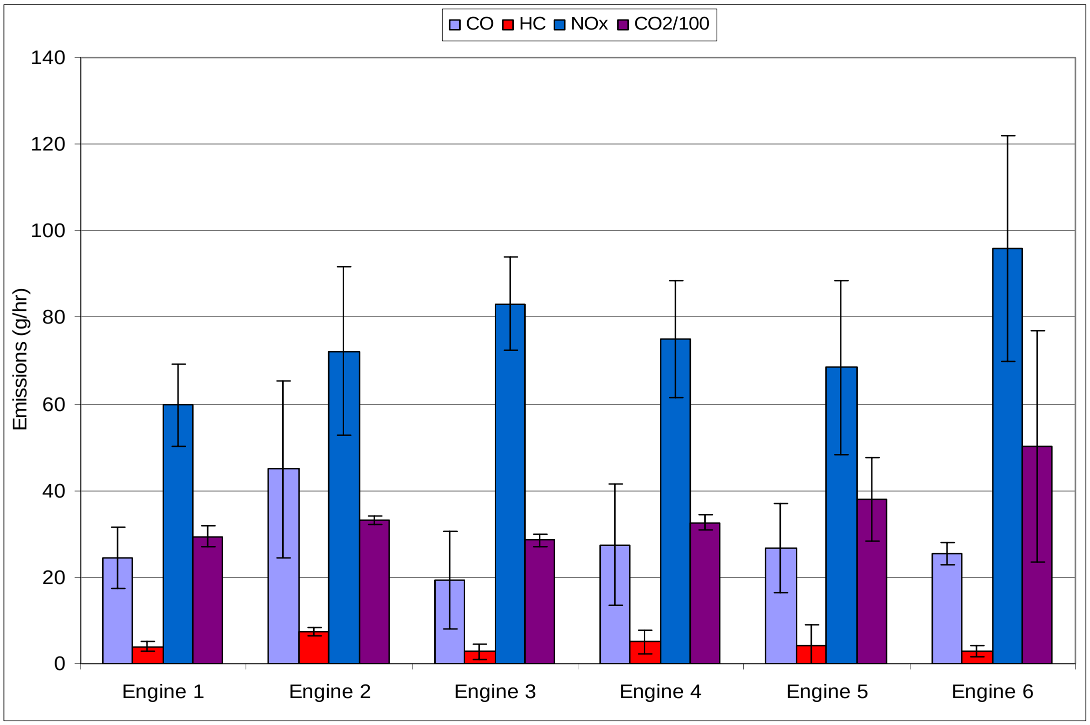

Figure 35: Engine idle emissions from six DDC Series 60 Engines

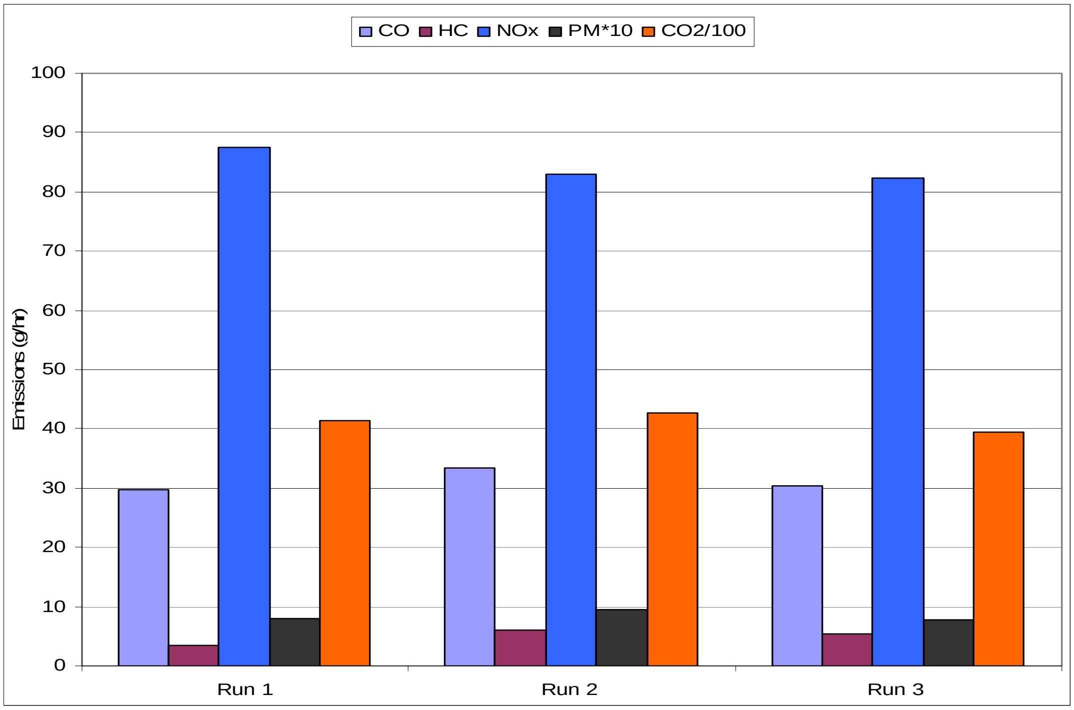

Figure 36: Engine idle emissions including PM from Engine 2

COMPARISON OF IDLE EMISSIONS MEASURED BY WVU WITH OTHER IDLE EMISSIONS DATA

Idle emissions data procured from the vehicles and engines idle emissions test program conducted by the WVU Translab and CAFEE are compared and contrasted with idle emissions available in literature. Comparison of idle emissions from various types of vehicle groups with different fuel types is neither simple nor conclusive because of the differences in vehicle pattern, MY, vehicle miles traveled (VMT) and ambient conditions on which the vehicles were tested. The comparison has been presented in
Table **7**, which takes into consideration the idle data from EMFAC 2000 (Both the summer and the winter data) [7], EMFAC 2002, version 2.2 [29], WVU vehicle idle data for MY 1975-1990 and post 1990 MY, WVU engine idle data, and other idle data available in literature [2, 4, 7-11].

EMFAC 2002 (version 2.2) has been developed from the E-55/59 Study conducted by WVU. Therefore, a strong similarity could be observed between these data. A similar pattern has been observed between the idle emissions reported by the ANL [4] and that presented on the EMFAC 2000 model for the summer and the winter condition [7]. ANL data included the effect of heating/cooling and elevated engine speed. Therefore, emissions data from the ANL Study was likely to differ from the other studies, which might not have included the heating or cooling load effects on idle emissions. Idle CO emissions from all studies were found to have similarity except from the ANL study and data obtained by McCormick et al [8]. Idle HC emissions varied from minimum 4.0 g/hr to maximum 25 g/hr for HDDV. Idle HC emissions from CNG buses were very high (86.1 g/hr), although HC from the CNG engines are primarily methane [30]. NOx and PM emissions were found be coherent amongst all studies with later MY engines emitting comparatively higher NOx but very low PM. CO_2 emissions and fuel consumption from the literature had limited variation except the ANL data, in which the CO_2 emissions and fuel consumption were approximately twice than the CO_2 emissions and fuel consumption in other studies. Idle emissions in the literature might include cooling fan, air compressor, air conditioner, and alternator loads, which can cause substantial variability in data collection.

Table 7: Comparison of Engine and Tailpipe Idle Emissions, and Fuel Consumption from WVU and Available Data

Source	**CO (g/hr)**	**HC (g/hr)**	**NOx (g/hr)**	**PM (g/hr)**	**CO_2 (g/hr)**	**Fuel (gal/hr)**	**Comments**
EMFAC 2000 Model	94	12.5	55	2.57	N/A	N/A	Summer (75ºF)
EMFAC 2000 Model	94.6	12.6	56.7	2.57	N/A	N/A	Winter (30ºF)
EMFAC 2002 Model	26.3	3.48	80.7	1.004*	4098	N/A	*1994+
WVU Vehicle Idle data	**23.32**	**9.5**	**83.31**	**1.41**	**4614**	**0.47**	**MY 1991-2004**
WVU Vehicle Idle data	**31.31**	**21.06**	**47.76**	**3.80**	**4504**	**0.46**	**MY 1975-1990**

WVU Engine Idle data	**29.46**	**4.84**	**74.88**	**0.84**	**3300**	**0.36**	**Post 1990 Model**
ANL [4]	94.6	12.6	56.7	2.57	10397	1.0*	* With Heating/Air condition
Brodrick et al. [9]	14.6	1.8	103	n/a	4034	0.36	Idling after cruise
Brodrick et al. [9]	15.9	2.9	105	n/a	4472	0.39	Idling after transient
Han Lim [2]	n/a	n/a	84.54	n/a	4256	0.42	1995 International
Pekula et al. [11]	n/a	n/a	97		5170	0.46	600 RPM, 65ºF
Storey et al. [10]	29.8	25.2	78.6	0.85	4720	0.4	600 RPM, 65ºF, 2001 Freightliner
McCormick et al. [8]	79.56	8.22	120.9	2.8	N/A	N/A	Diesel bus average
McCormick et al. [8]	67.14	86.1	16.02	0.18	N/A	N/A	CNG bus average

CONCLUSIONS

Idle emissions from the heavy-duty diesel buses and trucks are not desirable because of their effects on economy, environment, and human health. Long haul trucks are found to idle at truck stops for an extended period primarily for the heating and air conditioning of the drivers’ cabin, which cannot simply be proscribed because of the annual temperature profile in the USA. These trucks, in addition to adding criteria pollutants to the ambient environment, consumed millions of gallons of diesel fuel during idling. Idling also reduces engine life, and increases maintenance cost. A comprehensive database on idling emissions and fuel consumption is not available at present, although some studies were conducted to quantify idle emissions on a limited scale. Therefore, in order to create a comprehensive idle database, WVU tested over sixty heavy-duty diesel buses and trucks during the E-55/59 Study sponsored by the U.S. Department of Energy (DOE) Office of FreedomCAR and Vehicle Technologies through the National Renewable Energy Laboratory (NREL), the Coordinating Research Council Inc. (CRC), California Air

Resources Board (CARB), U.S. Environmental Protection Agency (USEPA), and the South Coast Air Quality Management District, and the Engine Manufacturers Association and the Gasoline-Diesel PM Split Study, sponsored by the US Department of Energy (DOE) Office of FreedomCAR and Vehicle Technologies through the NREL.

Idle emissions data for regulated pollutants like CO, HC, NOx, and PM have been collected, compiled, and reported in g/hr form a total of sixty six heavy-duty diesel vehicles consisted of sixty four trucks having 30,000 lbs or more GVW and two heavy-duty 2-stroke diesel buses. Out of these sixty-six HDDV, forty-eight trucks were tested during the E-55/59 Study and sixteen trucks and two buses were tested during the PM Split Study. Idle CO_2 emissions and fuel consumption for all these buses and trucks were also evaluated and reported in g/hr and gal/hr respectively. All these data were compared and contrasted with engine MY in order to observe their trend and identify possible effects on idle emissions from the remarkable advancement in automotive industry during the 90s. In addition, effect of elevated engine speed and accessory loadings such as A/C was observed. Idle emissions were also obtained from the continuous data of the Transient mode of the HHDDT Schedule. To give a sense of completeness vehicle idle emissions data were than compared with engine idle emissions data. This comparison provided the opportunity to compare and contrast engine idle emissions and real-world emissions from the vehicles. Finally, these data were compared with idle data available in literature, which is expected to provide a common platform in assessing idle emissions from old and new generation heavy-duty diesel buses and trucks.

It has been observed that ambient temperature and humidity along with difference in engine technologies were responsible for higher test-to-test variations. NOx/CO_2 ratio for the post 1990 MY vehicles was found to be high than the NOx/CO_2 ratio of the MY 1975-1990 vehicles. It indicated that manufacturer of these vehicles had advanced the timing of injection in order to ensure stability in idle and to avoid white smoking at light load or low temperature. It has also been observed that idle emissions varied with engine MY. Idle CO, HC and PM emissions were found to decrease with increasing engine MY in contrast to the idle NOx emissions, which increased with increasing engine MY because the modern electronic diesel engines control strategy provides for the advanced injection timing that increases NOx. Idle CO_2 emissions and fuel consumption from the tested vehicles were found to remain almost constant over the period. For one truck of MY 2003, the effect of air conditioning and elevated engine speed was observed and it was found that CO_2, NOx, PM, and fuel consumption increased by 25%, 30%, 20%, and 27% respectively with the use of A/C at 600 rpm engine speed and elevating the idle engine speed from 600 rpm to 1100 rpm caused an increase in CO_2, NOx, PM, and fuel consumption by 165%, 225%, 76%, and 170% respectively. Two 2-stroke diesel buses of MY 1982 and MY 1992 were tested during the PM Split Study and the third bus (MY 2000) was recently tested during the Transit Vehicle Exhaust Emissions Evaluation project, which has been sponsored by the US Department of Transportation, Federal Transit Administration. All emissions from the two 2-stroke diesel buses were higher than the MY 2000 bus except NOx, which was high for the MY 2000 bus.

Idle emissions were also obtained from the Transient mode of the HHDDT Schedule. These values were obtained from the continuous data of the Transient mode at hub horsepower close to zero. Overall, idle emissions obtained from the Transient mode of the HHDDT Schedule were higher than emissions from the idle cycles except NOx, which was less than NOx emissions from the idle cycles. The high idle values of CO, HC, and CO_2 from the Transient mode has been partly due to the effect of some accessory loadings such as fan and the compressors and partly due to the possible inclusion of emissions at initial acceleration while evaluating emissions from the continuous data. NOx emissions from the Transient mode were less than the NOx emissions obtained from the idle cycles, which is due to the advance injection timing during idle.

In addition to the vehicles' idle emissions, engine idle emissions and fuel consumption were also obtained from six DDC Series 60 engines of MY 1991, 1992, 1995, and 2000 in two separate sets, which were tested for fuel certification. These data showed a substantial variation in NOx and CO_2 when tested for warm idle than the variation observed when tested for hot idle. Engines in a test cell were found to consume fuel at only 70% of the level found in the PM Split Study and the E-55/59 data. This is because fan and compressor loads were absent in the test cell. The test cell engines did exhibit CO and NOx emissions similar to the post-1990 vehicles, but emitted PM at about half of the level from the post-1990 vehicles. While comparing these data with other idle data available in literatures, it has been observed that for similar engine and test conditions, they were in close relationship with each other except idle CO, NOx, and CO_2 emissions and idle fuel consumption. Idle emissions in the literature might include cooling fan, air compressor, air conditioner, and alternator loads, which can cause substantial variability in data collection. Variations in the CO_2/fuel consumption ratios might be partly due to correction for engine intake CO_2 mass.

This thesis has excellent potential both in terms of emissions inventory and economic implications. These data would provide 'the database' that the market was looking for. It is likely to give an insight into the idle emissions and the effects of engine MY on them. Projecting the effect of accessory loadings would provide an understanding of the increased idle emissions when heating or cooling is used. The thesis would also help in projecting the true potentials of the idle reduction technologies in reducing emissions and fuel consumption during idling.

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