2011

Characterization of the gaseous pollutant behavior over a period of three years inside a public transit bus

Srikar Velagapudi
The University of Toledo

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A Thesis

entitled

Characterization Of The Gaseous Pollutant Behavior Over A Period Of Three Years
Inside A Public Transit Bus

by

Srikar Velagapudi

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. Dong-Shik Kim, Committee Member

________________________________________
Dr. Patricia Komuniecki, Dean
College of Graduate Studies

The University of Toledo

May 2011
An Abstract of

Characterization Of The Gaseous Pollutant Behavior Over A Period Of Three Year Inside A Public Transit Bus

by

Srikar Velagapudi

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The University of Toledo
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This study presents a comprehensive three year trend analysis of the indoor gaseous pollutants in public transit buses running on bio-diesel (B20) and ultra low sulfur diesel (ULSD) in the city of Toledo. Additionally, mass balance modeling of carbon dioxide pollutant inside the public transport buses has been conducted. The pollutants monitored in this study are carbon dioxide (CO₂), carbon monoxide (CO), sulfur dioxide (SO₂), nitrogen oxide (NO), and nitrogen dioxide (NO₂). Two comfort level parameters of the passengers: temperature and relative humidity are also measured inside the buses.

Yearly variations of the five gaseous pollutants are studied and the accumulation of pollutant concentrations inside the bus was observed to be a result of variation in different parameters and not due to variation of a single parameter. The in-vehicle pollutant concentration trends are observed to be highly influenced by heavy traffic on the road. Over the three study period, relatively higher pollutant levels are observed for all the pollutants during winter season. Regression analysis has been used to identify the various factors that influence pollutant concentrations inside the bus. It was found that the pollutant levels are affected mainly by ventilation conditions of the bus, passenger
activity inside the bus, vehicular traffic around the bus, and ambient meteorological conditions. The study identifies the important variables that affect in-vehicle pollutants in each season across different years. For example, ambient temperature, wind speed, passengers, trucks, and run/close are identified as influential factors affecting the in-vehicle CO$_2$ concentrations in winter 2009.

A mass balance approach was used in modeling the levels of carbon dioxide (CO$_2$) inside buses running on B20 and ULSD fuels. The model was tested over different seasons for one year period. The mixing factors for the model were calculated for both B20 and ULSD buses using a reverse approach on a seasonal basis. The infiltration rate, outdoor concentrations, and source emission rate were estimated from the literature review when developing the mass balance model. The model evaluation showed that the proposed mass balance model is capable of predicting the CO$_2$ levels in both B20 and ULSD fueled buses in all the seasons with limited accuracy. The predictions of the proposed model heavily depend on the accurate knowledge of ambient CO$_2$ levels.
This thesis is dedicated to my parents Koteswara Rao Velagapudi, Uma Rani Velagapudi and brother Balaji Velagapudi
Acknowledgements

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.

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I would like to thank APRG and its members for their cooperation and support throughout Master’s period.

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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 sincere gratitude to the TARTA management and the employees for their continued interest and involvement in this work.
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Chapter One

Introduction

In our day-to-day life, different health risks are encountered when engaging in different activities like recreation, working at work place, spending time in home and during travel. Some of these risks encountered may be avoided by taking appropriate care and right decisions at the right time to avoid risks such as the health effects caused by indoor air pollution. The average commuting time a worker spends when commuting from home to work place is 25.5 minutes [Census (2000)].

It has been observed that there is an increase in commuters using public transit as a primary means of transportation to work. There is an increase in the number of regular commuters using public transit from 5.98 million in 2004 to 6.8 million in 2007, while the percentage of commuters using the transit as a means of transportation to work increased from 4.57% in 2004 to 4.88% in 2007 [APTA Fact Sheet, 2009]. It was observed from different surveys conducted on public transportation profiles that majority of the trips were for work during the morning and evening [Table 1.1]. The trip to school was next in order [APTA Report (2007)]. The increase in passenger activity emphasizes
the importance of indoor air quality in public transport system. Considering the amount of time people spend in travel, it is important to study the in-vehicle pollutant concentration levels and identify the risk associated with exposure to indoor air pollutants. Study of in-vehicle pollutant concentration variations is more complex as compared to the study in buildings due to the fact that the vehicle is always in a mobile condition.

Table 1.1: Summary of percentage trips for various purposes

<table>
<thead>
<tr>
<th>Purpose of trip</th>
<th>Percentage of all transit trips reported in on-board transportation</th>
</tr>
</thead>
<tbody>
<tr>
<td>For the work</td>
<td>59.2</td>
</tr>
<tr>
<td>For the school, including elementary, secondary, and college students</td>
<td>10.6</td>
</tr>
<tr>
<td>For shopping and dining</td>
<td>8.5</td>
</tr>
<tr>
<td>For personal business</td>
<td>6.3</td>
</tr>
<tr>
<td>For social purposes</td>
<td>6.8</td>
</tr>
<tr>
<td>For medical trips</td>
<td>3.0</td>
</tr>
<tr>
<td>For other trips</td>
<td>5.7</td>
</tr>
</tbody>
</table>

The present study is a part of the continuing research on the environmental impact assessment of alternative diesel fuels on TARTA buses funded by the United States (US) Department of Transportation. Since 1971, TARTA has been working with 40 routs as “Ride of Toledo” in and around Toledo. With the increasing travel time for people, it is required to monitor, study, and predict the concentrations of various pollutants inside TARTA buses. To study IAQ in buses, YES PLUS instrument was used to monitor the five gases namely carbon dioxide (CO₂), carbon monoxide (CO), sulfur dioxide (SO₂),
nitrogen dioxide (NO₂), and nitric oxide (NO). Two comfort parameters namely temperature and relative humidity were also monitored. The monitored data were used in obtaining the yearly trends and identifying the influential factors for the above mentioned gases for three years while modeling of CO₂ was done using data collected in 2008-2009.

The research objectives of this thesis are:

- To study the year-to-year trends of gaseous pollutant concentrations inside the bus.
- To identify the factors affecting the pollutant gases inside the bus based on seasons across different years.
- To model the in-vehicle CO₂ pollutant using mass balance approach and determine the limitations of the approach.
Chapter Two

Literature Review on Vehicular IAQ Studies

This chapter discusses the results from a comprehensive literature review on the reported studies and findings on indoor air quality inside vehicles. One of the major contributors for an increase in various pollutant levels in urban areas is vehicular exhaust. There are more than likely chances for penetration of pollutants from outside into vehicles. The need for vehicular indoor air quality research increased because people spend substantial quantity of time while travelling in vehicles and getting exposed to various pollutants which are at significant levels [Kaur et al. (2005)]. The exposure to various pollutants for a considerable period results in certain kinds of lung diseases and mortality [Dockery et al. (1994)].

The statistical significance of exposure of drivers and commuters along with variation of observed in vehicle pollutant concentrations in public transport buses running with B20 and ULSD fuels was studied by Kadiyala et al. [2010a]. The study also reported the mean 8-hour exposure of CO₂ and SO₂ to be higher inside a ULSD bus than in a B20 bus and it is the opposite for CO and NO. Kadiyala and Kumar (2010) studied the trend
analysis across different months and seasons and presented the statistical significance of
the monitored vehicular pollutants. Kadiyala and Kumar (2008, 2009) and Kadiyala
(2009) identified the factors affecting the in-vehicle pollutant concentrations using
MINITAB and CART. The study also reported that the regression tree analyses to be a
better way of identifying the factors affecting concentrations than the regression. Kumar
et al. (2009, 2011) studied the characterization of indoor air quality in public transport
buses operating on alternative fuels.

The studies conducted at Munich Transportation Systems, Germany, have shown
that the concentrations of pollutants inside the bus are dependent on ambient
concentrations and vehicular traffic [Praml et al. (2000)]. Chan (2003) observed that
concentration levels of CO₂ are changing not with the condition of the traffic but the
number of passengers inside the bus. The contribution of traffic related exposures inside
vehicles during various time periods of the day were observed. It is observed that in case
of cars air pumped in through the ventilation cannot be considered clean because of fan
facing the exhaust pipe [Chan et al. (2003)]. Fernandez et al. (1995), Ott et al. (1994),
Kadiyala (2008), Kadiyala and Kumar (2009, 2010) observed in-vehicle concentrations to
vary seasonally.

The indoor-outdoor air quality relationships were established for vehicles in
various ventilation modes, driving environments, fuel types, and for the variation in
climatic conditions [Chan (2003) and Kadiyala (2008)]. The infiltration of pollutant air
was observed to be increasing during heavy traffic congestions because of idling [Alm et
al. (1999) and Kadiyala (2008)]. The studies by Praml and Schierl (2000) and Alm et al.
revealed that the pollutant concentration inside the vehicles vary with ambient concentrations.

The development of various empirical models and exposure of CO in automobiles running on urban highways was studied by Ott et al. (1994). Rodes et al. (1998) studied exposure to PM10.0, PM2.5, metals, and thirteen organic compounds, carbon monoxide, fine particle counts and black carbon and also identified driving lane, roadway type, congestion level, time of day and exhaust from lead vehicles as significant factors affecting pollutant concentrations. Road type, following distance between the lead vehicle and follow vehicle, and exhaust location of the lead vehicle are identified as important factors by Fruin (2003). The pollutants studied in this study are black carbon, ultra fine particles, NOx, CO, CO2, PM2.5, PM size distribution and PM-bound PAH. Vijayan and Kumar (2008) have studied the IAQ relationships using regression analysis and identified meteorological variables, vehicle condition, passenger count and number of lead vehicles as the factors affecting the pollutants CO, CO2, SO2 and particulate matter.

The emissions of benzene, toluene, xylene and formaldehyde were monitored in parked vehicles at the underground parking which represents the exposure of materials in cabins to passengers and it was identified that emissions are high in relatively new vehicles compared to older vehicles by Zhang et al. (2008). According to Duffy and Nelson (1996), 1-3 butadiene and benzene were found to be 50% higher inside the bus as compared to new cars and 25% higher than old cars. Marion and Brent (2003) identified factors influencing the VOC levels in old and new vehicles as indoor temperature, vehicle make, age and type of deodorizer. Providing ventilation during driving helped reduce the
VOC levels significantly by 4-20 times as compared to the levels obtained under a stationary condition.

Jacobs et al. (2010) studied the influence of ventilation, age of vehicle, interior air temperature at level of driver’s breath position and also solar load intensity on VOC emissions in new vehicles using four different procedures. The exposure of VOC on six main roads was studied by Kuo et al (2000) and concluded that the traffic density was not showing any impact on VOC’s which was in negation to the observations of earlier studies. Diapouli et al. (2008) observed that the on road levels were highly influenced by rush hours while in-vehicle levels are influenced by stop and go traffic mainly at signals. The lane of travel, air conditioning system, internal sources, and ventilation settings were identified by Chan et al. (2002) as factors which affect the in-vehicle pollutant levels. It is observed by Chan and Liu (2001) that levels of pollutants increased in tunnels as compared to urban and sub-urban roads. The study also concluded that difference in levels of pollutants observed with air and non-air conditioned vehicles is not much. The influence of peak hours, road type, and ventilation settings are studied by Duffy and Nelson (1996) on in-vehicle concentrations of 1-3 butadiene and benzene.

Chan (2003) studied CO and CO₂ levels in different buses inside and outside using portable monitors and concluded that observed in-vehicle levels are 10 times higher as compared to outdoors and CO₂ levels mainly influenced by passengers and not driving environment. Alm et al. (1999) studied PM and CO concentrations along a route and identified higher in-vehicle levels caused as a result of higher traffic and exposure to pollutants influenced by time of day, average speed, wind speed and relative humidity. It is observed from the studies of Rodes et al. (1998), Solomon et al. (2001) and Wargo et
al. (2002) that the concentrations of in vehicle pollutants are higher than ambient concentrations.

Models are useful for determining work place pollutant exposures and predicting indoor concentrations. Various investigators have used the mass balance equation to predict pollutant concentrations from tobacco smoke sources in indoor locations for over four decades. Bin Xu and Yifang Zhu (2009) modified a mass-balance indoor particle dynamic model and investigated relationship between in cabin to on road ratio and airflow rate. Increasing efforts have been made to probe the link between outdoor and indoor PM10 and PM2.5 levels (Riley et al. 2002). The indoor-outdoor ratios were developed by Kadiyala (2008) for CO₂, CO, SO₂, NO, NO₂ and PM in bio-diesel and ultra low sulfur diesel buses. Advance artificial intelligent (AI) modeling has been done by Kadiyala et al. (2010b, 2010c)

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 concluded that for predicting 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.
The present review of literature found that none of the studies have identified factors affecting pollutants over three years inside public transport buses running on alternative fuels. Many studies [Vijayan and Kumar (2008), Vijayan and Kumar (2010), Adams et al. (2001), Gulliver and Briggs (2004), Gomez-Perales et al. (2004), and Chan et al. (1991)] have been reported in the literature to have focused on regression modeling of pollutants while limited studies [Kadiyala (2008)] have used regression tree analysis. The modeling of vehicular gaseous pollutants helps predict IAQ and its exposure levels.
Chapter Three

Methodology

It is necessary to have good planning for collecting data in order to study year-to-year variations among various indoor pollutant gases and developing a predictive model. Also, at the same time the data collected should be maintained properly so that there won’t be any errors. The following sections explain the detailed instrumentation involved while collecting data, data retrieval and collection, the method adapted for developing the database and the procedure and the software used in analyzing the data collected.

3.1 Experimental Design:

A detailed explanation about instrumentation inside the bus and the selection process involved in selecting the bus and the route to be assigned for keeping the instruments is given in this section.

There are more than 180 buses and 40 routes for TARTA in and around the city of Toledo. TARTA buses use following types of fuels.

1. B20 Fuel for the 506 bus during the entire period of study.
2. ULSD fuel for the 536 bus till the end of year 2007.
3. ULSD supreme for the 536 bus from 2008 till the end of the study.

The buses selected for the study are of 500 series which were Thomas built buses (acquired by Detroit Diesel) of the TARTA line up, with a Mercedes Benz MBE 900 engine. The route selected for the study was Route Number 20 which was shown in Figure 3-1. This runs between TARTA garage and Meijer on the Central Avenue strip. The buses were checked before selection to assume that the cameras were working which are used in video surveillance of the bus. Two buses for which everything was good are selected, one each for each type of fuel. Both these buses were operated on the same route with certain time lag between them. The bus and route selections were done so that the data collected should be consistent with the data retrieved from the Kadiyala (2008) and Vijayan (2007). The route used in the present study was represented in the map shown the Figure 3-1.

Figure 3-1: Map showing the rout (#20) used for the study
(Source: TARTA website, 2009)
A pair of Yes ‘Plus’ IAQ instruments were used for monitoring the concentrations of pollutant gases inside the bus. Each instrument was placed in each bus used for the run. The parameters monitored using Yes ‘Plus’ IAQ monitor are: CO₂, CO, NO, NO₂, SO₂, VOC and HCHO gases along with temperature and relative humidity using sensors.

For maintaining the instrument safety, the instruments were placed inside wired mesh cage, which acts as shield for the instruments and then the instruments were held to the base using Velcro attachments. As a whole this setup can be observed the Figure 3-2. This setup was placed at the height of the passenger seating level near the front end of the bus over the enclosure built for GPS systems inside the bus. This setup provides easy access to power supplied continuously from the AC adopters connected to an inverter inside the bus. At the same time the instrument safety is also maintained as it is in the view-point of driver.

Figure 3-2: Instrument Setup
3.2 Qualitative data collection and its maintenance

This section gives detailed explanation about the procedure adopted while collecting data, the maintenance of database and the way the quality of the data was maintained.

Table 3.1: Database showing details of data collected by the researchers.

<table>
<thead>
<tr>
<th>Bus #</th>
<th>Year</th>
<th>Months</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2007</td>
<td>January, April, May, June, July, August, September, October, November, December</td>
<td>Vijayan(2007) and Kadiyala(2008)</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>January, February, October, November, December</td>
<td>Kadiyala(2008) and Velagapudi (Present study)</td>
</tr>
<tr>
<td></td>
<td>2009</td>
<td>January, February, March, April, May, June, July, August, September</td>
<td>Velagapudi (Present study)</td>
</tr>
<tr>
<td>536</td>
<td>2006</td>
<td>December</td>
<td>Vijayan(2007)</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>January, February, October, November, December</td>
<td>Kadiyala(2008) and Velagapudi (Present study)</td>
</tr>
<tr>
<td></td>
<td>2009</td>
<td>January, February, March, April, May, June, July, August, September</td>
<td>Velagapudi (Present study)</td>
</tr>
</tbody>
</table>

The data collection was done by the researcher between the periods of October 2008 to August 2009. To plot the yearly variations among the various gaseous pollutants the data collected by the previous researchers Vijayan (2007) and Kadiyala (2008) was also used while analyzing the data. The Table 3.1 shows the data collected by the researchers. The data was monitored 24x7 on one second interval which provides an average at one minute interval. The data collected was stored in the built-in memory.
cards and the collected data was frequently downloaded to laptop to maintain quality of data.

The data collection has following steps:

1. Downloading data from instrument to the laptop.

2. Meteorological data were collected from the National Climatic Data Center website.

3. The real-time variables such as passenger, vehicle count, vehicle status and windows status were obtained from the hard drives using wave reader software in laboratory.

To study the effect of meteorology on indoor air quality, the unedited local climatological data which consists of unedited hourly details of temperature, relative humidity, wind speed, wind direction, total precipitation, and visibility are downloaded from the National Climatic Data Center website [NCDC, NOAA (2008)] and formatted to obtain the hourly details. The real-time variables such as passenger, vehicle count (small and heavy), vehicle status (Running-Closed, Idle-Closed, and Idle-Open), and windows open count. All the TARTA buses are installed with closed-circuit cameras which records the video footage onto a hard drive for up to 10 days. The equipment and the “Wave Reader” software were provided by the TARTA. The video footage recorded in the hard drive was analyzed to get the variable count which is a time-consuming task. So, depending on the availability of time, one minute or five-minute interval readings were collected while working with co-student in the air pollution research group.

The bus has five cameras installed in it: one facing the road through front windshield, two cameras facing the doors, one facing towards the back of the bus indoors
from front and the other facing to the front of the bus indoors from back. The Figures 3-3, 3-4 and 3-5 show the placement of cameras inside the bus.

![Figure 3-3: Cameras facing towards back and towards road placed front end of bus](image1)

(Images from left to right)

![Figure 3-4: Cameras one above the driver and another facing towards rear exit](image2)

(Images from left to right)

Yes ‘Plus’ monitors were calibrated at a regular interval of 7 days from the start of collection of data by the researcher. The calibration was done for the sensors of CO₂, CO, NO, NO₂ and SO₂ for both the Yes ‘Plus’ monitors using calibration gas cylinders supplied by CALGAZ. The equipment required for calibration consists of a 0.5 liter per minute (lpm) fixed flow regulator (since the instrument had a low draw rate) and a
factory supplied inlet fixture to flow gases. The Table 3.2 gives the details about the calibration of different sensors.

![Camera facing towards the front placed at back end of the bus](image)

**Table 3.2: Yes ‘Plus’ Calibration Details**

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Maximum Sensor Detection Limit, ppm</th>
<th>Span Calibration : Gas Concentration, ppm</th>
<th>Zero gas</th>
<th>Span Calibration Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>5000</td>
<td>2000</td>
<td>99.9% N₂</td>
<td>CO₂</td>
</tr>
<tr>
<td>CO</td>
<td>50</td>
<td>25</td>
<td>Zero air</td>
<td>CO</td>
</tr>
<tr>
<td>NO</td>
<td>100</td>
<td>50</td>
<td>99.9% N₂</td>
<td>NO</td>
</tr>
<tr>
<td>NO₂</td>
<td>20</td>
<td>5</td>
<td>Zero air</td>
<td>NO₂</td>
</tr>
<tr>
<td>SO₂</td>
<td>20</td>
<td>5</td>
<td>Zero air</td>
<td>SO₂</td>
</tr>
</tbody>
</table>

The sensor calibration procedure can be divided into two parts: zero calibration and span calibration. For zero calibration, the cylinder regulator is threaded onto the cylinder of zero gas and the valve opened to ensure that the pump in the instrument is not stalled. Flow of gas is checked by placing thumb near the outlet of the inlet fixture and the outlet is connected to the inlet port of the instrument. The gas to be zeroed in is then selected and the zero calibration is stopped once the “Zero Span Calibration Complete” is displayed on the LCD screen of the instrument. The cylinder regulator is then removed and thread onto the span calibration gas. The span calibration gas concentration is entered.
into the instrument and the outlet of the inlet fixture connected to the inlet port after making sure that the valve is opened and the span gas is flowing. The end of span calibration is indicated by a display of “Span Calibration Complete” on the LCD screen of the instrument. External filters were changed whenever a “Low Pump” error message was displayed.

3.3 Analysis Procedure using MINITAB 15

Different procedures were followed to process, understand, select and model the data collected. Minitab 15 was chosen for analyzing data and to develop database.

Minitab 15 (Minitab Inc., 2008) was used in performing the multiple regression analysis. This helps in identifying the independent variables which contribute to the variation of pollutant concentration levels. The independent variables which need to be included into or which needn’t be included into are identified using “Best Subset Regression”. The best subset regression which was conducted by using Minitab 15 helps in finding the important variables that are used in developing multiple regression models.

One needs to open the worksheet in Minitab which consists of the pollutant data to run the best subset regression. Select the options Stat-Regression-Best Subsets from the toolbar menu. Then a pop-up window opens which is shown in Figure 3-6. The response (pollutant concentration) and the free predictors (independent variables) should be selected from the menu on the left side and should click ‘OK’. Minitab then gives the results with R2, adjusted R2, Cp, and standard deviation(s) for each different set of variables considered that helps the user in identifying the important variables to be considered in model development.
In the set of results $R^2$ represents the percentage of variation in pollutant concentration accounted for by the independent variables, adjusted $R^2$ accounts for the difference in the number of independent variables and helps in selecting an optimal model. Standard deviation represents how widespread the values are in a dataset 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.

Figure 3-6: Screenshot of Best Subset Regression in Minitab

Minitab provides the best two models (with highest $R^2$) for each set of different number of predictors used. The important variables affecting pollutant concentrations are identified by analyzing the statistical results that have a higher adjusted $R^2$ after considering the standard deviation, and a Cp value close to the value of independent variable (number of predictors + 1) or less. If there is not much difference in the adjusted $R^2$ values when the number of variables is decreased, it is better to select a variable set
having lesser number of predictors. The best subset regression analysis helped to identify
the important variables affecting in-vehicle pollutant concentration. Once the important
variables affecting pollutant concentrations are determined as predictors, a regression
model can be developed by selecting the options Stat-Regression-Regression from the
toolbar menu. The response (pollutant concentration) and the predictors (all important
variables) are selected as input to develop a multiple regression model.
Chapter Four

Modeling

The indoor pollutant concentrations can be estimated using several approaches. The following are a few of them:

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

2. A variety of empirical approaches based on statistical evaluation of test data and usually least-squares regression analysis [Wadden et al. (1983)].

3. A combination of both forms, empirically fitting the parameter of the mass balance with values statistically derived from experimental measurements [Wadden et al. (1983)].

4. Numerical models

5. Artificial Intelligence (AI) methods [Kadiyala et al. 2010b, 2010c]

Each of these models has both advantages and disadvantages. The mass balance approach provides more generality while empirical models which were developed within the range of measurements from which they were developed may provide more accurate
Numerical models may be able to cover unlimited situations. AI models can predict the pollutant levels more accurately because of its capability to understand complex patterns.

A mass balance equation was applied for the prediction of the indoor concentrations of CO₂ gas in the public transport bus for the pollutant flow into and out of an indoor volume, including indoor sources. Pollutant materials can be generated by indoor sources and removed from indoor air through adsorption on indoor surfaces.

The pollutant flow into and out of the indoor volume, including recycling and interior sources and sinks can be expressed using Equation (1) and (2) [Wadden et al. (1983)]. Figure 4-1 describes the flow of pollutants into and out of an indoor compartment.

![Figure 4-1: Flow of pollutant into and out of an indoor volume](image-url)
Air mass balance:
\[ q_0 + q_2 = q_3 + q_4 \] (1)

Pollutant mass balance:
\[ V \frac{dC_i}{dt} = k q_0 C_0 (1 - F_0) + k q_1 C_1 (1 - F_1) + k q_2 C_0 - k (q_0 + q_1 + q_2) C_i + S - R \] (2)

where:
- \( C_i \) = Indoor Concentration
- \( C_0 \) = Outdoor Concentration
- \( C_s \) = Steady State Concentration
- \( t \) = time
- \( q_0 \) = Volumetric flow rate for make-up air
- \( q_1 \) = Volumetric flow rate for recirculation
- \( q_2 \) = Volumetric flow rate for infiltration
- \( q_3 \) = Volumetric flow rate for exfiltration
- \( q_4 \) = Volumetric flow rate for exhaust
- \( F_0 \) = Filter efficiency for make-up air
- \( F_1 \) = Filter efficiency for recirculation
- \( V \) = Volume of room
- \( S \) = Indoor source emission rate
- \( R \) = Indoor sink removal rate
- \( k \) = mixing factor

The solution for Equation (2) for the change in \( C_i \) with \( t \) and holding all factors constant with boundary conditions \( C_i = C_s \) at \( t = 0 \) [Wadden et al. (1983)] is Equation (3).
\[
C_i = \frac{k(q_0(1-F_0)+q_2)C_0 + S - R}{k(q_0 + q_1 F_1 + q_2)} \left[1 - e^{-\left(\frac{k}{V}\right)(q_0 + q_1 F_1 + q_2) t}\right] + C_x e^{-\left(\frac{k}{V}\right)(q_0 + q_1 F_1 + q_2) t} \tag{3}
\]

The model was applied to the CO\textsubscript{2} and passenger data collected during this study from fall 2008 to summer 2009. By applying the following assumptions for study environment the Equation (3) transforms to Equation (4):

- It is assumed that there is no recirculation of air
- Makeup air inside the bus was assumed to be 0%, 10%, 20% and 30% of volume per hour. The filter efficiency of makeup air was assumed to be 1 for the CO\textsubscript{2} pollutant.
- The thin gap of 0.5 centimeter is assumed over the doors and windows
- It is observed from the literature [Drivas (1996)] that there is no decay of CO\textsubscript{2}.

\[
C_i = \frac{k(q_0(1-F_0)+q_2)C_0 + S}{k(q_0 + q_2)} \left[1 - e^{-\left(\frac{k}{V}\right)(q_0 + q_2) t}\right] + C_x e^{-\left(\frac{k}{V}\right)(q_0 + q_2) t} \tag{4}
\]

### 4.1 Calculation of Mixing Factor

The mixing factor depends on various parameters which vary with time. Traditionally mixing factor is determined by the slope of a plot of the log of concentration versus time. A reverse method is used in estimating the mixing factor using Equation (5) [Wadden et al. (1983)].

\[
k = \frac{\log C_{i(n+1)} + \log C_{i(n)}}{t} \tag{5}
\]

where

- \(C_{i(n+1)}\) = Concentration of pollutant at \((n+1)^{th}\) minute
- \(C_{i(n)}\) = Concentration of pollutant at \(n^{th}\) minute
The hourly average concentrations of CO$_2$ gas were considered in estimating the mixing factor. The average mixing factor values were estimated for each season. The average mixing factor values for BD and ULSD bus can be tabulated in Table 3.3. The limiting values of the mixing factor vary with volume and air change rate. From Wadden et al. (1983) it can be observed that the mixing factor values range from 0.10 to 0.60 for various conditions inside houses.

Table 3.3: Values of mixing factors

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Fall</th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>BD</td>
<td>0.50</td>
<td>0.33</td>
<td>0.33</td>
<td>0.40</td>
</tr>
<tr>
<td>ULSD</td>
<td>0.28</td>
<td>0.40</td>
<td>0.35</td>
<td>0.28</td>
</tr>
</tbody>
</table>

4.2 Estimation of Infiltration Rate

The infiltration rate was calculated for each season by using the average wind speed over the particular season and the area of openings. The area of the gap is calculated over windows and doors by using Equation (6). The two conditions were considered in calculating the infiltration rate. The door closed conditions and door open conditions. In the door open condition the area of a door and the cross-sectional area of thin gap (0.5 centimeter) is considered. In the door closed condition just the area of thin gap is considered in the calculation. The infiltration rate was calculated using Equation (7). It is assumed that the door is not open for more than one minute on average over one hour period.
\[ A_g = P \times t_g \] \hspace{1cm} (6)

where

\[ A_g = \text{Area of gap} \]
\[ P = \text{Total length (perimeter) of the gap over the all windows and doors} \]
\[ t_g = \text{Thickness of the gap} \]

\[ Q_2 = A_g \times v_s \] \hspace{1cm} (7)

where

\[ v_s = \text{Average wind speed (velocity) for a season} \]

4.3 Outdoor Concentration Calculation

The outdoor concentrations were determined using the average indoor/outdoor ratios calculated by Kadiyala (2008) to the type of fuel used. The indoor concentration of the 1st hour of the day was used in calculating the ambient concentration of the particular day. The outdoor concentrations are calculated using the Equation (8). The ambient concentration was assumed constant throughout the day.

\[ C_0 = C_i / f_{i/o} \] \hspace{1cm} (8)

where \( f_{i/o} = \text{Indoor-Outdoor ratio} \)

4.4 Indoor Source Emission Rate Estimation

The indoor sources responsible for the gaseous pollutants were identified and the sources emission rates were estimated. Passengers inside the bus generate \( CO_2 \) through the natural process of respiration. The 1% of self exhaust from the bus is also assumed to be the source for the pollutants. The exhaust emission rate of \( CO_2 \) was estimated by Vijayan (2007) for the particular buses.
4.5 Model Evaluation

The following performance measures are used to evaluate the models used in this study.

(i) Fractional Bias

The bias is normalized to make it dimensionless. The fractional bias (FB) varies between +2 and -2 and has an ideal value of zero for an ideal model. The Fractional Bias is given by:

\[
\text{Fractional Bias (FB)} = 2 \left( \frac{C_0 - C_p}{C_0 + C_p} \right)
\]

(ii) Normalized Mean Square Error

Normalized Mean Square Error (NMSE) emphasizes the scatter in the entire data set. Hanna et al. (1985) modified the equation for mean square error to obtain Normalized Mean Square Error which is a dimensionless statistic. NMSE is not biased towards models that over predict and under predict. Smaller values of NMSE indicate better performance. The expression for NMSE is given by:

\[
\text{NMSE} = 2 \left( \frac{C_0 - C_p}{C_0 \times C_p} \right)^2
\]

(iii) Coefficient of Correlation

Correlation analysis involves statistical performance obtained by linear least squares regression. The value of coefficient of correlation (r) close to 1 indicates perfect correlation between the observed and predicted values which is a sign of good model performance. The coefficient of correlation is given by:
(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:

\[
Fa2 = \text{Fraction of data which } 0.5 \leq \frac{Cp}{Co} \leq 2
\]

\[
r = \frac{(C_0 - C_0)(C_p - C_p)}{\sigma C_p \times \sigma C_0}
\]
Chapter Five

Results and Discussions

This Chapter is divided into three sections. The first section discusses the trends in indoor air quality for a three year period based on the observations. The next section focuses on variables that could have possibly affect the observed pollutant concentrations. The yearly and seasonal variations are discussed by analyzing the factors affecting the pollutant concentrations. The last section evaluates the use of Equation (4) discussed in the previous chapter.

5.1 Indoor Pollutant Trends

5.1.1 CO₂ Concentrations

The carbon dioxide concentration levels were found to be mainly influenced by passenger ridership and vehicular traffic. Figure 5-1 shows that the carbon dioxide levels were peaked between 8:00 AM and 10:00AM while most of the people and children are going to their work places and schools whereas Figure 5.2 shows that the carbon dioxide levels were peaked between 4:00 PM and 6:00 PM while people are returning from their work places. The carbon dioxide levels decreased in the afternoon when there was a
decrease in the number of passengers in the bus. The carbon dioxide levels are observed to be higher during the year 2008 as compared to the year 2009, in which levels are higher than 2007 for BD bus. In case of ULSD bus carbon dioxide levels are observed to be higher during the year 2008 as compared to the year 2007, in which levels are higher than 2009. This observed trend possibly because of the variations in meteorology and number of passengers in the bus. During the video analysis it was found that there is indeed an increase in passenger ridership in subsequent years compared to the year 2007. In case of ULSD bus during the year 2009 the passenger ridership is observed to be less from video footage.

![Yearly Variation of CO2 (PPM)](image)

**Figure 5-1: Yearly CO2 Concentration Trend in B20 bus**

From a health point of view, the good news is that concentrations of carbon dioxide are less than 1000 ppm for all three years. The recorded values are less than 20% of Time Waited Average (TWA) value (5000 ppm).
It is also observed that the CO$_2$ levels are slightly higher in a biodiesel bus as compared to an ultra low sulfur diesel bus for the years 2007, 2008, and 2009. During these years, the passenger ridership was found to be higher in BD bus compared to the ULSD bus.

![Yearly Variation of CO2 (PPM)](image)

**Figure 5-2: Yearly CO$_2$ Concentration Trend in ULSD bus**

Figure 5-3 and Figure 5-4 represent the seasonal variation of carbon dioxide. Toledo area receives a fair amount of snowfall in winter. Increase in passenger ridership (2007 < 2008 < 2009) resulted in increase of CO$_2$ levels. There is 33% increase in the passenger ridership from spring 2007 to spring 2009. The concentrations were observed to be higher during winter, when windows were in closed position to keep the passengers warm resulting in low air exchange rate (AER).

CO$_2$ levels were almost equal during winter 07 and 08 and during summer 07 and 09 in the B20 bus. These can be related to the lower ventilation during winter 08 and
summer 09 as observed from video analysis. The concentrations were higher during winter because of relatively less ventilation when compared to other seasons. The CO$_2$ levels were higher during fall 08 and spring 09 when compared to winter 07 and 08. This can be related to higher passenger ridership during these seasons compared to winter season.

The CO$_2$ levels were higher during winter 08 compared to winter 09 due to relatively lower ventilation in winter 08 when compared to winter 09 in the ULSD bus. During spring and summer seasons, concentrations were observed to be higher during 07 compared to 09. More windows were kept closed during 07 when compared to 09. CO$_2$ levels were lower during winter 07 compared to other seasons in 07 because of lower passenger ridership during winter 07.

![Seasonal Variation of CO2 (PPM)](image)

**Figure 5-3: Seasonal CO$_2$ Concentration Trend in B20 bus**
Figure 5-4: Seasonal CO₂ Concentration Trend in ULSD bus

5.1.2 CO Concentrations

The yearly trends of carbon monoxide levels with time can be observed from Figures 5-5 and 5-6. The gradual increase in the carbon monoxide levels in the morning is due to the fact that most people are travelling to their work places and schools. CO levels decreased in the afternoon when less traffic is observed and increases once again in the evening when people return from their work places. The concentration levels during the year 2007 were higher than concentration levels during the years 2008 and 2009 and also the levels in 2009 are higher than 2008. It is observed from video footage that windows are kept closed most of the time during 2008 and 2009 compared to 2007 resulting in lower penetration of gases. Also it is observed that in case of ULSD bus for the year 2008 the lead traffic is less compared to remaining years resulting in the
reduction of penetration of pollutants. The concentrations of the CO are less than 20 ppm which are less than 40% of TWA value 50 ppm.

Figure 5-5: Monthly CO Concentration Trend in B20 bus

Figure 5-6: Monthly CO Concentration Trend in ULSD bus
From Figures 5-7 and 5-8 it is also observed that the CO concentration levels of the BD bus are higher when compared to the ULSD bus for the years 2007, 2008 and 2009. During these years, passenger ridership was found to be higher in BD bus compared to ULSD bus which automatically results in opening of bus door more number of times in BD bus compared to ULSD bus. Thus penetration of pollutants is increased comparatively.

![Seasonal Variation of CO (PPM)](image)

**Figure 5-7: Seasonal CO Concentration Trend in B20 bus**

Figures 5-7 and 5-8 represent the seasonal variation of carbon monoxide gas. Toledo area receives a fair amount of snowfall in winter. Relatively higher CO levels are observed during winter 09 when compared to winter 08, which is also higher than winter 07. Also the levels are higher during spring 07 when compared to the spring 09 and summer 07 are higher compared to summer 09 in BD bus possibly because of more penetration during these seasons. It is also observed that the CO levels are higher during
fall 07 compared to fall 08, levels are higher during winter 07 and 09 compared to 08 and levels are higher during summer 07 compared to 09 in ULSD bus possibly because of the higher penetration comparatively during these seasons. It is also observed that the CO levels are lower in ULSD bus compared to BD bus which would have been affected by higher lead traffic for BD bus compared to ULSD bus.

Figure 5-8: Seasonal CO Concentration Trend in ULSD bus

5.1.3 SO$_2$ Concentrations

The yearly trends of sulfur dioxide concentrations as observed from Figures 5-9 and 5-10 were found to be higher during morning peak hours and either remained same or decreased in the afternoon and once again increased during evening peak hours. It is observed that concentration levels of SO$_2$ are higher in ULSD bus during 2007 when compared to 2008 and 2009 which might be due to change in type of fuel used in 2008 from ULSD to ULSD supreme. It was observed that concentration levels were reduced.
from 2007 to 2009 which might be because of the reduction in penetration of pollutants as windows were kept closed most of the time as observed from video analysis. The higher concentrations observed in ULSD bus compared to BD bus could be a result of sulfur dioxide emissions coming from vehicle exhaust that penetrated indoors.

![Yearly Variation of SO2 (PPM)](image)

**Figure 5-9: Monthly SO2 Concentration Trend in B20 bus**

Figure 5-11 and Figure 5-12 provide seasonal variation of sulfur dioxide. The vehicular traffic around bus got reduced from 2007 to 2009 resulting in lesser concentration of SO2 over years. The SO2 levels were higher during winter compared to other seasons due to accumulation of lower levels of SO2 inside the bus even with less AER. The SO2 levels were observed to be almost equal during winter 07 and 08 in the B20 bus. The vehicular traffic was less during winter 07 compared to winter 08 contributing to low SO2. The concentration levels during winter 09 were observed to be lower compared to spring and summer 09 because of lower vehicular traffic. The
concentration levels of SO$_2$ in ULSD bus were higher during 2007 when compared to 2008 and 2009 which may be related to the change in type of fuel from ULSD to ULSD supreme. The SO$_2$ levels were observed to be almost equal during winter 08 and 09.

Figure 5-10: Monthly SO$_2$ Concentration Trend in ULSD bus

Figure 5-11: Seasonal SO$_2$ Concentration Trend in B20 bus

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Figure 5-12: Seasonal SO$_2$ Concentration Trend in ULSD bus

5.1.4 NO Concentrations

Figure 5-13: Monthly NO Concentration Trend in B20 bus
The yearly trends of nitric oxide levels with time can be observed from Figure 5-13 and Figure 5-14. The concentration levels increased in accordance with increase in traffic during the peak traffic periods. It is observed that NO levels are higher during the years 2007 and 2008 compared to 2009 for the BD bus possibly because of more penetration comparatively. The concentration levels are observed to be higher during morning hours for the ULSD bus during the years 2008 and 2009 compared to 2007 possibly because higher vehicular traffic during the years 2008 and 2009 compared to 2007. The concentration levels during 2008 for the ULSD bus are observed to be higher from 6:00 AM to 1:00 PM and lower from 2:00 PM to 6:00 PM which can be attributed to the decrease in the traffic of the from morning to evening comparatively. The concentration levels during 2008 for BD bus are observed to be lower during the morning session compared to afternoon session possibly because of the lower lead traffic during
morning compared to afternoon. The concentrations are observed to be less than 12.0ppm which is less than 50% of the TWA value 25ppm.

Figure 5-15: Seasonal NO Concentration Trend in B20 bus

Figure 5-16: Seasonal NO Concentration Trend in ULSD bus
It was also observed that NO levels were found to be higher in biodiesel bus as compared to ULSD bus during the year 2007 even though the number of lead vehicles for ULSD bus is higher indicating less ventilation in ULSD bus. Figure 5-15 and Figure 5-16 shows that NO levels are observed to be almost same for seasons winter, spring and fall for ULSD bus. Higher NO levels are observed in fall 07 compared to fall 08 in BD bus which might be because of more penetration caused due to higher ventilation in fall 07.

5.1.5 NO₂ Concentrations

![Yearly Variation of NO₂ (PPM)](image)

Figure 5-17: Monthly NO₂ Concentration Trend in B20 bus

The yearly trends of nitrogen dioxide (NO₂) levels with time can be observed from Figure 5-17 and Figure 5-18. NO₂ levels increased with increase in traffic during the peak hours. The NO₂ levels were observed to be higher for the BD bus compared to ULSD bus which possibly because of the higher lead traffic for the BD bus along with higher ventilation compared to the ULSD bus resulting in higher penetration of
pollutants. The concentration levels were observed to be less than 0.2ppm which is less than 7% of TWA value 3.0ppm.

Figure 5-18: Monthly NO₂ Concentration Trend in ULSD bus

Figure 5-19: Seasonal NO₂ Concentration Trend in B20 bus
Figure 5-20: Seasonal NO2 Concentration Trend in ULSD bus

NO2 levels were found to be higher in winter 09 compared to winters 07 and 08 and spring 07 compared to spring 09 in a biodiesel bus and did not show any variation in other seasons. The variations in the ULSD bus were observed only with variation in traffic levels during the peak traffic periods.

5.2 Factors Affecting IAQ in the Bus

The regression analysis was performed to identify the factors affecting in-vehicle pollutant gaseous concentrations for each month, and season using MINITAB software. The factors affecting IAQ are summarized in Tables 5.1, 5.2, 5.3, 5.4, 5.5 and 5.6 for different seasons and months during the study period. The important influential factors for each pollutant are listed below.

The criteria used in selecting the important influential factors affecting concentrations of pollutants are:

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• The magnitudes of coefficients in the equations were used in selecting the parameters. Both positively and negatively influencing parameters were considered depending on the magnitude of coefficients.

• The top four influential factors with respect to the weight-age affecting the concentrations were selected considering the magnitude of the coefficients.

5.2.1 Important Factors for B20 bus

The monthly influential factors over the study period affecting concentrations of CO₂ are passengers, idle/open, run/close and ambient temperature. Along with the monthly influential factors, the wind direction is observed to be influencing the seasonal variations of CO₂. Trucks, ambient temperature and wind speed are the monthly influential factors affecting concentrations of CO over the study period. Ambient temperature, ambient RH, indoor temperature are observed to be influencing the seasonal variations of CO.

Trucks, ambient temperature and wind speed are the monthly influential factors affecting concentrations of NO over the study period. Ambient RH and ambient temperature are observed to be influencing the seasonal variations of NO. The monthly influential factors over the study period affecting concentrations of NO₂ are trucks, run/close and ambient temperature. Along with the monthly influential factors the cars and wind direction are observed to be influencing the seasonal variations of NO₂.

Trucks, run/close and ambient temperature are the monthly influential factors over the study period affecting concentrations of SO₂. Ambient temperature and run/close are observed to be influencing the seasonal variations of SO₂.
5.2.2 Important Factors for ULSD bus

The monthly influential factors over the study period affecting concentrations of CO$_2$ are passengers, idle/open, indoor RH and ambient temperature. Along with the monthly influential factors the wind direction is observed to be influencing the seasonal variations of CO$_2$.

Ambient temperature, wind speed and run/close are the monthly influential factors affecting concentrations of CO over the study period. Along with the monthly influential factors the wind direction is observed to be influencing the seasonal variations of CO. Ambient temperature, wind speed and indoor RH are the monthly influential factors affecting concentrations of NO over the study period. Visibility and wind direction are observed to be influencing the seasonal variations of NO.

The monthly influential factors over the study period affecting concentrations of NO$_2$ are cars, run/close and ambient temperature. The wind direction, wind speed and ambient temperature are observed to be influencing the seasonal variations of NO$_2$. Trucks, run/close and ambient temperature are the monthly influential factors over the study period affecting concentrations of SO$_2$. Ambient temperature and wind direction are observed to be influencing the seasonal variations of SO$_2$.

The similarities are observed between the B20 and ULSD buses in the identification of seasonal influential factors for all the pollutant gases monitored. The common seasonal factors observed for both B20 and ULSD buses are meteorological parameters such as ambient temperature, wind speed and wind direction which are in agreement with the observations made by Kadiyala and Kumar (2008, 2009).
Table 5.1: CO\textsubscript{2} and CO Monthly Influential Factors for B20 Bus

<table>
<thead>
<tr>
<th>Pollutant →</th>
<th>CO\textsubscript{2}</th>
<th>CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Months ↓</td>
<td>2007</td>
<td>2008</td>
</tr>
<tr>
<td></td>
<td>2009</td>
<td>2007</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>2009</td>
</tr>
<tr>
<td></td>
<td>2009</td>
<td>2009</td>
</tr>
<tr>
<td>Jan</td>
<td>NA</td>
<td>Indoor Temperature, Wind Speed</td>
</tr>
<tr>
<td></td>
<td>Passengers, Indoor RH</td>
<td>Wind direction, Indoor Temperature,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wind Speed, Ambient Temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Indoor Temperature, Wind Speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wind Speed, Indoor RH</td>
</tr>
<tr>
<td>Feb</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Passengers, Ambient RH, Wind speed, Ambient Temperature</td>
<td>Ambient Temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ambiant Temperature, Passengers, Cars</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wind Speed, Ambiant Temperature</td>
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<tr>
<td></td>
<td></td>
<td>Wind Speed, Wind Direction</td>
</tr>
<tr>
<td>Mar</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Wind direction, Passengers, Wind speed, Ambient RH</td>
<td>Indoor Temperature, Wind Speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wind Speed, Ambient Temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wind Speed, Indoor RH</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wind Speed, Wind Direction</td>
</tr>
<tr>
<td>Apr</td>
<td>Idle/Open, Wind direction, Passengers</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ambient Temperature, Cars, Ambient</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RH</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wind direction, Wind Speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wind Speed</td>
</tr>
<tr>
<td>May</td>
<td>Passengers, Wind direction, Idle/Close, Run/Close</td>
<td>Indoor RH, Wind direction, Ambient</td>
</tr>
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<td></td>
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<td>RH, Wind Speed, Ambient RH</td>
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<td>Wind Speed, Wind Direction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ambient Temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Indoor Temperature</td>
</tr>
<tr>
<td>Month</td>
<td>Data Points</td>
<td>Ambient RH</td>
</tr>
<tr>
<td>-------</td>
<td>-------------</td>
<td>------------</td>
</tr>
<tr>
<td>Jun</td>
<td>Passengers, Ambient RH, Ambient Temperature</td>
<td>NA</td>
</tr>
<tr>
<td>Jul</td>
<td>Wind direction, Trucks, Indoor Temperature, Ambient Temperature</td>
<td>NA</td>
</tr>
<tr>
<td>Aug</td>
<td>Indoor RH</td>
<td>NA</td>
</tr>
<tr>
<td>Sep</td>
<td>Passengers</td>
<td>NA</td>
</tr>
<tr>
<td>Oct</td>
<td>Indoor Temp, Wind speed, Passengers, Trucks</td>
<td>Indoor Temp, Wind speed, Passengers</td>
</tr>
<tr>
<td>Nov</td>
<td>Wind speed, Indoor</td>
<td>NA</td>
</tr>
<tr>
<td>Dec</td>
<td>Passengers, Wind direction, Ambient RH, Indoor Temperature, Wind speed</td>
<td>Temperature, Ambient Temperature</td>
</tr>
<tr>
<td>-----------</td>
<td>------------------------------------------------------------------------</td>
<td>---------------------------------</td>
</tr>
</tbody>
</table>

Table 5.2: NO, NO\(_2\) and SO\(_2\) Monthly Influential Factors for B20 Bus

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>NO</th>
<th>NO(_2)</th>
<th>SO(_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>NA</td>
<td>Ambient RH</td>
<td>Indoor Temperature, Ambient RH, Indoor Rh</td>
</tr>
<tr>
<td>Feb</td>
<td>NA</td>
<td>Ambient RH</td>
<td>Ambient Temperature, Wind Speed, Passengers, Run/Close</td>
</tr>
<tr>
<td>Month</td>
<td>NA</td>
<td>Indoor Temperature, Indoor RH</td>
<td>Ambient Temperature, Wind Direction, Ambient RH</td>
</tr>
<tr>
<td>-------</td>
<td>----</td>
<td>-------------------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Mar</td>
<td>NA</td>
<td>Indoor Temperature, Indoor RH</td>
<td>NA</td>
</tr>
<tr>
<td>Apr</td>
<td>Wind speed, Wind direction, Indoor RH</td>
<td>NA</td>
<td>Indoor Temperature, Wind Direction, Cars, Run/Close</td>
</tr>
<tr>
<td>May</td>
<td>Wind direction, Cars</td>
<td>NA</td>
<td>Ambient Temperature, Ambient RH, Indoor Temperature</td>
</tr>
<tr>
<td>Jun</td>
<td>Indoor RH, Ambient RH</td>
<td>NA</td>
<td>Indoor Temperature, Wind Speed, Wind Direction, Passengers</td>
</tr>
<tr>
<td>Jul</td>
<td>Indoor Temperature</td>
<td>NA</td>
<td>Ambient Temperature</td>
</tr>
</tbody>
</table>

49
<table>
<thead>
<tr>
<th>Month</th>
<th>, Wind direction, Ambient Temperature</th>
<th>, Wind Speed, Wind Direction, Passengers, Trucks</th>
<th>, Wind Direction, Trucks, Run/Close</th>
<th>Temperature</th>
<th>, Wind Speed, Wind Direction, Passengers, Trucks, Run/Close</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug</td>
<td>Wind direction, Idle/Open, Idle/Close, Indoor Temperature</td>
<td>NA</td>
<td>NA</td>
<td>Indoor RH</td>
<td>NA</td>
</tr>
<tr>
<td>Sep</td>
<td>Wind direction, Indoor Temperature, Passengers</td>
<td>NA</td>
<td>NA</td>
<td>Indoor RH, Ambient RH</td>
<td>NA</td>
</tr>
<tr>
<td>Oct</td>
<td>Indoor Temperature, Wind direction, Ambient Temperature</td>
<td>Ambient Temperature, Wind Speed, Wind Direction, Trucks, Run/Close</td>
<td>NA</td>
<td>Indoor RH</td>
<td>NA</td>
</tr>
</tbody>
</table>

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## Table 5.3: CO₂ and CO Monthly Influential Factors for ULSD Bus

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>CO₂</th>
<th>CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Months ↓</td>
<td>2007</td>
<td>2008</td>
</tr>
<tr>
<td><strong>Jan</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indoor Temperature, Indoor RH</td>
<td>Passengers, Indoor RH</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Feb</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind direction, Indoor temp,</td>
<td>Wind direction, Indoor</td>
<td>NA</td>
</tr>
<tr>
<td>Ambient Temperature, Wind speed, Visibility, Ambient RH</td>
<td>Trucks</td>
<td>NA</td>
</tr>
</tbody>
</table>

Table 5.3: CO₂ and CO Monthly Influential Factors for ULSD Bus

<table>
<thead>
<tr>
<th><strong>Table 5.3: CO₂ and CO Monthly Influential Factors for ULSD Bus</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pollutant</strong></td>
</tr>
<tr>
<td><strong>Months ↓</strong></td>
</tr>
<tr>
<td><strong>Jan</strong></td>
</tr>
<tr>
<td>Indoor Temperature, Indoor RH</td>
</tr>
<tr>
<td><strong>Feb</strong></td>
</tr>
<tr>
<td>Wind direction, Indoor temp,</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Month</th>
<th>Wind speed, Passengers, Cars</th>
<th>Temperature, Passengers</th>
<th>Temperature, Indoor RH</th>
<th>Cars, Run/Close</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar</td>
<td>Wind speed, Visibility, Indoor RH</td>
<td>NA</td>
<td>Indoor Temperature, Wind speed, Wind direction, Idle/Close</td>
<td>Indoor Temperature, Wind speed, Trucks</td>
</tr>
<tr>
<td>Apr</td>
<td>Idle/Open, Run/Close, Wind direction, Cars, Trucks, Passengers</td>
<td>NA</td>
<td>Ambient Temperature, Wind speed, Wind direction, Idle/Close</td>
<td>Ambient Temperature, Trucks, Run/Close</td>
</tr>
<tr>
<td>May</td>
<td>Wind direction, Visibility, Ambient Temperature, Ambient RH</td>
<td>NA</td>
<td>Indoor Temp, Wind speed, Wind direction</td>
<td>Ambient Temperature, Passengers, Trucks, Run/Close</td>
</tr>
<tr>
<td>Jun</td>
<td>Ambient RH, Passengers, Wind direction, Wind speed</td>
<td>NA</td>
<td>Wind direction, Ambient Temperature, Ambient Temperature</td>
<td>Ambient Temperature, Ambient RH, Wind Speed</td>
</tr>
<tr>
<td>Month</td>
<td>Ambient Temperature</td>
<td>Wind speed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>---------------------</td>
<td>------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jul</td>
<td>NA</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aug</td>
<td>Passengers</td>
<td>Wind speed, Wind Direction, Passengers, Trucks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sep</td>
<td>Passengers, Indoor RH</td>
<td>Indoor Temp, Ambient Temp, Wind speed, Wind direction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct</td>
<td>Passengers, Ambient Temperature, Indoor RH</td>
<td>Cars, Wind direction, Indoor Temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nov</td>
<td>Indoor Ambient</td>
<td>Wind speed, Indoor Temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pollutant</td>
<td>NO</td>
<td>NO\textsubscript{2}</td>
<td>SO\textsubscript{2}</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>----</td>
<td>----------------</td>
<td>----------------</td>
<td></td>
</tr>
<tr>
<td>Indoor Temperatures</td>
<td>Indoor Temperature, Ambient Temperature, Wind Speed, Wind Direction</td>
<td>Indoor Temperature, Wind Speed, Wind Direction</td>
<td>Indoor Temperature, Wind Speed, Wind Direction</td>
<td></td>
</tr>
<tr>
<td>Jan</td>
<td>Indoor Temperature</td>
<td>NA</td>
<td>NA</td>
<td>Indoor Temperature</td>
</tr>
<tr>
<td>Jan</td>
<td>Indoor Temperature</td>
<td>NA</td>
<td>Indoor Temperature</td>
<td>Indoor Temperature, Wind Speed, Wind Direction</td>
</tr>
<tr>
<td>Dec</td>
<td>Run/Close, Passengers, Indoor Temperature, Wind direction, Ambient Temperature</td>
<td>Ambient Temperature, Wind Speed, Passengers, Run/Close</td>
<td>Indoor Temperature, Ambient Temperature, Passengers</td>
<td>Indoor Temperature, Trucks, Run/Close</td>
</tr>
<tr>
<td>Month</td>
<td>Indoor Temperature, Wind direction, Ambient Temperature</td>
<td>NA</td>
<td>Indoor Temperature, Wind Direction, Passengers, cars, Run/Close</td>
<td>NA</td>
</tr>
<tr>
<td>-------</td>
<td>--------------------------------------------------------</td>
<td>----</td>
<td>------------------------------------------------------------</td>
<td>----</td>
</tr>
<tr>
<td>Feb</td>
<td>NA</td>
<td>NA</td>
<td>Ambient Temperature, Wind Speed, Wind Direction, Passengers, Cars, Run/Close</td>
<td>NA</td>
</tr>
<tr>
<td>Mar</td>
<td>Passengers, Trucks, Ambient Temperature, Wind direction</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Apr</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Month</td>
<td>Parameters</td>
<td>Run/Close</td>
<td>Parameters</td>
<td>Run/Close</td>
</tr>
<tr>
<td>-------</td>
<td>------------------------------------------------</td>
<td>-----------</td>
<td>------------------------------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>May</td>
<td>Ambient RH, Visibility, Ambient Temperature</td>
<td>NA</td>
<td>Ambient Temperature, Wind Speed, Cars, Trucks, Run/Close</td>
<td>NA</td>
</tr>
<tr>
<td>Jun</td>
<td>Ambient RH, Ambient Temperature, Wind speed, Wind direction</td>
<td>NA</td>
<td>Ambient Temperature, Wind Speed, Wind Direction</td>
<td>NA</td>
</tr>
<tr>
<td>Jul</td>
<td>NA</td>
<td>NA</td>
<td>Ambient Temperature, Wind Speed, Ambient RH</td>
<td>NA</td>
</tr>
<tr>
<td>Aug</td>
<td>Wind direction, Wind speed</td>
<td>NA</td>
<td>Ambient Temperature, Wind Speed, Wind Direction, Passengers, Visibility, Run/Close</td>
<td>NA</td>
</tr>
<tr>
<td>Month</td>
<td>Indoor Temperature, Ambient RH</td>
<td>Ambient Temperature, Wind Direction, Wind Speed, Trucks, Run/Close</td>
<td>Wind direction, Indoor Temperature, Ambient Temp, Wind Speed, Wind Speed, Visibility</td>
<td>Ambient RH, Wind Speed, Cars, Indoor RH</td>
</tr>
<tr>
<td>-------</td>
<td>-------------------------------</td>
<td>---------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------</td>
<td>-----------------------------------------</td>
</tr>
<tr>
<td>Sep</td>
<td>Wind direction NA</td>
<td>Ambient RH, Ambient Temp, Wind Speed NA NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Oct</td>
<td>Indoor Temperature, Ambient RH</td>
<td>NA</td>
<td>Amb Indoor Temperature, Wind Speed, Passengers, Vehicles, Indoor RH, Wind Speed</td>
<td>NA</td>
</tr>
<tr>
<td>Nov</td>
<td>Visibility, Ambient Temperature, Ambient RH</td>
<td>NA</td>
<td>Amb Indoor Temperature, Wind Speed, Passengers, Vehicles, Indoor RH, Wind Speed</td>
<td>NA</td>
</tr>
<tr>
<td>Dec</td>
<td>Passengers</td>
<td>Ambient Temperature, Wind Direction, Wind Speed, Trucks</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
### Table 5.5: Gaseous Pollutants Seasonal Influential Factors for B20 Bus

<table>
<thead>
<tr>
<th>Gas →</th>
<th>( \text{CO}_2 )</th>
<th>( \text{CO} )</th>
<th>( \text{NO} )</th>
<th>( \text{NO}_2 )</th>
<th>( \text{SO}_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>Ambient RH, Wind Direction</td>
<td>NA</td>
<td>Ambient Temperature, Wind Speed, Wind Direction, Idle/Open</td>
<td>Indoor Temperature, Wind Speed, Wind Direction, Idle/Open</td>
<td>NA</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Gas</th>
<th>CO₂</th>
<th>CO</th>
<th>NO</th>
<th>NO₂</th>
<th>SO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>Wind direction, Passengers, NA</td>
<td>Ambient RH, Wind Speed, Passengers, Wind direction, NA</td>
<td>Ambient Temperature, Wind Speed, Wind direction, Visibility, Ambient RH, NA</td>
<td>Indoor Temperature, Ambient RH, Cars, Trucks, Run/Close</td>
<td>Ambien RH, Wind Speed, Wind direction, NA</td>
</tr>
</tbody>
</table>

Table 5.6: Gaseous Pollutants Seasonal Influential Factors for ULSD Bus
<table>
<thead>
<tr>
<th>Season</th>
<th>Passengers</th>
<th>Ambient Temperature, Passengers, Cars</th>
<th>Ambient RH</th>
<th>Indoor Temperature, Trucks, Run/Close</th>
<th>Visibility, Ambient RH, Ambient Temperature</th>
<th>Wind Speed, Wind Direction, Passengers, Trucks, Run/Close</th>
<th>Ambient RH, Wind direction</th>
<th>Ambient Temperature, Wind Speed, Wind Direction, Trucks, Run/Close</th>
<th>Ambient RH, Ambient Temp</th>
<th>Indoor Temp, Ambient Temp, Passengers, Cars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>NA</td>
<td>Wind direction, Ambient Temperature, Indoor Temperature, Ambient RH, Passengers</td>
<td>NA</td>
<td>Indoor Temp, Ambient Temp, Passengers, Cars, Run/Close</td>
<td>Indoor Temperature, Ambient Temperature, Wind direction, Ambient RH</td>
<td>Indoor Temp, Ambient RH, Trucks, Visibility</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Summer</td>
<td>Passengers</td>
<td>NA</td>
<td>Ambien</td>
<td>Indoor Temperature, Ambient Temperature</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Fall</td>
<td>Passengers, Indoor Temperature, Indoor RH</td>
<td>NA</td>
<td>Indoor Temperature, Ambient Temperature</td>
<td>Ambien</td>
<td>NA</td>
<td>Ambien Temperature, Wind Speed, Wind Direction, Passengers, Cars</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
5.3 Model Evaluation

For an ideal and perfect model both the fractional bias and normalized mean square error should equal to zero. To determine the reliability of the model, the criteria used is as set in a study by Kumar et al., (1993). The performance of the model can be deemed as acceptable if:

\[ \text{NMSE} \leq 0.5 \]
\[ -0.5 \leq \text{FB} \leq +0.5 \]
\[ \text{Fa2} \geq 0.8 \]

5.3.1 B20 Bus

The performance measures of the predictive model using mass balance approach are presented in Table 5.7. These performance measures are developed using observed concentration \( C_o \) and predicted concentration \( C_p \) for the \( \text{CO}_2 \) gas monitored in B20 bus for different cases by varying makeup air. It can be seen from the Tables 5.7, 5.8, 5.9 and 5.10 that the model meet the criteria requirements set by Kumar et al. (1993) for the B20 bus in all the cases.

Table 5.7: Performance Measures of \( C_o \) and \( C_p \) for \( \text{CO}_2 \) in B20 bus with 0% Makeup Air

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Fall 2008</th>
<th>Winter 2009</th>
<th>Spring 2009</th>
<th>Summer 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of correlation</td>
<td>0.82</td>
<td>0.45</td>
<td>0.35</td>
<td>0.49</td>
</tr>
<tr>
<td>Normalized Mean Square Error</td>
<td>0.23</td>
<td>0.18</td>
<td>0.17</td>
<td>0.14</td>
</tr>
<tr>
<td>Fractional Bias</td>
<td>-0.32</td>
<td>-0.30</td>
<td>-0.32</td>
<td>-0.29</td>
</tr>
<tr>
<td>Factor of 2</td>
<td>0.90</td>
<td>0.92</td>
<td>0.92</td>
<td>0.97</td>
</tr>
<tr>
<td>Mean ( C_o )</td>
<td>2190.96</td>
<td>1695.08</td>
<td>1496.77</td>
<td>1481.33</td>
</tr>
<tr>
<td>Mean ( C_p )</td>
<td>3040.15</td>
<td>2287.66</td>
<td>2066.08</td>
<td>1992.51</td>
</tr>
</tbody>
</table>

Figures 5-21, 5-22, 5-23 and 5-24 illustrate the scatter plots of observed versus predicted values obtained from modeling in various seasons for various cases of 0%,
10%, 20% and 30% makeup air with ideal predictions denoted by the $C_o = C_p$ line. From these figures, it can be inferred that the predictions of the model are reasonable for the lower concentrations and predicted concentrations are higher when compared to the monitored concentrations after certain levels for different seasons in all the cases.

Table 5.8: Performance Measures of $C_o$ and $C_p$ for CO$_2$ in B20 bus with 10% Makeup Air

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Fall 2008</th>
<th>Winter 2009</th>
<th>Spring 2009</th>
<th>Summer 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of correlation</td>
<td>0.82</td>
<td>0.45</td>
<td>0.35</td>
<td>0.49</td>
</tr>
<tr>
<td>Normalized Mean Square Error</td>
<td>0.23</td>
<td>0.18</td>
<td>0.16</td>
<td>0.13</td>
</tr>
<tr>
<td>Fractional Bias</td>
<td>-0.32</td>
<td>-0.29</td>
<td>-0.32</td>
<td>-0.29</td>
</tr>
<tr>
<td>Factor of 2</td>
<td>0.90</td>
<td>0.92</td>
<td>0.92</td>
<td>0.97</td>
</tr>
<tr>
<td>Mean $C_o$</td>
<td>2190.96</td>
<td>1695.08</td>
<td>1496.77</td>
<td>1481.33</td>
</tr>
<tr>
<td>Mean $C_p$</td>
<td>3032.74</td>
<td>2281.48</td>
<td>2058.77</td>
<td>1987.35</td>
</tr>
</tbody>
</table>

Table 5.9: Performance Measures of $C_o$ and $C_p$ for CO$_2$ in B20 bus with 20% Makeup Air

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Fall 2008</th>
<th>Winter 2009</th>
<th>Spring 2009</th>
<th>Summer 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of correlation</td>
<td>0.82</td>
<td>0.45</td>
<td>0.35</td>
<td>0.49</td>
</tr>
<tr>
<td>Normalized Mean Square Error</td>
<td>0.22</td>
<td>0.18</td>
<td>0.16</td>
<td>0.13</td>
</tr>
<tr>
<td>Fractional Bias</td>
<td>-0.32</td>
<td>-0.29</td>
<td>-0.31</td>
<td>-0.29</td>
</tr>
<tr>
<td>Factor of 2</td>
<td>0.90</td>
<td>0.92</td>
<td>0.92</td>
<td>0.99</td>
</tr>
<tr>
<td>Mean $C_o$</td>
<td>2190.96</td>
<td>1695.08</td>
<td>1496.77</td>
<td>1481.33</td>
</tr>
<tr>
<td>Mean $C_p$</td>
<td>3025.36</td>
<td>2275.35</td>
<td>2051.51</td>
<td>1982.22</td>
</tr>
</tbody>
</table>

Table 5.10: Performance Measures of $C_o$ and $C_p$ for CO$_2$ in B20 bus with 30% Makeup Air

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Fall 2008</th>
<th>Winter 2009</th>
<th>Spring 2009</th>
<th>Summer 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of correlation</td>
<td>0.82</td>
<td>0.45</td>
<td>0.35</td>
<td>0.50</td>
</tr>
<tr>
<td>Normalized Mean Square Error</td>
<td>0.22</td>
<td>0.17</td>
<td>0.16</td>
<td>0.13</td>
</tr>
<tr>
<td>Fractional Bias</td>
<td>-0.32</td>
<td>-0.29</td>
<td>-0.31</td>
<td>-0.29</td>
</tr>
<tr>
<td>Factor of 2</td>
<td>0.90</td>
<td>0.92</td>
<td>0.92</td>
<td>0.99</td>
</tr>
<tr>
<td>Mean $C_o$</td>
<td>2190.96</td>
<td>1695.08</td>
<td>1496.77</td>
<td>1481.33</td>
</tr>
<tr>
<td>Mean $C_p$</td>
<td>3018.03</td>
<td>2269.25</td>
<td>2044.31</td>
<td>1977.12</td>
</tr>
</tbody>
</table>
Figure 5-21: Observed Vs Predicted Values of CO₂ in case of 0% Makeup Air for BD Bus
Figure 5-22: Observed Vs Predicted Values of CO₂ in case of 10% Makeup Air for BD Bus
Figure 5-23: Observed Vs Predicted Values of CO$_2$ in case of 20% Makeup Air for BD Bus
Figure 5-24: Observed Vs Predicted Values of CO$_2$ in case of 30% Makeup Air for BD Bus
5.3.2 ULSD Bus

The performance measures of the predictive model using mass balance approach are presented in Table 5.8. These performance measures are developed using observed concentration $C_o$ and predicted concentration $C_p$ for the CO$_2$ gas monitored in ULSD bus for different cases by varying makeup air. It can be seen from the Tables 5.11, 5.12, 5.13 and 5.14 that the model meet all the criteria except Factor of two (Fa2) requirements set by Kumar et al. (1993) for the ULSD bus in all the cases. In all the cases during winter season the Fa2 values were less than 0.9 indicating that majority of predicted concentrations are either less than half or greater than double the observed concentrations. Figures 5-25, 5-26, 5-27 and 5-28 illustrate the scatter plots of observed versus predicted values obtained from modeling in various seasons for various cases of 0%, 10%, 20% and 30% makeup air with ideal predictions denoted by the $C_o = C_p$ line. From these figures, it can be inferred that the predictions of model are reasonable for the lower concentrations and predicted concentrations are higher when compared to the monitored concentrations after certain levels for different seasons in all the cases.

Table 5.11: Performance Measures of $C_o$ and $C_p$ for CO$_2$ in ULSD bus with 30% Makeup Air

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Fall 2008</th>
<th>Winter 2009</th>
<th>Spring 2009</th>
<th>Summer 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of correlation</td>
<td>0.65</td>
<td>0.14</td>
<td>0.55</td>
<td>0.61</td>
</tr>
<tr>
<td>Normalized Mean Square Error</td>
<td>0.09</td>
<td>0.24</td>
<td>0.18</td>
<td>0.16</td>
</tr>
<tr>
<td>Fractional Bias</td>
<td>-0.24</td>
<td>-0.41</td>
<td>-0.37</td>
<td>-0.36</td>
</tr>
<tr>
<td>Factor of 2</td>
<td>1.00</td>
<td>0.84</td>
<td>0.98</td>
<td>1.00</td>
</tr>
<tr>
<td>Mean $C_o$</td>
<td>1830.18</td>
<td>1108.38</td>
<td>1110.74</td>
<td>1135.18</td>
</tr>
<tr>
<td>Mean $C_p$</td>
<td>2324.01</td>
<td>1680.79</td>
<td>1615.96</td>
<td>1633.56</td>
</tr>
</tbody>
</table>
Table 5.12: Performance Measures of $C_o$ and $C_p$ for CO$_2$ in ULSD bus with 30% Makeup Air

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Fall 2008</th>
<th>Winter 2009</th>
<th>Spring 2009</th>
<th>Summer 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of correlation</td>
<td>0.65</td>
<td>0.14</td>
<td>0.51</td>
<td>0.61</td>
</tr>
<tr>
<td>Normalized Mean Square Error</td>
<td>0.09</td>
<td>0.24</td>
<td>0.17</td>
<td>0.16</td>
</tr>
<tr>
<td>Fractional Bias</td>
<td>-0.24</td>
<td>-0.41</td>
<td>-0.35</td>
<td>-0.36</td>
</tr>
<tr>
<td>Factor of 2</td>
<td>1.00</td>
<td>0.84</td>
<td>0.98</td>
<td>1.00</td>
</tr>
<tr>
<td>Mean $C_o$</td>
<td>1830.18</td>
<td>1108.38</td>
<td>1110.74</td>
<td>1135.18</td>
</tr>
<tr>
<td>Mean $C_p$</td>
<td>2318.10</td>
<td>1676.17</td>
<td>1579.88</td>
<td>1637.30</td>
</tr>
</tbody>
</table>

Table 5.13: Performance Measures of $C_o$ and $C_p$ for CO$_2$ in ULSD bus with 30% Makeup Air

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Fall 2008</th>
<th>Winter 2009</th>
<th>Spring 2009</th>
<th>Summer 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of correlation</td>
<td>0.65</td>
<td>0.14</td>
<td>0.52</td>
<td>0.61</td>
</tr>
<tr>
<td>Normalized Mean Square Error</td>
<td>0.09</td>
<td>0.24</td>
<td>0.17</td>
<td>0.16</td>
</tr>
<tr>
<td>Fractional Bias</td>
<td>-0.23</td>
<td>-0.41</td>
<td>-0.35</td>
<td>-0.36</td>
</tr>
<tr>
<td>Factor of 2</td>
<td>1.00</td>
<td>0.85</td>
<td>0.98</td>
<td>1.00</td>
</tr>
<tr>
<td>Mean $C_o$</td>
<td>1830.18</td>
<td>1108.38</td>
<td>1110.74</td>
<td>1135.18</td>
</tr>
<tr>
<td>Mean $C_p$</td>
<td>2312.22</td>
<td>1671.58</td>
<td>1574.18</td>
<td>1632.82</td>
</tr>
</tbody>
</table>

Table 5.14: Performance Measures of $C_o$ and $C_p$ for CO$_2$ in ULSD bus with 30% Makeup Air

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Fall 2008</th>
<th>Winter 2009</th>
<th>Spring 2009</th>
<th>Summer 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of correlation</td>
<td>0.65</td>
<td>0.14</td>
<td>0.52</td>
<td>0.62</td>
</tr>
<tr>
<td>Normalized Mean Square Error</td>
<td>0.09</td>
<td>0.23</td>
<td>0.16</td>
<td>0.15</td>
</tr>
<tr>
<td>Fractional Bias</td>
<td>-0.23</td>
<td>-0.40</td>
<td>-0.34</td>
<td>-0.36</td>
</tr>
<tr>
<td>Factor of 2</td>
<td>1.00</td>
<td>0.85</td>
<td>0.98</td>
<td>1.00</td>
</tr>
<tr>
<td>Mean $C_o$</td>
<td>1830.18</td>
<td>1108.38</td>
<td>1110.74</td>
<td>1135.18</td>
</tr>
<tr>
<td>Mean $C_p$</td>
<td>2306.38</td>
<td>1667.01</td>
<td>1568.53</td>
<td>1628.37</td>
</tr>
</tbody>
</table>
Figure 5-25: Observed Vs Predicted Values of CO₂ in case of 0% Makeup Air for ULSD Bus
Figure 5-26: Observed Vs Predicted Values of CO$_2$ in case of 10% Makeup Air for ULSD Bus
Figure 5-27: Observed Vs Predicted Values of CO₂ in case of 20% Makeup Air for ULSD Bus
Figure 5-28: Observed Vs Predicted Values of CO$_2$ in case of 30% Makeup Air for ULSD Bus
Chapter 6

Conclusion

A field study to collect real-world on-road indoor air quality data from public transit buses is carried out successfully. This study presents in vehicle gaseous pollutant trends over three years for the buses fueled with B20 and ULSD and the factors affecting pollutant levels over the considered study period. A simple mass balance model was evaluated for predicting the concentrations of carbon dioxide. The proposed equations worked with limited success for CO₂. The mass balance model requires the use of ambient concentrations and the values were not available from the USEPA network.

The following conclusions can be drawn from the study of trends for yearly and seasonal patterns:

- The concentrations of CO₂ increased from 2007 to 2009 in B20 bus. In ULSD bus the levels are higher in 2008 when compared to 2009 and levels during 2009 are higher when compared to 2007. The levels of CO₂ are relatively higher during winter for both B20 and ULSD buses due to lower ventilation rate.
The levels of CO decreased from 2007 to 2009 in B20 bus. The concentrations in ULSD bus are higher during 2007 than 2009 and levels during 2009 are higher than 2008. The levels of CO are relatively higher during winter for both B20 and ULSD buses due to lower ventilation rate.

The concentrations of SO$_2$ decreased from 2007 to 2009 in both B20 and ULSD buses. The SO$_2$ are very high during 2007 in ULSD bus when compared to the 2008 and 2009 which can be related to change in type of fuel from ULSD to ULSD supreme. The levels of SO$_2$ are relatively higher during winter for both B20 and ULSD buses due to lower ventilation rate.

The levels of NO decreased from 2007 to 2009 in the B20 bus. The concentrations in ULSD bus are almost equal in entire study period except in the peak traffic times during 2007 where the concentrations are high. The levels of NO are relatively higher during winter for both B20 and ULSD buses due to lower ventilation rate.

The concentrations of NO$_2$ are almost zero at any particular time. The levels of NO$_2$ are relatively higher during winter for both B20 and ULSD buses due to lower ventilation rate.

The following conclusions can be drawn from the model evaluation part of the study:

- The proposed model is able to predict concentrations of CO$_2$ in both B20 and ULSD fueled buses during all the seasons with limited success.
- The mixing factors are determined in this study for B20 and ULSD buses during various seasons. The calculated factors are function of season as well as the type
of fuel used in the bus. The experience from this study indicates that further research is needed to study the flow rates and mixing factors.

6.1 Recommendations for Future Work

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 investigation into the ventilation system for determining the flow rate in the public transport buses.
- Determination of mixing factor using direct approaches.
- Detailed monitoring of the ambient concentrations.
- Development of alternative predictive models.
References


