Study of particulate number concentrations in buses running with bio diesel and ultra low sulfur diesel

Dinesh Chandra Somuri

The University of Toledo

Follow this and additional works at: http://utdr.utoledo.edu/theses-dissertations

Recommended Citation

http://utdr.utoledo.edu/theses-dissertations/726

This Thesis is brought to you for free and open access by The University of Toledo Digital Repository. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of The University of Toledo Digital Repository. For more information, please see the repository's About page.
A Thesis

Entitled

Study of Particulate Number Concentrations in Buses running with Bio diesel and Ultra Low Sulfur diesel

by

Dinesh Chandra Somuri

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the Master of Science Degree in Civil Engineering

________________________________________
Dr. Ashok Kumar, Committee Chair

________________________________________
Dr. Andrew G. Heydinger, Committee member

________________________________________
Dr. Vijay Devabhaktuni, Committee member

________________________________________
Dr. Patricia Komuniecki, Dean
College of Graduate Studies

The University of Toledo

May 2011
An Abstract of

Study of Particulate Number Concentrations in Buses Running With Biodiesel and Ultra Low Sulfur Diesel

by
Dinesh Chandra Somuri

Submitted to the Graduate Faculty in partial fulfillment of the requirement for the Master of Science Degree in Civil Engineering

The University of Toledo
May 2011

Most of the air quality standards available today are mass based and confined to PM$_{2.5}$ and PM$_{10}$ fractions. Size of most particles released from combustion sources is of submicron range, which has minor contribution to mass concentration. Therefore it is essential to obtain inventories for particulate number concentrations in this range.

The study was mainly focused on in-vehicle particulate number concentrations in public transport buses running on alternative fuels in the city of Toledo. The in-vehicle particulate number concentrations were collected over a period of one year from July 2008 to June 2009, in Biodiesel and Ultra low sulfur diesel fueled buses. The size of particulates found was in the range of 0.3µm and 20µm. Using the above measured particulate concentration data, the diurnal, monthly, and seasonal variations were studied. Various factors effecting in-vehicle particulate concentrations like number of passengers
in the bus, vehicles moving near the bus, ambient temperature, relative humidity, wind speed, wind direction, precipitation were also analyzed using regression tree analysis.

It was found that 65-70 % of particulates observed were in the size range of 0.3-0.4 µm. From this we were able to conclude that particulates emitted from diesel vehicles mostly consisted of fine particles. It was observed that particulate concentrations in biodiesel bus were slightly more when compared to ultra low sulfur diesel bus concentrations. From diurnal graphs, it was found that maximum particulate concentrations were obtained during the early mornings, when bus starts its run. From monthly and seasonal trends, it was obtained that maximum concentrations were found during the winter season, because of limited air exchange rate within the bus compartment. From the above trends it was clearly understood that in-vehicle particulate number concentrations were mainly influenced by peak hours, vehicular traffic, positioning of doors and windows, and passengers travelling. Regression analysis showed that in-vehicle particulate concentrations were influenced by meteorology. Wind speed and wind direction were found to have a significant impact on particulate concentrations. Various combinations of variables explained the pattern of monitored concentrations.

The measured in-vehicle particulate number concentrations in B20 and ULSD buses were converted into mass concentrations of PM$_{1.0}$, PM$_{2.5}$ and PM$_{10}$. These PM mass concentrations were compared with previously measured two years PM concentrations in the same buses. Using all the above data annual and seasonal PM trends were studied. It was observed that PM mass concentrations increased in the year 2009 compared to 2008 concentration levels. In all the three years, particulate matter
concentrations were found to be more in winter season when compared to other seasons in both BD and ULSD buses.

A screening mass balance model was developed for modeling of in-vehicle PM$_{2.5}$ concentrations for buses. The model was tested over four different seasons during a one year period. The air exchange rate and, deposition loss rate were estimated from literature review and from the analysis of monitored concentrations when developing the mass balance model. The developed model predicts the in-vehicle PM$_{2.5}$ levels inside buses for four seasons performed well up to 1:00 PM. It is suggested that a forecasting model should be used for ambient concentrations to improve the accuracy during afternoon hours.
This thesis is dedicated to my friends and family who helped me a lot throughout my career.
Acknowledgments

I would like to express my sincere gratitude to my advisor, Dr. Ashok Kumar, for his invaluable support, guidance and encouragement during the course of this thesis project and throughout my study at The University of Toledo. Without his moral support, persistent help, and continuous guidance enabled this dissertation would not have been possible. I am thankful to him for giving me the opportunity to work in this project. I would also like to thank Dr. Andrew G. Heydinger and Dr Vijay Devabhaktuni for serving on my thesis committee.

I would also like to thank my friends for their input and support throughout my work. Special thanks to Srikar Velagapudi, Prabhu Kilaru, Srihari Teella, Subash Pothula, Ratnam Mantripragada, Agasteswar Vadlamani and Ganesh Shanmugam.

I would like to thank the United States Department of Transportation (USDOT) and the Toledo Area Regional Transit Authority (TARTA) for the alternative fuel grant awarded to the Intermodal Transportation Institute (ITI) of The University of Toledo. I would also like to express my sincere gratitude to the TARTA management and the employees for their continued interest and support during the tough times.
Contents

Abstract iii
Acknowledgments vi
Contents viii
List of Tables ix
List of Figures x
1 Introduction 1
2 Literature Review 8
  2.1 Particular Matter Classification .............................................................. 8
  2.2 Particulate Matter Standards ................................................................. 9
  2.3 Health Concerns .................................................................................. 10
  2.4 Effect of fuel types on particulate emissions ....................................... 12
  2.5 Previous Studies on Vehicular Indoor Air Quality ............................ 14
3 Materials and Methods 18
  3.1 Experimental design ........................................................................ 18
  3.2 Instrumentation ................................................................................ 19
  3.3 Instrumentation Setup ..................................................................... 22
  3.4 Data Collection ................................................................................ 23
3.5 Meteorological data ........................................................................................................ 24
3.6 Traffic and Ridership data ............................................................................................. 24
3.7 Data Quality .............................................................................................................. 26
3.8 Experimental Procedure: Data Collected and Data used for Analysis ...................... 26
3.9 Regression Analysis Using Minitab 15 ...................................................................... 29
3.10 Modeling .................................................................................................................. 30
  3.10.1 Calculation of Air Exchange Rate .................................................................... 32
  3.10.2 Calculation of Deposition Rate ....................................................................... 33
  3.10.3 Outdoor PM$_{2.5}$ Concentrations .................................................................. 33
  3.10.4 Model Evaluation .............................................................................................. 34

4 Results and Discussion ............................................................................................... 36
  4.1 Particulate Number Concentrations ......................................................................... 36
    4.1.1 Particulate Number Concentrations based on Size Distribution .................... 36
  4.2 Particulate Matter Mass Concentrations .................................................................. 44
  4.3 Identification of Influential Factors Using Regression Analysis ............................. 52
    4.3.1 Effect of Passengers ..................................................................................... 57
    4.3.2 Effect of Cars and Trucks/Buses .................................................................. 57
    4.3.3 Effect of Ventilation Settings ....................................................................... 57
    4.3.4 Effect of Wind speed .................................................................................... 58
    4.3.5 Effect of Ambient Temperature and Ambient Relative Humidity .............. 58
    4.3.6 Effect of Indoor Temperature and Indoor Relative Humidity ....................... 58
    4.3.7 Effect of Wind direction ................................................................................ 58
  4.4 Model Evaluation .................................................................................................... 59
4.4.1 PM$_{2.5}$ concentration for Summer 2008 ............................................................. 59
4.4.2 PM$_{2.5}$ concentration for Fall 2008 ................................................................. 62
4.4.3 PM$_{2.5}$ concentration for Winter 2009 ............................................................... 64
4.4.4 PM$_{2.5}$ concentration for Spring 2009 ............................................................... 66

5 Conclusion 68

5.1 Recommendations for Future Research ................................................................. 70

References 71
List of Tables

1.1 Particle Counts in Southern California (Source: Westerdahl, 2003) ............................ 4
4.1 Particulate Number Concentrations with respect to size ............................................ 37
4.2 Important Factors Affecting Particulate Number Concentrations in a B20 Bus from Monthly MINITAB Results .............................................................................................. 54
4.3 Important Factors Affecting Particulate Number Concentrations in a ULSD Bus from Monthly MINITAB Results .............................................................................................. 55
4.4 Important Factors Affecting Particulate Number Concentrations in a B20 Bus from Seasonal MINITAB Results ............................................................................................. 56
4.5 Important Factors Affecting Particulate Number Concentrations in a ULSD Bus from Seasonal MINITAB Results ............................................................................................. 56
4.6 Performance Measures for Straight $X_0$ and $X_p$ for PM$_{2.5}$ for summer 2008 ........... 60
4.7 Performance Measures for Straight $X_0$ and $X_p$ for PM$_{2.5}$ for fall 2008 ......................... 62
4.8 Performance Measures for Straight $X_0$ and $X_p$ for PM$_{2.5}$ for winter 2009 .................. 64
4.9 Performance Measures for Straight $X_0$ and $X_p$ for PM$_{2.5}$ for spring 2009 .................. 66
List of Figures

1-1 Typical Mass and Number-weighted Size Distribution of Diesel PM ......................... 5
3-1 Map showing Route # 20 ............................................................................................ 19
3-2 GRIMM Dust monitor 1.108 ...................................................................................... 20
3-3 Concept of a typical GRIMM Dust monitor ............................................................... 21
3-4 Instrument placed in a cage in the bus ........................................................................ 23
3-5 Hard Drive equipment .............................................................................................. 25
3-6 Monitoring the Hard Drive ....................................................................................... 25
4-1 Hourly particulate number concentration trends inside B20 buses ......................... 39
4-2 Hourly particulate number concentration trends inside ULSD buses ..................... 40
4-3 Monthly Particle Number Concentration Trends inside B20 buses ......................... 41
4-5 Seasonal Particle Number Concentration Trends inside B20 buses ......................... 42
4-6 Seasonal Particle Number Concentration Trends inside ULSD buses .................... 43
4-7 Weekday and Weekends Particulate Number Concentration Trends ....................... 44
4-8 Yearly Variation of PM$_{1.0}$ in ULSD buses ............................................................ 46
4-9 Yearly Variation of PM$_{2.5}$ in ULSD buses ............................................................ 46
4.10 Yearly Variation of PM$_{10}$ in ULSD buses .......................................................... 47
4.11 Yearly Variation of PM$_{10}$ in BD buses ................................................................. 47
4.12 Yearly Variation of PM$_{2.5}$ in BD buses ................................................................. 48
4.13 Yearly Variation of PM$_{10}$ in BD buses ................................................................. 48
4-14 Seasonal PM$_{1.0}$ Concentration Trend inside B20 fueled buses ......................... 49
4-15 Seasonal PM$_{2.5}$ Concentration Trend inside B20 fueled buses ......................... 50
4-16 Seasonal PM$_{10}$ Concentration Trend inside BD fueled buses ......................... 50
4-17 Seasonal PM$_{1.0}$ Concentration Trend inside ULSD fueled bus .......................... 51
4-18 Seasonal PM$_{2.5}$ Concentration Trend inside ULSD fueled bus ......................... 51
4-19 Seasonal PM$_{10}$ Concentration Trend inside ULSD fueled bus .......................... 52
4-20 Observed Vs Predicted PM$_{2.5}$ during summer 08 from 6 AM to 6 PM ............. 61
4-21 Observed Vs Predicted PM$_{2.5}$ during summer 08 from 6 AM to 1 PM ............. 61
4-22 Observed Vs Predicted PM$_{2.5}$ during summer 08 from 2 PM to 6 PM ............. 61
4.23 Observed Vs Predicted PM$_{2.5}$ during fall 08 from 6 AM to 6 PM ...................... 63
4-24 Observed Vs Predicted PM$_{2.5}$ during fall 08 from 6 AM to 1 PM ...................... 63
4-25 Observed Vs Predicted PM$_{2.5}$ during fall 08 from 2 PM to 6 PM ...................... 63
4-26 Observed Vs Predicted PM$_{2.5}$ during winter 09 from 6 AM to 6PM .................. 65
4-27 Observed Vs Predicted PM$_{2.5}$ during winter 09 from 6 AM to 1 PM .................. 65
4-28 Observed Vs Predicted PM$_{2.5}$ during winter 09 from 2 PM to 6 PM .................. 65
4-29 Observed Vs Predicted PM$_{2.5}$ during spring 09 from 6 AM to 6 PM ............... 67
4-30 Observed Vs Predicted PM$_{2.5}$ during spring 09 from 6 AM to 1 PM ............... 67
4-31 Observed Vs Predicted PM$_{2.5}$ during spring 09 from 2 PM to 6 PM ............... 67
Chapter I

Introduction

Numerous studies have demonstrated a strong correlation between exposures to particulate matter (PM) and increasing rates of mortality, morbidity, respiratory and cardiovascular problems (U.S. EPA, 2004). Population based studies have shown an association between long term exposure to fine particulate air pollution and mortality (Pope et al., 2009). This study concluded that reduced exposure to ambient fine-particulate air pollution resulted in significant improvement in life expectancy in United States. However, the database is limited in terms of both number of studies, number of subjects and geographical restrictions to allow clear conclusion on the mode of action or generalization of other settings. Therefore further studies need to be initiated to improve our understanding of fine particles and health concerns.
Apart from health issues, these particles also have an impact on the environment in a number of ways. One of the major causes of concern is the reflection of solar radiation by the particles, leading to a cooling of our climate system (IPCC, 2001); they also have an impact on the hydrological cycle (Ramanathan et al., 2001). The revised 2006 EPA standards categorizes particles pollution into fine particles (PM$_{2.5}$), which are 2.5 micrometers in diameter and smaller; and inhalable coarse particles (PM$_{10}$) which are smaller than 10 micrometers and larger than 2.5 micrometers. The 24-hour fine particle standard for PM$_{2.5}$ has been tightened from 65 microgram per cubic meter ($\mu g/m^3$) to 35 $\mu g/m^3$ retaining the annual fine particle standard at 15 $\mu g/m^3$. EPA retained the 24-hour PM$_{10}$ standard of 150 $\mu g/m^3$ and due to lack of proof for health problems linking to long term exposure to coarse particles; the Agency withdrew the annual PM$_{10}$ standard.

The direct emissions of PM$_{2.5}$ include organic carbon, elemental carbon, sulfur dioxide, NOx, volatile organic compounds (VOCs) and crustal material. Exposure to VOCs, NOx, CO has been strongly associated with vehicle use (Wallace, 1987). Studies indicated that travelling inside vehicles during peak traffic hours results in exposure to higher concentration of particulate matters than ambient concentrations in suburban areas. This suggests that usage of fixed site monitoring data would give an underestimated value for exposure to air pollutants by commuters. A study found that VOC measurement was higher inside the vehicle when compared to the fixed site on urban roadways 50m from the streets (Chan et al., 1991) Thus to reasonably estimate the exposure of population to the particulate matters, it is necessary to determine as accurately as possible, the total exposure to the particulate matters inside the vehicles.
Indoor particle concentration depends on penetration of outdoor particles, way of air exchange, the operating mode of indoor environment during the presence of travelers. The physical properties of the ambience, like the wind speed, direction, the difference in the density of indoor/outdoor air, the difference in the indoor/ambient temperature etc also play an important role in determining the transport of particulate matter into the bus. Natural ventilation and infiltration define air exchange rate and thus the amount of PM entering the bus. The efficiency of the filters integrated in the ventilation system and the natural ventilation caused by open windows helps us estimate the particle penetration based on ambient PM concentration. A study found that air conditioning and open vent with fan on resulted in lowest levels of VOCs (Chan et al., 1991). Particle deposition is a prominent means of loss of PM suspended in the buses.

Fine particles account for a negligible fraction of the total mass concentration, even though their number count is very high, thus the measurement of particles in this sub micrometer range is more commonly based on particle number rather than mass concentration. Particle number concentration and particle size distribution are usually measured in real time, while particle mass concentration, mass size distribution and morphology require first the sample data to be collected and then analyzed and calculated.

There are several existing methods for particle number and size measurements. A number of studies reporting particle number and size distribution applied electrostatic classifiers (EC) and condensation particle counters (CPC) manufactured by TSI. The other widely used instrument is called the GRIMM or air ion mobility spectrophotometer,
which has enabled measurements down to 0.4µm (Mirme et al., 2007). In our study, continuous monitoring of particulate matter in each bus was done using GRIMM 1.108 instrument.

Chemical composition of particles depends on source of the particle as well as the post formation transformations the particle has undergone. Internal combustion engines have been identified as a significant source of ultrafine particles. Diesel emission particles have a significantly smaller diameter less than 0.1 µm. Particles emitted by gasoline powered engines have a diameter less than 0.08 µm. The majority of particles from compressed natural gas fueled engines have a diameter between 0.02 µm and 0.06 µ. Typically particles emitted are a mixture of solid particles formed during combustion and more volatile particles. The solid particles mainly consist of agglomerated elemental carbon (soot) and act as an absorbent for the volatile organics formed during combustion. Some of the spherical particles may be formed in the engine, while a majority is formed outside the engine by nucleation of hydrocarbons, sulfuric acid and water vapor as the exhaust undergoes natural processes of dilution and cooling in the atmosphere. Figure 1-1 shows a typical diesel engine exhaust mass and number weighted size distributions.

Fine particle number and mass concentrations are not regularly measured in U.S. Thus, there is little data on long term trends. In urban environment, high particle number concentrations are localized and dependent on nearby source activity; they also show large geographical and temporal variation (Table 1.1). Studies show that average particle counts tend to be higher in winter, compared to spring and summer. This can be supported by the fact that due to lower temperatures, organics emitted from vehicles form
particles, PM formation is also favored by decreased atmospheric mixing height and more stagnant conditions increasing the influence of localized emissions (Sioutas et al., 2004).

Table 1.1: Particle Counts in Southern California (Source: Westerdahl, 2003)

<table>
<thead>
<tr>
<th>Area</th>
<th>Particle Number Concentration (Particles/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal area</td>
<td>600-2000</td>
</tr>
<tr>
<td>Office spaces</td>
<td>500-2000</td>
</tr>
<tr>
<td>Urban air</td>
<td>10,000-40,000</td>
</tr>
<tr>
<td>Freeways</td>
<td>40,000-1,000,000</td>
</tr>
<tr>
<td>Industrial site</td>
<td>Up to 100,000</td>
</tr>
</tbody>
</table>

Major factors thus effecting the formation of particulates are the hydrocarbon particle precursors and sulfur content of the fuel and the composition of lubricating oil. Hydrocarbon precursors are effectively removed by oxidation catalyst technology. A significant reduction in number of fine particles is observed when fuel with lower sulfur levels is used. This is because a fraction of sulfur in the fuel is oxidized to sulfur trioxide, SO$_3$, which bounds with water forming sulfuric acid, one of the gas phase species that can nucleate to form new smaller particles. Thus, the experimental study presented here deals with the behavior of in-vehicle particulate matter in public transport buses operating on B20 biodiesel and Ultra Low Sulfur Diesel (ULSD) in the city of Toledo, Ohio. So, in order to assess the impact of alternate diesel fuels on environment, Toledo Area Regional Transit Authority (TARTA) public transport buses were used. It has more than 180 buses running throughout the day contributing significant amount of particulate matter to the
environment. To quantify the environmental particulate matter and to setup boundaries, TARTA using alternate fuels including B20 and ULSD is used.

![Figure 1-1: Typical Mass and Number-weighted Size Distribution of Diesel PM (Kittelson et al., 1998).](image)

Thus investigation of the levels of particulate matter emitted from individual vehicles continues to be the subject of research. However our knowledge about the quantities of total particulate matter emitted from urban motor vehicles fleets, especially ultrafine particle emissions are still a subject of uncertainty. Thus, this work concentrates on developing comprehensive inventories for particle numbers and mass emitted from Toledo Area Regional Transit Authority (TARTA) buses.
The two very important characteristics of effective particle emission inventories include:

- Particle emission inventories should be size resolved as particle size is an important determining factor for deposition in the human respiratory tract and the depth of its deposition (Morawska et al., 2008). Thus it is important from a health perspective.

- Particle emission inventories need to quantify both particle number and emissions for different particle mass size fractions. This relates to the fact that particles with diameter <1µm are prolific in terms of their numbers but have little mass and are therefore measured in terms of particle number; whereas larger-sized particles with diameter > 1µm have greater mass and are most effectively measured in terms of different particle mass size fractions.

Effective and least costly means of fine particle emission reduction should be based on a firm physical understanding of the processes and parameters controlling formation and evolution of fine particles in vehicles. Such an understanding would help us establish various other associated parameters like engine design, operation, after treatment and fuel and lubricating oil composition modifications that would efficiently decrease particulate emissions. Such an understanding is also important for assessing health, chemical and climatic effects of aerosols.

Thus developing inventories of emissions provide data that enable comparisons to be made between quantified emissions and current air quality standards, thereby helping in developing air quality guidelines and regulations and health impact assessments.
Although there are various kinds of pollutants associated with vehicles, the studies reviewed here are limited to the investigation of particulate matter because of the increased association between ambient fine particle concentrations and mortality or morbidity of urban population.

Therefore the main objectives of this study include:

- Develop a database of particulate number concentration for a 3-year period.
- Study of diurnal, monthly, and seasonal data of particulate matter inside vehicles.
- Determine factors affecting indoor air quality inside buses running on B20 biodiesel and ULSD.
- Determine air exchange rate and, deposition loss rates inside diesel buses.
- Develop a screening mass balance model for determining the in-vehicle PM$_{2.5}$ concentration when ambient PM$_{2.5}$ concentration is known.
Chapter II

Literature Review

A literature review including EPA resources, textbooks, journal articles, and internet resources is conducted in order to acquire basic background information relevant to the present work. Particulate matter in terms of classification, standards, health concerns, and how fuel type can effect emissions is discussed in detail along with past research work.

2.1 Particular Matter Classification

Particulate matter (PM) is broadly classified as coarse PM with a diameter of 2.5µm to 10µm and fine PM with a diameter less than 2.5µm. Ultrafine particles are loosely defined as those with diameter less than 0.1µm (or 100nm). The decision by the US EPA to introduce 2.5µm as the upper limit for the fine particles and as a basis for a standard (Reference US Federal Register) was influenced by the fact that the available epidemiological data at the time were obtained using PM$_{2.5}$ measurements (Dockery et al., 1993). Another classification is focused on particles size and production mechanisms.
This classification includes nucleation mode (<0.1µm), accumulation mode (0.1-1µm) and coarse particle mode (>1µm) (Jaenicke et al., 1993). The accumulation mode particles are formed by coagulation of ultrafine particles and condensation of gases and vapors on pre-existing particles of nucleation and accumulation mode.

However, the modes of classification generally depend on the metric being referred to, such as particle number, particle volume, surface area or mass. Modes also change depending on the mathematical transformation used. For example, the conversion of number distribution to particle volume distribution resulted in three modal size ranges: the nuclei mode (< 0.1 µm), the accumulation mode (0.1-2 µm) and coarse particle mode (> 2 µm) (Baron and Willeke et al., 2001). With the development of instruments with small size limit to 3nm, nuclei mode has been separated into nucleation mode (< 0.01 µm) and an Aitken nuclei mode (0.01-0.1 µm) (USEPA 2004).

2.2 Particulate Matter Standards

The Clean Air Act requires EPA to set National Ambient Air Quality Standards for pollutants which were considered harmful to public health and the environment. There are two types of standards established, primary and secondary standards. Primary standards are set to protect public health, including the health of sensitive population such as asthmatics, children, and the elderly. Secondary standards are set to protect public welfare, including protection against decreased visibility, damage to animals, crops, vegetation, and buildings. The EPA Office of Air Quality Planning and Standards (OAQPS) has set National Ambient Air Quality Standards for six principal pollutants called the "criteria" pollutants. Particulate matter is one among them. Units of measure
for the standards are micrograms per cubic meter of air (µg/m$^3$). The nation's air quality standards for particulate matter were first established in 1971 and were not significantly revised until 1987, when the EPA changed the indicator of the standards to regulate inhalable particles smaller than, or equal to, 10 micrometers in diameter. EPA revised the air quality standards for particle pollution in 2006. The 2006 standards tightened the 24-hour fine particle standard from the initial level of 65 micrograms per cubic meter (µg/m$^3$) to 35 µg/m$^3$, and retained the current annual fine particle standard at 15 µg/m$^3$. The Agency decided to retain the then existing 24-hour PM$_{10}$ standard of 150 µg/m$^3$. The Agency revoked the annual PM$_{10}$ standard, because available evidence did not suggest a link between long-term exposure to PM$_{10}$ and health problems. These standards are reviewed every five years. For particulate matter, secondary standards are the same as primary standards.

2.3 Health Concerns

These ultrafine and fine particles with larger surface area can act as a carrier for trace metals and organic compounds into the lungs. These smaller particles can also be inhaled and deposited deeper into the lungs when compared to larger particles which are exhaled out by nose. Ultrafine particles elicit greater inflammatory and oxidative stress response when compared to larger particles at comparable mass doses. After inhalation, these particles penetrate rapidly into lung tissue and some portion may be transported to other organs of the body. Some particles are transported via neural cells from nose and pharynx to the olfactory bulb of the brain (Oberdoster et al., 2004). Ultrafine particles
also have the capability to penetrate mitochondria and induce structural damage (Li et al., 2003).

Epidemiological studies (US-EPA, 2004; WHO, 2005) have associated adverse and severe health outcomes with exposure to ambient air particulate matter that is less than 2.5 μm in aerodynamic diameter (PM$_{2.5}$), especially among susceptible sub-populations; infants, elderly and subjects with cardiopulmonary diseases. In urban areas, a large fraction of the PM$_{2.5}$ pollution originates from local mobile sources, mainly diesel powered vehicles (Kinney et al., 2000).

Concerns over emissions focus on several of its components. Particulate matter has been associated with respiratory and cardiovascular disease and death (Pope et al., 1995). PM or diesel exhaust components may also cause lung cancer. Diesel Particulate Matter’s (DPM) danger lies in its small size, large surface area, and its ability to absorb organic compounds. It is inhaled deep into the lungs, carrying large quantities of ash, organic carbon, organic compounds and sulfates deep into the lower respiratory tract, where they can be eluted, metabolized and transported throughout the body. Numerous international health agencies have concluded that diesel exhaust is a probable or known carcinogen. Various U.S. studies estimating the lifetime excess cancer risk caused by air pollution have concluded that DPM is responsible for 70 – 89% of the total cancer risk caused by air pollution in the U.S. Certain groups have an even higher risk of developing respiratory problems and cancer as they are exposed to higher than average ambient air concentrations of DPM. Although we cannot totally avoid the risk from DPM, we can reduce the impact by taking proper measures which can reduce the emissions and
improve the indoor air quality. The present work will provide crucial information to indoor air quality regulators and decision makers in understanding the IAQ in transit vehicles and to regulate IAQ standards.

2.4 Effect of fuel types on particulate emissions

Fuel type plays an important role in particulate emissions from vehicles. Diesel, compressed natural gas, and biodiesel are some of the fuels that are being used in vehicles. Each fuel emission is different. The present work focused on ultra low sulfur diesel (ULSD) and biodiesel (BD20). So, these fuels will be discussed in more detail.

Although changes in diesel engine technology over time have changed the chemical composition of particulate matter, total Polycyclic Aromatic Hydrocarbons (PAH) emissions are believed to have remained the same and PM from diesel engines continues to pose a public health risk. Alternate fuels can substantially reduce particulate matter emissions compared to conventional heavy-duty diesel. Sulfate particulate and sulfur dioxide emissions are emitted in direct proportion to the amount of sulfur in diesel fuel. ULSD has been mandated by the U.S. EPA to replace low sulfur diesel. ULSD is a refined diesel fuel that has dramatically lower sulfur content than regular on-road diesel. The sulfur content ranges from 15 to 30 ppm while regular diesel has a maximum of 500 ppm of sulfur.

The lower sulfur content in ULSD produces fewer sulfate emissions and most importantly, it enables the use of emission reduction equipment, like particulate traps to lower emissions of particles. Use of these systems in combination with ULSD can reduce emissions of fine particulates by more than 90%. Even without emission reduction
equipment, use of ULSD will moderately reduce sulfate pollutants. Apart from the benefits, there are some concerns associated with ULSD: a) it is very expensive to manufacture and thus the costs is passed through to the end user b) there is not enough ULSD available to adequately meet the immense demands c) ULSD can only be used in diesel engines specifically designed for ultra low sulfur diesel.

Biodiesel is a diesel replacement fuel made from a blend of vegetable oils and animal fats. Just like petroleum diesel, biodiesel operates in compression-ignition engines. Blends of up to 20% biodiesel can be used in nearly all diesel equipment and are compatible with most storage and distribution equipment. These low level blends generally do not require any engine modifications. Higher blends and even pure biodiesel (100% biodiesel or B100), can be used in many engines built since 1994 with little or no modification. Using biodiesel in a conventional diesel engine reduces emissions of unburned hydrocarbons, carbon monoxide, sulfates, and particulate matter. But the use of biodiesel also has some concerns: a) It is more expensive than conventional diesel and less efficient b) Engines burns 2% - 5% more fuel c) Fuel tanks must be disassembled and cleaned every few months due to build up of fatty residues along interior walls d) According to Engine Manufacturers Association, biodiesel fuels reduce emissions of hydrocarbons and carbon monoxide but it increases nitrogen dioxide emissions when compared to petroleum-based diesel fuel. So, biodiesel or its blends should not be used in air quality ozone non-attainment areas. e) It is also stated that in equipment designed for petroleum fuels, blends greater than B5 can cause reduced product service life and equipment failures.
2.5 Previous Studies on Vehicular Indoor Air Quality

Numerous studies are reported in the literature to assess the personal exposure to particulate matter in different vehicle environments. Some of these studies also identified the factors that influence the in-vehicle pollutant levels. According to the study by Rodes et al., (1998), which mainly focused on the factors that influence in-vehicle pollutant concentrations concluded that type of the roadway, the driving lane, congestion level, and the time of day had significant effect on in-vehicle pollutant level. And also found that in-vehicle fine particulate counts were significantly higher when following diesel vehicles. Another study conducted by Fitz et al., (2003) who mainly focused on children’s exposure to different pollutants while traveling in a school bus had noticed that vehicle exhaust, self pollution and ventilation settings are the main factors that affect in-vehicle pollutant levels. Praml and Schierl (2003) have observed that outdoor concentrations and traffic surrounding the vehicle have a significant impact on in-vehicle particulate matter. While Adams et al., (2001b) studied the effect of meteorology data on in-vehicle PM$_{2.5}$ in five different microenvironments that included bicycle, bus, car and underground railway. Diapouli et al., (2008) studied exposure to PM$_{10}$ and ultra fine particles on-road and in-vehicle and observed that the exposure was higher in areas of heavy traffic and during the peak hours. Traditional ambient air quality monitoring network provide very useful assessments of broad trends and patterns, and in some cases may provide fairly reliable estimates of relative risks to human health. But, as this study seems to indicate,
data from ambient air quality monitoring stations can grossly underestimate the absolute risks to air pollution.

Study by Joshua (2004) focused on quantifying the impact of particulate matter on health. The results indicated that Emission Control Diesel (ECD) produced great reductions in health damages compared to conventional diesel. It was also observed that ECD was far more cost effective than CNG. They also discussed the uncertainty of results due to simplified assumptions and very limited data availability on emissions and costs. This unavailability of data strengthens the idea that there is a great need for inventories of reliable data.

The study by M.c Fondelli (2008) focused on characterization of PM$_{2.5}$ mass levels & PM$_{2.5}$ bound element concentrations in typical workday traffic conditions. This was done by positioning a filter sampler in buses, which is similar to the approach used for the present work. It was observed in the study that PM$_{2.5}$ mass concentrations inside the vehicles correlated well with the urban ambient air PM$_{2.5}$ concentrations. The results from this study could be used to plan interventions to minimize the PM$_{2.5}$ citizen exposures in commuting. The assessment results suggested that the user’s exposure encountered on-board of buses during commuting or riding is of greater importance due to long travel time spent per day and the high peak population levels. Today, there is very limited information about PM$_{2.5}$ self pollution inside diesel powered bus cabins. Adar et al., (2008) observed that up to 33% of the in-vehicle PM$_{2.5}$ originated from the bus’s own emission sources by comparing the differences in PM$_{2.5}$ levels between the buses and
lead vehicles. The present work will help improve the understanding of these concentrations in buses.

Recent studies suggested that particle number is more important than particle mass in determining health effects. A study by Davyda (2007) focused on particle numbers unlike many studies which worked on particle mass. The study compared three different fuels CNG, conventional diesel and oxidation-catalyst diesel to estimate relative in-vehicle particulate exposures. It was observed from the study that the conventional diesel buses had average particle count concentrations approximately three to four times greater than that of others and particle number concentrations were also noticeably affected by bus idling behavior and ventilation options such as wind positioning and air conditioning. Another study by Wargo et al., (2002) found that window ventilation, bus idling behavior, and outdoor concentrations on bus routes had significant influence on the in-vehicle particulate concentrations. According to the EPA, emissions from individual diesel buses have declined substantially over the past decade. Improvements in diesel engine technology, such as introduction of filters and reduction catalysts, have resulted in heavy-duty diesel engines that emit 50-90% less particulate matter than diesel engines of the previous decade. A study by Holmen (2004) indicated that there is limited data available to quantify the extent to which alternative fueled transit buses provide passenger exposure benefits in urban areas during normal operation. This study also stresses the need for reliable data which can play a key role in decision making.

From the literature review, it was found that various factors ranging from air conditioning to methodology used for estimation can affect the PM levels (Seksana et al.,
Wayne et al. (2007) has studied the relationship between vehicle speed, ventilation settings and window positions with air change rates. Fletcher and Saunders (1994) studied air change rates (ACH) of five vehicles for different wind speeds and wind directions and derived an empirical equation for the ACH versus speed. Park et al. (1998) measured air change rates in three stationary automobiles at four different conditions with windows closed and no mechanical ventilation and he concluded that the prediction of indoor concentrations of pollutants air change rate of a vehicle is important. The studies of Fletcher and Saunders (1994) and Ott et al. (1994) gave air change rates in moving vehicles under different ventilation and window settings. All these studies are based on automobiles but not on buses. Fuel type has a direct impact on the health issues and availability of limited data on emissions is one factor that is keeping regulators away from taking proper measures to counter the emissions (Joshua T et al., 2004). Indoor air quality is of greater importance due to long travel time spent per day by an individual and high peak population levels (Mc. Fondelli et al., 2008). It is also observed that particle number is more important than particle mass for various reasons including health concerns (Davyda et al., 2007). Some of these observations have set the objective for this thesis to develop inventories for particulate matter and others were instrumental in the development of model.
Chapter III

Materials and Methods

This research required the collection and analysis of a large amount of data that should be handled carefully. In order to obtain the objectives of the research work, the instrumentation and methodology used are described briefly in the following sections.

3.1 Experimental design

This section mainly deals with the selection of the buses in which instruments are placed, how these instruments are safeguarded within the bus and the route in which these buses have their daily run. These experiments are carried out in Toledo Area Regional Transit Authority (TARTA) buses that run in and around the Toledo region. TARTA has about 180 buses which run within Toledo and has about 9 fleets. The buses selected for this study belong to 500 series with a Mercedes Benz MBE 900 engine. These buses were built in 2001 and have a total seating capacity of 32 people per bus. The route selected was Route # 20 as shown in Figure 3-1. In this selected route, the bus runs between TARTA garage and Meijer on the Central Avenue strip. After selecting the
route, two buses were selected from the 500 fleet and tests were conducted to find out whether all the cameras and GPS units were working properly within these buses. The buses selected for this work were bus number 506 and 536. Bus number 506 run on biodiesel (B20) and bus number 536 run on ultra low sulfur diesel (ULSD). The two buses selected were operated on the same route # 20 with a time lag of 12 minutes between each run. This helps in comparing the indoor particulate number concentrations inside the two selected test buses.

![Map showing Route # 20 (Source: TARTA website, 2010)](image)

**3.2 Instrumentation**

In-vehicle particulate number concentrations data were monitored continuously for the selected two buses 506 and 536 operating on B20 and ULSD fuel. Grimm Dust
monitor 1.108 shown in Figure 3-2 was installed in each bus for measurement of particulate number concentrations.

Figure 3-2: GRIMM Dust monitor 1.108 (Source: www.grimm-aerosol.com)

For this study a GRIMM 1.108 aerosol spectrometer, a portable optical particle counter, was used to measure indoor particulate number concentrations within the buses. This instrument is lightweight, easy to handle and operates effectively for a given time resolution. The GRIMM aerosol spectrometer uses light scattering technology to calculate number of particles per unit volume of air. The instrument delivers single particle counts and size classifications in real time. As shown in Figure 3-3, the air sample (1) in form of various sized particles is constantly being drawn via a column controlled pump (3,4) through a flat beam of light which is produced by a (6) focused laser diode (8), at 90° so the particle color changes can be neglected. This pulse is analyzed by an integrated pulse height analyzer (9) and is classified in (8, 15) different
size ranges (10) and then counted. These counts or masses (per size range) are stored on the data storage card (11) and are displayed in intervals of one minute (12).

![Diagram of GRIMM Dust monitor](https://www.grimm-aerosol.com)

**Figure 3-3: Concept of a typical GRIMM Dust monitor (Source: www.grimm-aerosol.com)**

The collected particulate number concentrations can be converted into mass concentrations via mathematical formulas. This instrument consists of four operational modes: environmental, occupational health, mass distribution and count distribution. The Dust monitor consists of 15 channels of size ranging from 0.23 - 20 µm for measuring particulate number concentrations with a concentration range of 1-2,000,000 particles/liter (for count distribution mode) and a mass concentration range of 1-100,000 µg/m³ (for mass distribution, environmental and occupational health modes). The
sensitivity of the Dust monitor is 1 particle/liter or 1 µg/m³, and instrument reproducibility is ± 2%. Ambient air is drawn into the unit via an internal volume controlled pump at a rate of 1.2 liter/min. A stainless steel tube provided by the manufacturer was used as the instrument inlet. The Dust monitor consists of a rechargeable Li-Fe battery (holds power for 6 h of run time) and a 4 MB storage internal data card.

At the start of each measurement the instrument initiates a system self test and zero calibration check. For this study, the instrument was operated in count distribution mode to produce number concentrations versus time data. The measured real time number concentrations data are transferred at 1 minute intervals to a data storage card. The measured data were then downloaded to the system from the data storage card using Grimm 1177 program.

3.3 Instrumentation Setup

The Grimm 1.108 Dust monitor was installed within the bus in a wire mesh box and was held at the bottom using a Velcro attachment, so that the instrument is tightly gripped inside the bus without any disturbances during the motion of the bus as shown in Figure 3-4. The box was placed on an enclosure built for GPS system inside the bus and was secured using a locking mechanism. This complete setup was located on the front end of the bus on the left side and 3 m away from the wind shield. The location of the instrument is also based on the accessibility of power supply and safety of the instrument. The power supplied to the instrument is through an AC adapters connected to inverter inside the bus and care is taken to provide continuous power supply to the instrument.
The instrument was placed at a height that equals the breathing height of the seated passengers.

![Figure 3-4: Instrument placed in a cage in the bus](image)

### 3.4 Data Collection

The in-vehicle particulate number concentrations for diesel buses were measured in between July 2008 and June 2009. Grimm Dust monitor conducted real-time particulate number concentrations calculations (24x7) at every 1 second interval and provided output as 1-minute averages. The data from the instrument were frequently downloaded to a laptop. In order to have a complete study of the variations and the
factors effecting number concentrations over a three year period, the data collected by the previous researcher were also used for the analysis. Data collection included downloading the data from the instrument, monitoring the real time variables such as passengers entering and leaving the bus, vehicles surrounding the bus, positioning of doors, windows etc., and also obtaining the meteorological data.

3.5 Meteorological data

Meteorological data for Toledo region were collected from the National Climatic Data centre website. The data obtained from this site consists of hourly details of temperature, relative humidity, wind speed, wind direction, cloud cover, precipitation etc. This information was used to analyze the influence of meteorology on indoor particulate number concentrations within the bus. Ambient PM$_{1.0}$ and PM$_{2.5}$ data is obtained from the U.S EPA website.

3.6 Traffic and Ridership data

The buses used for the study consisted of 5 cameras which were installed inside the bus at different positions. One Camera faces road, two cameras face the doors, one faces towards the back of the bus indoors and one face to the front of the bus indoors from back. Few cameras were placed facing outside the bus which were used to notice traffic (buses, cars and trucks) surrounding the bus. Few faced indoors of the bus were used to find out the positioning of doors and windows of the bus.

All this video information was stored in a hard drive shown in Figure 3-5 which is placed in the bus. TARTA has provided software “Wave Reader” to read the information
in the hard drive. The hard drive is analyzed on a time scale of 5-minute basis shown in Figure 3-6.

Figure 3-5: Hard Drive equipment

Figure 3-6: Monitoring the Hard Drive
3.7 Data Quality

To make sure that the data collected are of excellent quality, the Grimm Dust monitor 1.108 was regularly cleaned with canned air and the particulate filter was replaced on at regular time intervals. The nozzles were cleaned regularly to obtain good quality data. The removed filters were carefully placed in Ziploc plastic bags and were labeled with date, time and bus numbers. These filters were being analyzed by another student for his research. The Grimm monitors were regularly calibrated to ensure quality data from it. At the start of each measurement, the instrument does a self test and zero calibration tests. After transportation or storage of the instrument at low temperatures, the instrument should be allowed to warm up for sufficient time prior to operation. Otherwise, the condensation in the units pumping mechanism will cause the pump to malfunction. In such an event, the unit will automatically shut down. The lithium battery of this instrument can function continuously for only 15-20 h without charging and so proper charging should be provided with external power supply. The instrument was regularly sent to factory for verification calibration of laser optics, gravimetric correlation verification, and optical calibration.

3.8 Experimental Procedure: Data Collected and Data used for Analysis

Indoor air quality data were collected from July 2008 to June 2009 during field program. Data collected from March 2006 to June 2007 by Vijayan (2007) and from June 2007 to April 2008 by Kadiyala (2008) were also used for data analysis and comparison. During the data collection, there were several small troubles encountered with the instrumentation and its setup, with a majority of troubles associated with bus operation
and maintenance. But these troubles are common troubles expected from any transport bus system. So, as part of experimental work, it is necessary to document these problems in order to take precautions prior to future tests. Some of the key troubles faced during data collection are discussed here.

The test buses did not take the requested route and in many cases were not sent out on run. Thus, such days were excluded from our study. Also due to the negative impact of the Toledo roads, the buses broke down on a regular basis, thus reducing the on road period of a bus for several days. In such situations, the researcher changed the test bus as soon as they were informed.

Another commonly encountered trouble was associated with the power supply connection to the instrument. Since the IAQ instruments are capable of running a maximum of 15-20 hours on their in-built battery, they were connected to an external power drawn from bus battery (DC). This power was converted to 110V AC and used continuously by the instruments using a power strip. But on many occasions, the power strip was disconnected as a result of which the instruments ran to zero power and were eventually shut down. To overcome this trouble, the adapters were wired to power strips and power box was locked.

Some of the cameras installed in the buses also did not work properly. This led to a reduced data bank for that selected test bus. Also, TARTA did not have additional cameras, as a result of which the problem could not be fixed for a long time. Thus the days without proper video output were removed from analysis.
Apart from the camera trouble, the hard-drives connected to this camera’s were removed and replaced without any record keeping. As a result, the traffic passenger activities, bus operation data were jumbled causing a significant reduction in the completeness of the data. The hard disks collecting the video output inside the bus had memory just sufficient to record data for 10 days. On a number of occasions, the data was collected many days after the 10 day period, thus leading to loss of video data. Also, there tends to be some error in data perception (e.g. counting the number of vehicles ahead of the bus) if the video monitoring part was analyzed by different set of people.

Heavy particulate dust inside the compartment and instrumentation lead to the internal clogging of the filters. Thus they had to be cleaned more frequently using pressurized air. The instrument was also sensitive to dust as a result sometimes the instrument had to be reset. The problem was later solved by providing adequate padding to the instrument. Though most of the troubles occurred at different time periods, allowing the research to continue without hindrance, the amount of data collected for comparing ULSD and B20 got restricted.

Thus the data which were not affected by any of the above problems were taken and used for further analysis. The GRIMM instrument placed in B20 biodiesel and ultra low sulfur diesel buses yielded one year of quality data on particle number concentration from July 2008 to June 2009. The data were studied for different seasons; winter (January-March), spring (April-June), summer (July-September) and fall (October-December). Regression and regression tree analysis was performed to identify the significant variables and their contribution for a given season.
3.9 Regression Analysis Using Minitab 15

The effect of various independent factors like metrological conditions, traffic intensity, passenger count, ventilation settings, type of lead vehicle influencing the dependent particulate concentration are identified using the regression analysis. Multiple regression analysis can be used to study the effect of two or more independent factors on the dependent particulate concentration level.

To do the regression analysis, one has to initially identify which independent variables need to be considered in the regression model. The best subset regression in Minitab helps in prioritizing the variables that must be considered in developing multiple regression models.

To work on best subset regression in Minitab, one needs to first open a worksheet in Minitab consisting of the pollutant data and variables affecting particulate concentration. In the toolbar menu, Stat-Regression-Best subsets option is selected. In the Minitab window that comes up, select the response (particulate concentration) and the free predictors (independent variables) from the menu on the left side. Minitab then comes out with statistic results with $R^2$, adjusted $R^2$, $Cp$ (measure of the error in the best subset model, relative to the error incorporating all variables) and standard deviation for each set of variables considered. The $R^2$ represents the percentage of variation in particulate concentration accounted for by the independent variable and; adjusted $R^2$ indicates the difference in the number of independent variables thus helping in the selection of optimal model. Standard deviation indicates the range of values in a data set.
and Cp statistic is used to identify an adequate model by choosing a model that has the lowest Cp value (approximately equal to number of independent variables + 1).

Minitab provides the best two models for each set of different number of predictors used. The statistical results are analyzed to determine the important variables affecting the particulate concentrations. The higher the adjusted $R^2$ value after considering the standard deviation and Cp value, the more important the variable is. If there is little difference in adjusted $R^2$ value when the number of variables is decreased, it is better to select a variable set having lesser number of predictors. Once the important variables affecting particulate concentration are determined, a regression model is developed using the Stat-Regression-Regression option.

### 3.10 Modeling

The indoor PM 2.5 can be estimated using several approaches. Few of them are listed below:

1. Air pollution exposure model for individuals (EMI model), is developed for estimation of PM concentrations within the homes. This model predicts indoor PM$_{2.5}$ mass concentrations based on outdoor concentrations. (Breen et al., 2009).

2. The deterministic models based on a pollutant mass balance around a particular indoor volume (Wadden et al., 1983).

3. Stochastic Human Exposure and Dose Simulation (SHEDS-PM) model from the US EPA, which helps in predicting indoor PM concentrations using ambient concentrations. (Deshpande et al., 2009).

4. Artificial Intelligence methods (Kadiyala et al. 2010b, 2010c).
5. Several Numerical models are available for predicting indoor concentrations.

Each of these models has several limitations for predicting indoor concentrations. Of the entire available models, mass balance model is the most simple and general model, while remaining models were developed for certain site-specific environmental conditions. Numerical models were able to deal with numerous situations and are complex in nature. Artificial Intelligence models were able to model more accurately because of its capability to understand complex patterns for a given situation.

A mass balance equation developed by (Thatcher et al., 2003) for predicting indoor PM$_{2.5}$ concentrations in residential buildings was modified to predict in-vehicle PM$_{2.5}$ concentrations in TARTA buses using estimated ambient PM$_{2.5}$ concentrations. Two conditions considered in this model are infiltration of outdoor concentrations and, deposition rate of indoor PM concentrations. The simple mass balance equation used is:

\[
\frac{\partial C_I}{\partial t} = C_o P \lambda_v - C_I (\lambda_v + K) \]

(1)

Where: $C_I$ = indoor particulate concentrations at time $t$ ($\mu$g/m$^3$),

$t = \text{time (h}^{-1})$,

$C_o = \text{outdoor particulate concentrations at time } t$ ($\mu$g/m$^3$),

$P = \text{penetration factor}$,

$\lambda_v = \text{air exchange rate (h}^{-1})$, and
$K =$ deposition rate (h$^{-1}$).

The solution of the above equation for change in $C_i$ with $t$ holding all factor constants with boundary conditions $C_i = C_g$ (garage concentration at 6AM) at $t = 0$ is given below.

$$C_i = \frac{P \lambda \nu C_g}{(\lambda + K)} \left[ 1 - e^{-(\lambda + K)t} \right] + C_g e^{-(\lambda + K)t}$$

……………………………………………… (2)

The above screening equation is used to predict in-vehicle PM$_{2.5}$ concentrations for over a period of 1 year from summer 2008 to spring 2009. The following assumptions are made.

- It is assumed that when bus starts its run at 6AM, the indoor particulate concentration is equal to the PM$_{2.5}$ concentration in the garage.
- $C_g$ is replaced with previous hour predicted $C_i$ after bus leaves the garage.
- The ambient concentrations used are 1.2 times indoor concentrations at any given time after the bus leaves garage. The indoor versus outdoor PM$_{2.5}$ concentrations ratio was observed from the work done by Abhilash (2007). Hourly average PM$_{2.5}$ concentrations were unavailable from US EPA.

The penetration factor for PM$_{2.5}$ diesel vehicles is assumed 1 based on the work by Esber et al., 2007.

### 3.10.1 Calculation of Air Exchange Rate

The air exchange rate depends on several factors such as ventilation system within the bus, opening and closing of doors, wind speed and direction, and type of windows
in the bus. Generally, air exchange rate is measured by using a tracer gas (SF\textsubscript{6} or CO). In this study we used monitored CO\textsubscript{2} concentrations for calculating air exchange rate for the bus. The air exchange rate \( \lambda \) is related to change in CO\textsubscript{2} concentrations with time shown in below equation.

\[
\lambda = \frac{\log C_{i(n+1)} - \log C_{i(n)}}{t}
\]

(3)

Where,

\( C_{i(n+1)} \) = CO\textsubscript{2} Concentration at \((n+1)\text{th}\) time

\( C_{i(n)} \) = CO\textsubscript{2} Concentration at \(n\text{th}\) time

3.10.2 Calculation of Deposition Rate

Recent studies have used a new approach to calculate particulate deposition rates as stated below (Abt et al. 2000; Vette et al 2001; He et al. 2005)

\[
\ln \left( \frac{C_t}{C_0} \right) = -(\lambda + K)t
\]

(4)

\( C_t \) and \( C_0 \) are particulate concentrations measured at times \( t \) and \( t_0 \)

3.10.3 Outdoor PM\textsubscript{2.5} Concentrations
The ambient concentrations used are 1.2 times indoor concentrations at any given time after the bus leaves garage.

3.10.4 Model Evaluation

To evaluate the quality of the data obtained and identify what model improvements are needed, model evaluation is done.

i. Fractional Bias

It is expressed mainly as percentage, normalized by the average of the gross observed and predicted values. It is a bound statistic varying between -200% and +200%. It is given by:

\[
\text{Fractional Bias (FB)} = 2 \left( \frac{X_o - X_p}{X_o + X_p} \right)
\]

ii. Normalized Mean Square Error

Normalized Mean Square Error (NMSE) is a dimensionless statistic. It gives us information regarding the scatter present in the data set. The equation for mean square error was modified by Hanna et al. (1985) to obtain Normalized Mean Square Error. It does not give biased results for models that over predict and under predict. Smaller values of NMSE indicate better performance. The equation for NMSE is given by:

\[
\text{NMSE} = \frac{(X_o - X_p)^2}{\overline{X_p} \times \overline{X_p}}
\]

iii. Coefficient of Correlation

The strength of the linear relationship between two quantitative variables is calculated with correlation coefficient (r). Perfect correlation would result in all the data
points falling on a line with a slope of ± 1, less perfect correlations will fall between these extreme values. Lack of any linear correlation would give r=0. The coefficient of correlation is given by:

\[
r = \frac{(\bar{X}_o - \bar{X}_o)(\bar{X}_p - \bar{X}_p)}{\sigma_{X_p} \times \sigma_{X_o}} \tag{7}
\]

iv. **Factor of Two**

Factor of two is defined as the percentage of prediction within a factor of two of the observed values. Factor of two (Fa2) is given by:

\[Fa2 = \text{Fraction of data which } 0.5 \leq X_p/X_o \leq 2\]
Chapter IV

Results and Discussion

The data collected during this study and previous two studies were used to draw conclusions on year-to-year variations along with diurnal, monthly, and seasonal trends. The discussion includes both the bio diesel and ultra low sulfur diesel buses. Regression analysis was done to identify important variables contributing to the indoor particulate concentrations.

4.1 Particulate Number Concentrations

4.1.1 Particulate Number Concentrations based on Size Distribution

Particulate number concentrations were collected from both the buses from July 2008 to June 2009 and tabulated as shown in Table 4.1. It was found that about 65 % of particles observed were of the size range from 0.3-0.4 μm. From this we can conclude that most of the particulates obtained from the diesel buses are fine particulates.
Table 4.1: Particulate Number Concentrations with respect to size

<table>
<thead>
<tr>
<th>Size (µm)</th>
<th>Particulate Number Concentration (Particles/l)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3-0.4</td>
<td>64043.05</td>
<td>67.89</td>
</tr>
<tr>
<td>0.4-0.5</td>
<td>18339.88</td>
<td>19.44</td>
</tr>
<tr>
<td>0.5-0.65</td>
<td>6841.59</td>
<td>7.25</td>
</tr>
<tr>
<td>0.65-0.80</td>
<td>2766.97</td>
<td>2.93</td>
</tr>
<tr>
<td>0.80-1.0</td>
<td>1304.36</td>
<td>1.38</td>
</tr>
<tr>
<td>1.0-1.6</td>
<td>511.19</td>
<td>0.54</td>
</tr>
<tr>
<td>1.6-2.0</td>
<td>237.51</td>
<td>0.25</td>
</tr>
<tr>
<td>2.0-3.0</td>
<td>154.72</td>
<td>0.16</td>
</tr>
<tr>
<td>3.0-4.0</td>
<td>69.20</td>
<td>0.07</td>
</tr>
<tr>
<td>4.0-5.0</td>
<td>34.78</td>
<td>0.03</td>
</tr>
<tr>
<td>5.0-7.5</td>
<td>18.55</td>
<td>0.01</td>
</tr>
<tr>
<td>7.5-10.0</td>
<td>4.81</td>
<td>0.005</td>
</tr>
<tr>
<td>10.0-15.0</td>
<td>1.84</td>
<td>0.001</td>
</tr>
<tr>
<td>15.0-20.0</td>
<td>0.26</td>
<td>0.0002</td>
</tr>
<tr>
<td>&gt;20.0</td>
<td>0.09</td>
<td>0.000099</td>
</tr>
<tr>
<td>Total</td>
<td>94328.87</td>
<td>100.00</td>
</tr>
</tbody>
</table>

The in-vehicle particulate number concentrations for both B20 and ULSD buses were collected for one year from July 2008 to June 2009. Figures 4-1 and 4-2 show the average hourly variations of particulate number concentrations in both the buses. The maximum concentrations in both the buses were mainly observed during the morning.
times in between 5:00 am to 9:00 am, and follow a consistently decreasing trend till around 5:00 pm. And again from 6:00 pm the particulate number concentrations increased slightly. These variations can be explained by the combined effects of ambient particulate concentrations, passenger activity on the route which peaks during morning and late evening hours, traffic volumes which are high during morning and evening commute. These observations agree well with the findings of similar studies performed by Kadiyala et al., (2008) and, Vijayan et al., (2007). Particulate number concentrations not only depend on passenger’s activity and traffic surrounding the bus but also on the positioning of doors and windows of the bus. The in-vehicle ventilation system also plays an important factor in determining particulate concentration inside the vehicles. Previous studies have shown that air conditioning inside the vehicle resulted in the improvement of in-vehicle air quality (Chan et al., 2002 and, Riediker et al., 2003). When the bus is in running condition, particulate numbers were found to be on lower side, as the infiltration of outside air is minimal due to closing of windows and doors for most of the time. A few peaks were observed when the doors of the bus were opened to permit the passengers into the bus at bus stops, and also in cases when the bus stopped at signals. These observations are in agreement with the results presented by Hammond et al., (2007) who suggested that vehicle idling and window/door position would impact in-vehicle PM concentrations. Particulate concentrations generally tend to increase if the doors and windows are closed and the bus is running on air conditioning system. This tendency can be explained by the concept of self pollution, which is the amount bus’s own exhaust found inside its cabin. This result is similar to Alto et al., (2005) study, who observed that
particulate number concentrations were high during the start of the day and decreases as the day goes on.

In this study, buses in-vehicle particulate number concentrations range from 30,000 to 120,000 particles per liter. In this particular study, it was found that particulate number concentrations from Bio diesel bus are slightly higher compared to the ULSD bus.

![Average Hourly Particulate Number Concentrations of size >0.30 µm](image)

**Figure 4-1**: Hourly particulate number concentration trends inside B20 buses
Figure 4-2: Hourly particulate number concentration trends inside ULSD buses

Figures 4-3 and 4-4 represent the monthly variation of particulate number concentrations from July 2008 to June 2009. For both Bio diesel and ULSD bus maximum and minimum concentrations were observed during the months of January and July respectively. This result was similar to Alto et al., (2005) study, who observed that particulate number concentrations were highest in the month of January and least in the months of July and August. This observed monthly variations trend may be because of the variations in number of passengers travelling in the bus, vehicles travelling beside the bus, ventilation system and meteorological conditions. And it was also observed that for most of the month’s particulate number concentrations in biodiesel bus were slightly higher compared to ultra low sulfur diesel bus.
Figure 4-3: Monthly Particle Number Concentration Trends inside B20 buses

Figure 4-4: Monthly Particle Number Concentration Trends inside ULSD buses
Figures 4-5 and 4-6 represent the seasonal variation of particulate number concentrations for both the buses. For both biodiesel and ultra low sulfur diesel buses particulate concentrations tends to be higher during the winter season compared to other seasons. Similar observations were found in studies by Kadiyala et al., (2008) and, Alto et al., (2005). This increase in particulate number concentrations was due to the reason that Toledo area receives a fair amount of snowfall in winter and the buses run with all their windows closed and air conditioning on. Therefore, the infiltration of ambient air into the bus decreases, which leads to build up of more particulates in the bus. But during summer and fall seasons the bus runs with windows open that results in greater air exchange rate in the bus, which results in decrease of in-vehicle concentrations. Studies conducted by Behrentz et al., (2005) stated that buses running with windows closed tend to be more self polluted compared to buses running with windows open.

![Time Series Plot of >0.30 μm](image)

*Figure 4-5: Seasonal Particle Number Concentration Trends inside B20 buses*
Figure 4-6: Seasonal Particle Number Concentration Trends inside ULSD buses

Figure 4-7 shows particulate number concentration trend in diesel buses during weekdays and weekends. Particulate concentrations were higher during the weekdays compared to weekends. Particulate concentrations were higher during morning times from 6:00 am to 9:00 am and gradually tend to decrease as the day goes on. Similar pattern was observed during the weekends but particulate number concentrations observed on weekends were much lower compared to weekdays. This decrease in concentrations may be due to low vehicular traffic and decrease in passenger activity.
**4.2 Particulate Matter Mass Concentrations**

In this section, we compare the average hourly PM mass concentrations collected from January 2007 to July 2009. We also look at how PM trends to vary inside the transit buses yearly and seasonally. Figure 4-8 to Figure 4-13 shows the hourly comparisons of PM$_{1.0}$, PM$_{2.5}$, and PM$_{10.0}$ mass concentrations averaged over a period of 3 years for both biodiesel and ultra low sulfur diesel buses. The overall trend shows that PM$_{1.0}$ and PM$_{2.5}$ concentrations follow a similar “μ-shaped” trend throughout the day. The PM concentrations were high during morning times between 6:00 am to 9:00 am. This peak is observed mainly due to heavy traffic on roads during morning times, and passenger activity in the bus. Ambient particulate concentrations also effect in vehicle PM
concentrations. These observations are in agreement with results presented by Abhilash et al., (2007). However, PM$_{10}$ concentration trends followed a slight different pattern; concentrations were found to be higher even during the afternoon times.

The particulate matter levels in biodiesel bus were slightly higher compared to the ultra low sulfur diesel bus. This variation in the particulate concentrations is mainly due to the vehicular traffic surrounding the bus. The particulate matter levels were observed to be higher during the year 2009 as compared to the year 2008 for both the buses. Highest PM levels were found in year 2007 compared to these three years. The observed trend may be due to the reason that older engines in the bus released more number of particulates. The number of passengers travelling in the bus would also effect the in-vehicle PM levels. From the video analysis, it was observed that during the year 2009 the passenger ridership is reduced compared to other years.
Figure 4-8: Yearly Variation of PM$_{1.0}$ in ULSD buses

Figure 4-9: Yearly Variation of PM$_{2.5}$ in ULSD buses
Figure 4.10: Yearly Variation of PM$_{10}$ in ULSD buses

Figure 4.11: Yearly Variation of PM$_{10}$ in BD buses
Figure 4.12: Yearly Variation of PM$_{2.5}$ in BD buses

Figure 4.13: Yearly Variation of PM$_{1.0}$ in BD buses
Figure 4-14 through Figure 4-19 represents seasonal particulate matter trends for both bio diesel and ultra low sulfur diesel buses for three different years. For all the years PM levels are higher during the winter season. Winter and spring seasons were the seasons when high particulate concentrations were observed for both bio diesel and ultra low sulfur diesel buses. Similar to studies conducted by Kadiyala et al., (2008). These higher concentrations were observed due to improper ventilation within the bus. While during fall and summer seasons the particulate matter levels tends to be low.

Figure 4-14: Seasonal PM$_{1.0}$ Concentration Trend inside B20 fueled buses
Figure 4-15: Seasonal PM$_{2.5}$ Concentration Trend inside B20 fueled buses

Figure 4-16: Seasonal PM$_{10}$ Concentration Trend inside BD fueled buses
Figure 4-17: Seasonal PM$_{1.0}$ Concentration Trend inside ULSD fueled bus

Figure 4-18: Seasonal PM$_{2.5}$ Concentration Trend inside ULSD fueled bus
4.3 Identification of Influential Factors Using Regression Analysis

Regression analysis was performed using MINITAB 15 to identify various factors affecting vehicular particle numbers across different size ranges. Different trends were observed for varying particle size ranges and the factors influencing different size ranges also varied. Various factors considered in the analysis are ambient temperature, ambient relative humidity, wind speed, wind direction, precipitation, indoor temperature, indoor relative humidity, passenger count, bus status (bus position/door position - idle/open, idle/close, run/close), number of cars and buses/trucks ahead, and visibility. The “Best Subset” regression method, adopted by Kadiyala et al., (2007) was used and the results are provided in Tables 4.2 to Table 4.5. Tables 4.2 and 4.3 summarize the influential
factors on a monthly basis while Tables 4.4 and 4.5 summarize the influential factors on a seasonal basis for B20 and ULSD buses respectively.

The regression analysis helped us to study various factors that are effecting the particulate number concentrations for different months and seasons. These findings were different from the previous studies as most of them grouped the data to identify the important factors or did not have a good representative sample for each month or season to get a comprehensive outlook of important variables that could effect.
Table 4.2: Important Factors Affecting Particulate Number Concentrations in a B20 Bus from Monthly MINITAB Results

<table>
<thead>
<tr>
<th>Month and Year</th>
<th>0.3-0.4 µm</th>
<th>1.0-1.6 µm</th>
<th>2.0-3.0 µm</th>
<th>7.5-10.0 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jul'08</td>
<td>Cars, Wind Direction, Idle/Open</td>
<td>Indoor Temp., Ambient RH, Wind Direction</td>
<td>Indoor Temp., Indoor RH, Cars, Trucks</td>
<td>Passengers, Cars, Idle/Open, Wind Direction</td>
</tr>
<tr>
<td>Aug'08</td>
<td>Passengers, Indoor RH, Wind Speed, Indoor Temp., Cars</td>
<td>Visibility, Wind Direction, Run/Close</td>
<td>Wind Speed, Wind Direction, Cars</td>
<td>Cars, Trucks, Idle/Open, Wind Speed</td>
</tr>
<tr>
<td>Sep'08</td>
<td>Ambient RH, Wind Speed, Wind Direction</td>
<td>Ambient RH, Indoor Temp.</td>
<td>Indoor Temp., Indoor RH, Ambient RH</td>
<td>Wind Speed, Wind Direction, Passengers</td>
</tr>
<tr>
<td>Oct'08</td>
<td>Passengers, Indoor RH, Cars</td>
<td>Passengers, Visibility, Indoor RH</td>
<td>Visibility, Passengers, Cars, Idle/Open</td>
<td>Passengers, Wind Speed</td>
</tr>
<tr>
<td>Nov'08</td>
<td>Indoor Temp., Ambient RH, Wind Direction</td>
<td>Visibility, Wind Direction, Indoor Temp.</td>
<td>Ambient RH, Ambient Temp., Visibility</td>
<td>Ambient Temp., Cars, Trucks</td>
</tr>
<tr>
<td>Dec'08</td>
<td>Visibility, Ambient Temp., Idle/Open, Cars, Wind Speed</td>
<td>Ambient Temp., Idle/Open, Trucks</td>
<td>Visibility, Ambient Temp., Cars, Trucks</td>
<td>Passengers, Visibility, Wind Direction</td>
</tr>
<tr>
<td>Jan'09</td>
<td>Indoor Temp., Ambient RH, Wind Speed, Passengers, Trucks</td>
<td>Ambient RH, Passengers, Indoor Temp., Cars</td>
<td>Ambient, Temp., Indoor RH, Wind Direction, Cars</td>
<td>Ambient Temp., Passengers, Wind Speed</td>
</tr>
<tr>
<td>Feb'09</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Apr'09</td>
<td>Indoor RH, Wind Speed, Passengers, Idle/Open</td>
<td>Passengers, Cars, Ambient RH</td>
<td>Wind Speed, Cars, Trucks</td>
<td>Cars, Trucks</td>
</tr>
<tr>
<td>May'09</td>
<td>Ambient Temp., Indoor RH, Cars, Trucks</td>
<td>Ambient Temp., Cars, Trucks, Visibility</td>
<td>Indoor RH, Ambient Temp., Cars, Idle/Open</td>
<td>Passengers, Cars, Trucks</td>
</tr>
<tr>
<td>Jun'09</td>
<td>Ambient Temp., Passengers, Idle/Open, Cars, Wind Speed</td>
<td>Passengers, Idle/Open, Cars</td>
<td>Ambient Temp., Passengers, Cars</td>
<td>Wind Speed, Wind Direction, Idle/Open</td>
</tr>
</tbody>
</table>
Table 4.3: Important Factors Affecting Particulate Number Concentrations in a ULSD Bus from Monthly MINITAB Results

<table>
<thead>
<tr>
<th>Month and Year</th>
<th>Particle Size Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.3-0.4 µm</td>
</tr>
<tr>
<td><strong>Jul'08</strong></td>
<td>Indoor Temp., Wind Direction, Indoor, RH</td>
</tr>
<tr>
<td><strong>Aug'08</strong></td>
<td>Indoor RH, Wind Speed, Indoor Temp., Cars</td>
</tr>
<tr>
<td><strong>Sep'08</strong></td>
<td>Ambient RH, Wind Speed, Ambient Temp., Cars, Trucks</td>
</tr>
<tr>
<td><strong>Oct'08</strong></td>
<td>Indoor Temp., Indoor RH, Cars, Passengers</td>
</tr>
<tr>
<td><strong>Nov'08</strong></td>
<td>Ambient Temp., Ambient RH, Wind Speed, Wind Direction</td>
</tr>
<tr>
<td><strong>Dec'08</strong></td>
<td>Ambient Temp., Visibility, Indoor RH, Cars</td>
</tr>
<tr>
<td><strong>Jan'09</strong></td>
<td>Indoor Temp., Ambient Temp., Wind Speed, Trucks</td>
</tr>
<tr>
<td><strong>Feb'09</strong></td>
<td>Ambient Temp., Passengers, Cars, Wind Direction</td>
</tr>
<tr>
<td><strong>Apr'09</strong></td>
<td>Indoor RH, Wind Speed, Passengers, Idle/Open</td>
</tr>
<tr>
<td><strong>May'09</strong></td>
<td>Indoor Temp., Indoor RH, Passengers</td>
</tr>
<tr>
<td><strong>Jun'09</strong></td>
<td>Ambient Temp., Passengers, Idle/Open, Cars, Wind Speed</td>
</tr>
</tbody>
</table>
### Table 4.4: Important Factors Affecting Particulate Number Concentrations in a B20 Bus from Seasonal MINITAB Results

<table>
<thead>
<tr>
<th>Month and Year</th>
<th>Particle Size Ranges</th>
<th>0.3-0.4 µm</th>
<th>1.0-1.6 µm</th>
<th>2.0-3.0 µm</th>
<th>7.5-10.0 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall'08</td>
<td>Visibility, Indoor RH, Wind Speed, Indoor Temp., Cars</td>
<td>Visibility, Wind Speed, Cars, Idle/Open</td>
<td>Indoor RH, Indoor Temp., Wind Direction, Cars</td>
<td>Visibility, Cars, Trucks, Idle/Open, Wind Speed</td>
<td></td>
</tr>
<tr>
<td>Winter'09</td>
<td>Indoor Temp., Ambient Temp., Ambient RH, Wind Speed, Wind Direction</td>
<td>Indoor RH, Indoor Temp., Wind Speed, Passengers</td>
<td>Indoor Temp., Ambient Temp., Visibility, Ambient RH</td>
<td>Ambient Temp., Wind Direction, Passengers</td>
<td></td>
</tr>
<tr>
<td>Spring'09</td>
<td>Ambient Temp., Passengers, Indoor RH, Cars, Idle/Open</td>
<td>Ambient RH, Ambient Temp., Cars, Trucks</td>
<td>Visibility, Passengers, Cars, Idle/Open</td>
<td>Indoor Temp., Wind Speed, Passengers</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4.5: Important Factors Affecting Particulate Number Concentrations in a ULSD Bus from Seasonal MINITAB Results

<table>
<thead>
<tr>
<th>Month and Year</th>
<th>Particle Size Ranges</th>
<th>0.3-0.4 µm</th>
<th>1.0-1.6 µm</th>
<th>2.0-3.0 µm</th>
<th>7.5-10.0 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer'08</td>
<td>Indoor Temp., Cars, Ambient Temp., Passengers</td>
<td>Indoor RH, Indoor Temp., Cars, Trucks</td>
<td>Passengers, Indoor Temp., Indoor RH, Cars, Trucks</td>
<td>Indoor Temp., Passengers, Cars, Idle/Open, Wind Direction</td>
<td></td>
</tr>
<tr>
<td>Fall'08</td>
<td>Visibility, Indoor RH, Wind Speed, Indoor Temp., Cars</td>
<td>Ambient Temp., Visibility, Indoor RH, Wind Speed,</td>
<td>Passengers, Indoor Temp., Indoor RH, Wind Direction, Cars</td>
<td>Ambient temperature, Passengers, Cars, Trucks, Idle/Open, Wind Speed</td>
<td></td>
</tr>
</tbody>
</table>
Some of the general observations that are effecting particulate concentrations during the study of regression analysis are discussed below.

### 4.3.1 Effect of Passengers

This parameter does not have much influence on the particulate number but a large increase in the number of passengers inside the bus does have an influence on the particulate number, this can be linked to the increased cabin surface area which leads to increased deposition rates. Smoking inside buses also resulted in higher levels of particulates.

### 4.3.2 Effect of Cars and Trucks/Buses

The particulate concentration inside the bus is influenced by the vehicular traffic near the bus. This positive correlation can be explained by the fact that increased vehicular traffic results in increased particulate concentration surrounding the bus.

### 4.3.3 Effect of Ventilation Settings

The effect of ventilation system has greater impact on particulate number concentrations in the cabin. It depends on several factors like cabin air exchange rate, filter efficiency of the ventilation system. Particulate concentrations are tending to be higher in an idling bus with door opened or closed as compared to a running bus with doors closed.
4.3.4 Effect of Wind speed

During higher wind speeds the concentrations within the bus tend to be low. Wind speed affects dispersion and dilution and thus atmospheric mixing and resuspension of particles. Another trend was also observed by Hussein et al. (2005) who showed that particulate number concentrations decrease linearly with wind speed.

4.3.5 Effect of Ambient Temperature and Ambient Relative Humidity

Particulate number concentrations are observed to decrease as the ambient temperature increases. Particulate concentrations are found to be higher during morning times and decreases gradually during the afternoon periods. Particulate number concentrations also showed seasonal variations with winter season having higher particulate concentration compared to other seasons.

4.3.6 Effect of Indoor Temperature and Indoor Relative Humidity

With increase in indoor temperature and indoor RH the particulate number concentrations tend to decrease.

4.3.7 Effect of Wind direction

The wind direction is found to be categorical variable for the regression tree analysis i.e. the best split condition is in the form of wind direction coming at certain angles grouped as one set rather than having wind directions less than a certain value as a single set. Relative higher pollutant concentrations are observed when the wind is blowing from the north due to the geographical position of Detroit, an industrial city to the north of Toledo as compared to the surrounding areas. Since the bus position was not
considered with respect to wind direction no additional facts on pollutant concentration build up could be determined.

4.4 Model Evaluation

The ideal model will have NMSE = 0, FB = 0, r =1, Fa2 = 1.0. The reliability of the model is determined by the criteria set in a study by Kumar et al., (1993). The model is acceptable if:
NMSE ≤ 0.5
-0.5 ≤ FB ≤ +0.5
Fa2 ≥ 0.8

4.4.1 PM$_{2.5}$ concentration for Summer 2008

- The NMSE value is a measure of precision, the lower the NMSE value the lesser is the variance. For all the time intervals, NMSE is close to zero, which indicates that the values predicted by the model are a good indicator of the monitored values.
- The fractional bias is in the range of +0.5 to -0.5 which indicates that the predicted results are in close approximation of the observed data.
- The Factor of 2 is also greater than 0.8 for all the three time intervals thus indicating that the model is providing a good estimate of the monitored data.
- The coefficient of correlation is approximately 0.9 for all the cases which implies that there exists a linear dependence between the model and the observed values.
### Table 4.6: Performance Measures for Straight X<sub>0</sub> and X<sub>p</sub> for PM<sub>2.5</sub> for summer 2008

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>6:00 AM-6:00 PM</th>
<th>6:00 AM-1:00 PM</th>
<th>2:00 PM-6:00 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of correlation</td>
<td>0.94</td>
<td>0.89</td>
<td>0.88</td>
</tr>
<tr>
<td>Normalized Mean Square Error</td>
<td>0.03</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>Fractional Bias</td>
<td>0.09</td>
<td>-0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>Factor of 2</td>
<td>1.00</td>
<td>0.97</td>
<td>0.94</td>
</tr>
<tr>
<td>Mean X&lt;sub&gt;0&lt;/sub&gt;</td>
<td>16.21</td>
<td>17.14</td>
<td>14.68</td>
</tr>
<tr>
<td>Mean X&lt;sub&gt;p&lt;/sub&gt;</td>
<td>17.66</td>
<td>16.42</td>
<td>15.05</td>
</tr>
</tbody>
</table>
Figure 4-20: Observed Vs Predicted PM$_{2.5}$ during summer 08 from 6 AM to 6 PM

Figure 4-21: Observed Vs Predicted PM$_{2.5}$ during summer 08 from 6 AM to 1 PM

Figure 4-22: Observed Vs Predicted PM$_{2.5}$ during summer 08 from 2 PM to 6 PM
4.4.2 PM$_{2.5}$ concentration for Fall 2008

- The NMSE value is closer to zero for the first two time intervals when compared to the afternoon time. This indicates that the values predicted by the model is a good indicator of the values actually observed for the first two cases.

- The fractional bias is in the range of $+0.5$ to $-0.5$ which indicates that the predicted results are in close approximation of the observed data.

- The Factor of 2 is also greater than 0.8 for all the three time intervals thus indicating that the model is a good estimate of the monitored data.

- The coefficient of correlation is greater than 0.8 for the first two time intervals, which implies that there exists a linear dependence between the model and the observed values. But during the afternoon time interval, the coefficient of correlation is low. This can be explained by the fact that during the afternoon interval, there was a lot of variation in the observed and predicted concentration. Thus for the afternoon interval, the model does not give a linear correspondence to the observed data. Therefore, more changes are needed for the afternoon hours.

Table 4.7: Performance Measures for Straight X$_0$ and X$_p$ for PM$_{2.5}$ for fall 2008

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>6:00 AM-6:00 PM</th>
<th>6:00 AM-1:00 PM</th>
<th>2:00 PM-6:00 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of correlation</td>
<td>0.95</td>
<td>0.90</td>
<td>0.69</td>
</tr>
<tr>
<td>Normalized Mean Square Error</td>
<td>0.00</td>
<td>0.20</td>
<td>0.15</td>
</tr>
<tr>
<td>Fractional Bias</td>
<td>0.05</td>
<td>-0.14</td>
<td>-0.05</td>
</tr>
<tr>
<td>Factor of 2</td>
<td>0.98</td>
<td>0.94</td>
<td>0.91</td>
</tr>
<tr>
<td>Mean X$_o$</td>
<td>8.55</td>
<td>9.20</td>
<td>8.15</td>
</tr>
<tr>
<td>Mean X$_p$</td>
<td>8.59</td>
<td>8.02</td>
<td>7.78</td>
</tr>
</tbody>
</table>
Figure 4.23: Observed Vs Predicted PM$_{2.5}$ during fall 08 from 6 AM to 6 PM

Figure 4-24: Observed Vs Predicted PM$_{2.5}$ during fall 08 from 6 AM to 1 PM

Figure 4-25: Observed Vs Predicted PM$_{2.5}$ during fall 08 from 2 PM to 6 PM
4.4.3 PM$_{2.5}$ concentration for Winter 2009

- The NMSE value is closer to zero for the first two time intervals when compared to the afternoon time. This indicates that the values predicted by the model is a good indicator of the values actually observed for the first two cases.
- The fractional bias is in the range of +0.5 to -0.5 which indicates that the predicted results are in close approximation of the observed data.
- The Factor of 2 is also greater than 0.8 for all the three time intervals thus indicating that the model is a good estimate of the monitored data.
- The coefficient of correlation is greater than 0.8 for the first two time intervals, which implies that there exists a linear dependence between the model and the observed values. But during the afternoon time interval, the coefficient of correlation is low. This can be explained by the fact that during the afternoon interval, there was a lot of variation in the observed and predicted concentration. Thus for the afternoon interval, the model does not give a linear correspondence to the observed data.

Table 4.8: Performance Measures for Straight X0 and Xp for PM$_{2.5}$ for winter 2009

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>6:00 AM-6:00 PM</th>
<th>6:00 AM-1:00 PM</th>
<th>2:00 PM-6:00 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of correlation</td>
<td>0.91</td>
<td>0.90</td>
<td>0.59</td>
</tr>
<tr>
<td>Normalized Mean Square Error</td>
<td>0.08</td>
<td>0.10</td>
<td>0.27</td>
</tr>
<tr>
<td>Fractional Bias</td>
<td>0.05</td>
<td>-0.02</td>
<td>-0.05</td>
</tr>
<tr>
<td>Factor of 2</td>
<td>0.96</td>
<td>0.91</td>
<td>0.84</td>
</tr>
<tr>
<td>Mean X$_o$</td>
<td>12.72</td>
<td>12.81</td>
<td>12.58</td>
</tr>
<tr>
<td>Mean X$_p$</td>
<td>13.43</td>
<td>12.49</td>
<td>11.99</td>
</tr>
</tbody>
</table>
Figure 4-26: Observed Vs Predicted PM$_{2.5}$ during winter 09 from 6 AM to 6PM

Figure 4-27: Observed Vs Predicted PM$_{2.5}$ during winter 09 from 6 AM to 1 PM

Figure 4-28: Observed Vs Predicted PM$_{2.5}$ during winter 09 from 2 PM to 6 PM
4.4.4 PM$_{2.5}$ concentration for Spring 2009

- The NMSE value is closer to zero for the first two time intervals when compared to the afternoon time. This indicates that the values predicted by the model is a good indicator of the values actually observed for the first two cases.
- The fractional bias is in the range of $+0.5$ to $-0.5$ which indicates that the predicted results are in close approximation of the observed data.
- The Factor of 2 is also greater than 0.8 for all the three time intervals thus indicating that the model is a good estimate of the monitored data.
- The coefficient of correlation is greater than 0.8 for the first two time intervals, which implies that there exists a linear dependence between the model and the observed values. But during the afternoon time interval, the coefficient of correlation is low. This can be explained by the fact that during the afternoon interval, there was a lot of variation in the observed and predicted concentration. Thus for the afternoon interval, the model does not give a linear correspondence to the observed data. There is a need to add more physics in the model for afternoon hours.

**Table 4.9: Performance Measures for Straight $X_0$ and $X_p$ for PM$_{2.5}$ for spring 2009**

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>6:00 AM-6:00 PM</th>
<th>6:00 AM-1:00 PM</th>
<th>2:00 PM-6:00 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of correlation</td>
<td>0.93</td>
<td>0.87</td>
<td>0.66</td>
</tr>
<tr>
<td>Normalized Mean Square Error</td>
<td>0.09</td>
<td>0.12</td>
<td>0.24</td>
</tr>
<tr>
<td>Fractional Bias</td>
<td>0.07</td>
<td>-0.1</td>
<td>-0.28</td>
</tr>
<tr>
<td>Factor of 2</td>
<td>0.94</td>
<td>0.89</td>
<td>0.86</td>
</tr>
<tr>
<td>Mean $X_0$</td>
<td>18.94</td>
<td>19.98</td>
<td>19.16</td>
</tr>
<tr>
<td>Mean $X_p$</td>
<td>19.47</td>
<td>19.1</td>
<td>18.68</td>
</tr>
</tbody>
</table>
Figure 4-29: Observed Vs Predicted PM$_{2.5}$ during spring 09 from 6 AM to 6 PM

Figure 4-30: Observed Vs Predicted PM$_{2.5}$ during spring 09 from 6 AM to 1 PM

Figure 4-31: Observed Vs Predicted PM$_{2.5}$ during spring 09 from 2 PM to 6 PM
Chapter V

Conclusion

In-vehicle particulate number concentrations within the diesel buses were collected successfully for one year. The in-vehicle particulate matter concentrations trends were studied over a period of three years by combining the data from two previous studies for Bio diesel and Ultra low sulfur diesel buses. Factors affecting these concentrations and the contributions of outdoor generated contaminants to these indoor concentrations are identified using regression analysis. A simple mass balance model was applied to predict PM$_{2.5}$ concentrations inside the bus.

The following conclusions can be drawn from the study of yearly, seasonal and diurnal trends:

- It was found that most of the in-vehicle particulates observed were in the size range 0.3µm-0.4µm.
- The particulate number concentrations trend with respect to time of a day is the same for both Bio diesel and Ultra low sulfur diesel buses.
In-vehicle particulate number concentrations were higher during morning hours, when the bus starts its run. This peak in concentrations is mainly due to high traffic on road and more passenger activity.

Indoor particulate concentrations were observed more during winter season compared to other seasons. This pattern is due to low air exchange rate in the bus during the winter season.

Concentrations tend to increase whenever bus stops at traffic signals, i.e. when bus is in idle position along with other vehicles.

Particulate number concentrations were higher during the weekdays when compared to the weekends.

From regression analysis, it was observed that wind speed, wind direction, temperature, relative humidity, cars, and trucks play a major role in effecting in-vehicle particulate number concentrations.

The PM mass concentrations were increased from 2008 to 2009 for both Bio diesel and Ultra low sulfur diesel buses. But 2007 concentrations were more compared to these two years.

For all the three years, the PM mass concentrations were observed higher during the winter season compared to other seasons for both B20 and ULSD buses.

A screening model given by equation 3.2 has been modified for estimating indoor concentrations. A new equation 3.3 is derived. The performance of the model is good from 6 AM to 1 PM for all the four seasons. It is proposed that ambient particulate concentrations should be predicted using a forecasting model similar to
the one appeared in the literature or using the USEPA AIRNOW forecasting system.

- During peak hours predicted in-vehicle PM$_{2.5}$ concentrations were lower when compared to observed PM$_{2.5}$ concentrations.

5.1 Recommendations for Future Research

The following recommendations are an outcome of the knowledge gained in the course of conducting this research. The identified objectives may improve and add further to the knowledge base and fill in the information gaps currently in the field of IAQ in buses.

- More detailed study on how much exhaust particulate concentrations are effecting the in vehicle concentrations.
- Ambient particulate number concentrations should be monitored directly.
- There should be detailed study regarding the ventilation system for determining the flow rate in the public transport buses.
- Hourly ambient PM$_{2.5}$ concentrations were unavailable, which is a major problem in modeling in-vehicle PM$_{2.5}$ concentrations. So predicted concentrations were on lower side when compared to observed concentrations during peak hours.
- Effect of passengers travelling inside the bus has a significant effect on in-vehicle particulate matter, which should be studied in detail in the future studies.
References


   “Ambient nano and ultrafine particles from motor vehicle emissions: Characteristics, ambient processing and implications on human exposure.”


34. National Climatic Data Center (NCDC NOAA), Available from http://cdo.ncdc.noaa.gov/ulcd/ULCD.


42. **Sioutas C.** “Operation of SMPS and Low Temperature TEOM in Locations of the USC Children’s Health Study (CHS) and the Los Angeles Supersite”. *Report submitted to South Coast AQMD*, 2004.


