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Experimental Analysis of Exhaust Emissions from Transit Buses Fuelled with Biodiesel

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Abstract: This paper presents a real life data set that incorporates results from a Toledo Area Regional Transit Authority (TARTA) biodiesel project. The research is carried out to study the effect of biodiesel on the exhaust emissions from the public transport buses.

A comprehensive exhaust emission testing protocol is developed to identify the emission variations of transit buses fuelled with blends of biodiesel under different operating modes. The study is divided into two groups: real-world on-road emission and idle-engine emission testing. Exhaust emissions of oxygen (O_2), carbon monoxide (CO), sulfur dioxide (SO_2), oxides of nitrogen (NO_x), and carbon dioxide (CO_2) have been reported in this study.

The effects of biodiesel on vehicular emissions vary from pollutant to pollutant and are primarily dependent on engine characteristics and the concentration of biodiesel in the base fuel. The lower emissions are observed during the on-road test mode of CO, CO_2, and SO_2, with the increase in percentage of biodiesel in the base fuel. On the contrast, idle-engine emissions, except CO_2, increase with the increase in percentage of biodiesel in the fuel. The emissions of NO_x, SO_2, and CO_2 during cold-start are observed to be higher than that of the hot-start conditions.

Keywords: Idle emissions, On-road emissions, Biodiesel, Mobile emissions, Modeling.

INTRODUCTION

Mobile emissions are considered seriously because of the fact that they are generally ground level pollutant sources and have maximum impact on public health. Since 1950 the world-wide population has been increasing rapidly, with an increase in number of cars by a factor of 10. This increase in vehicular traffic made the transportation sector a significant contributor of air pollutants along with more consumption of fossil fuels, which are non-renewable. Concerns over fossil fuel consumption and the associated vehicle emissions increased the importance of renewable clean burning alternative fuels. Biodiesel is a nontoxic promising alternative to conventional diesel fuel with no engine modifications needed when used in blends. This study characterizes the exhaust emissions of public transport buses fuelled with biodiesel in different operating modes.

Several studies have been conducted to investigate the potential of biodiesel as an alternative fuel for diesel engines and most of the results observed decrease in CO, CO_2, SO_2, particulate matter (PM), and hydrocarbons (HC). Only NO_X emissions are reported to be increased, which can be controlled by taking necessary changes in the engine characteristics. Dorado *et al.* [1] reported that the use of biodiesel confirmed the lower emissions of CO, CO_2, nitric oxide (NO), and SO_2, with a substantial increase in nitrogen dioxide (NO_2) emissions.

Wang *et al*. [2] observed that the higher oxygen content in biodiesel encourages more complete combustion reducing CO emissions, and, due to shorter ignition delay, NO_X emissions from biodiesel fuels were observed to be slightly higher than diesel fuels. They commented that these exhaust emissions also depend on oxygen content and combustion temperature. By increasing the concentration of biodiesel, the injection timing is advanced, therefore leading to higher NO_X emissions. Kegl and Hribernik [3] suggested that the higher NO_X exhaust emissions can be reduced by retarding injection timing. In their study on real-world tailpipe emissions, Mazzoleni *et al*. [4] found that there was a substantial increase for cold-start CO and hot-start HC emissions using B20 instead of petroleum diesel. In a similar study Mc Cormick *et al.* [5] observed that as the percentage of biodiesel blend in the fuel increases, the amount of NO_X released increase but the concentrations of CO, HC, and PM will be decreased. Agarwal [6] indicated that biodiesel blend improved the peak thermal efficiency of the engine by 2.5%, reduced the exhaust emissions and the brake specific energy consumption to a large extent, and overall combustion characteristics were quite similar for biodiesel blend (B20) and mineral diesel. Thus, biodiesel is a potential candidate for the application in compression ignition (CI) engines. Carrarreto *et al*. [7] suggested that the use of biodiesel involves a substantial reduction of emitted pollutants becoming a key solution in reducing urban air pollution. They also stated that the global emission of CO_2 is greatly reduced and that the net energy requirement is positive. The United States Environmental Protection Agency (U.S. EPA) [8] has conducted a comprehensive analysis on the emission impacts of soy-bean based biodiesel on heavy-duty highway engines and observed a proportional increase in NO_X, and a linear de-

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crease of PM, HC, and CO emissions with respect to the percent of biodiesel in the base fuel.

Younglove *et al.* [9] commented that exhaust emissions and fuel consumption of a vehicle are influenced by various factors including different vehicle characteristics, driving behavior, traffic interruptions, sudden stops high acceleration, idling, passenger load, road grade, turnings, and meteorological conditions. Along with alternative fuels necessary strategies can be developed in engine operating conditions to reduce exhaust emissions and to conserve energy resources by identifying factors that are responsible for variability in emissions and fuel usage.

Chen *et al.* [10] explained that variations of emission rate and fuel economy significantly depend on speed and acceleration. Many researchers have stated that emissions vary for “cold-start” and “hot-start” conditions of a vehicle. The rate of exhaust emission for a cold-start or a hot-start depends on the ambient and engine temperatures. Martin *et al.* [11] observed that exhaust emissions are significantly higher during a cold-start, i.e. the warm-up phase of the vehicle. The duration of the warm-up phase and the emissions produced during this period depend on the ambient temperature as well as the initial temperature of the vehicle’s system. Jensen [12] stated that cars with colder engines are found to have 10-20% and 5-10% higher emissions of CO and HC respectively.

Mazzoleni *et al.* [4] commented that the real-world emission analysis represents not only an important scientific research tool, but also a method to measure the quality of new commercial fuels to meet the relevant fuel standards. Brodrick *et al.* [13] concluded that exhaust emissions and fuel consumption vary with engine model year, accessory loading, and engine speed. By increasing the engine speed with the air conditioning enabled resulted in increased emissions of CO, NO_X, and CO_2, also affecting fuel economy. Storey *et al.* [14] observed that ambient temperature affects the concentration of PM emissions. The emission concentration of PM decreased with an increase in ambient temperature. Vijayan *et al.* [15] found that engine operation factors such as engine revolutions per minute (rpm), maintenance history, engine temperatures, and engine technology substantially influence exhaust emissions.

The above literature review indicates that the effects of biodiesel blends have not been studied on the exhaust emissions from urban transit buses during their regular service. The objective of this study is to understand the variation of diesel engine exhaust emissions fuelled with biodiesel and operating under real-world on-road and idle-engine conditions. The American Society of Testing Materials (ASTM) has suggested the use of 20% or lower biodiesel blends due to the concerns of the manufacturers of engine and fuel injectors regarding the cold flow properties, fuel stability, and biological growth of biodiesel fuels. This study is restricted up to the use of 20% biodiesel blend in order to avoid any problems to the buses.

METHODOLOGY

It is important to design the data collection program carefully so that the measured data can be used to its maximum extent for emission characterization. There are four second-by-second datasets, each containing exhaust emission and engine diagnostic data collected simultaneously. Each of these datasets are collected from transit buses fuelled with Ultra Low Sulfur Diesel supreme (ULSD) and three different biodiesel blends. The data is collected in the months of June and July of 2008. This study deals with two different kinds of experimental set-up, on-road emission testing, and idle-engine emission testing. They are explained below:

I. On-Road Emission Testing

Route selection and bus selection are the two primary steps involved in this study. In order to obtain the emission data under real-world traffic conditions, the selected route must be a regular bus route with passengers on-board. Real time emission data is collected when the selected bus goes out on its regular specified route. The Route starts from the TARTA garage and ends at Franklin Mall Park. It is entirely urban, the length of the route is 4.7 miles and the testing time was approximately 15-17 minutes. On the day of testing, the equipment was installed on the bus in the garage. It takes around 15-20 minutes to install and remove the set-up from the bus. The testing is carried out in such a way that one bus was tested for each day, and the driver remained the same for the complete study. Set up was installed on the rear seats of the bus powered from the bus electrical system. The power was supplied to the instruments from the vehicle’s power control panel. The desired engine parameters are collected by connecting the on-board diagnostic (OBD) unit to the engine computer module (ECM) of the bus and to the laptop.

II. Idle-Engine Emission Testing

Idle-engine emission testing was conducted in an open space outside the garage with the engine in idle mode (i.e. acceleration and the speed will be zero). Hot-start emissions are collected during nights when the bus come back to the garage from its regular route and the cold-start emissions are taken in the mornings before the bus left for its specified route. The desired engine parameters are collected by connecting the OBD unit to the ECM of the bus and to the laptop. The analyzer set-up was connected to the exhaust pipe and both the engine parameter readings and exhaust analyzer readings are measured simultaneously. Duration of the test cycle was 15 minutes.

Two different engines are employed in this study, as summarized in Table **1**. The applications of both the engines are for urban transit services.

Table 1. Details of the Test Engines

Engine	Chassis Manufacture	Vehicle Class	Gross Vehicle Weight Rating (GVWR) lbs
2005 Cummins (ISB)	Bluebird	Medium	29841
2003 Mercedes Benz (MBE)	Thomas	Medium	28580

Table 2. Properties of Test Fuels

Property	Fuel	ULSD
	Biodiesel (B99.9%)	
Cetane number	47	40
Cloud point (summer) (°F)	-	20
Cloud point (winter) (°F)	42.8	15
Flash point (°F)	>320	125
Sulfur (ppm)	<1	15
Water & sediment (moisture) (Vol. %)	<0.005	0.05
Kinematic Viscosity, 40°C (mm^2/sec)	4	1.9-3.4

Both the engines are turbocharged, having equal number of combustion chambers with MBE having engine capacity of 7.2 liters and Cummins with 5.9 liters. Also, both the engines have exhaust gas recirculation (EGR) and employed with common rail direct fuel injectors.

Soy based biodiesel with different mixes, 0% (B0), 5% (B5), 10% (B10), and 20% (B20), with the base fuel as ULSD, are used as test fuels. The properties of biodiesel and ULSD are given in Table **2.** The fuel tank for each selected bus was filled with B0, B5, B10, or B20 and allowed to run for four hours on the road, before the actual testing was started, so that the entire fuel system was rinsed with the required fuel and was ready for the testing. Each bus was tested for two consecutive days using the desired fuel to conduct a sensitivity analysis.

The portable emission measurement system (PEMS) used for collecting exhaust emission data is Testo350XL. It measures continuously up to six gases: O_2, CO_2, CO, SO_2, NO, and NO_2 with calculated NO_X, and a temperature sensor with an integrated thermoelectric cooler for continuous temperature compensation for accurate measurement. The units of O_2 and CO_2 are given in the percentgae of gas present in the volume of air analyzed by the sensor. The values of O_2 and CO_2 are automatically calculated by the analyzer in terms of volume percent (%). The instrument was set up for one second concentration measurement and connected to the laptop to download the data simultaneously.

This study includes numerous operational and engine variables influencing the emission behavior of pollutant concentrations. In order to verify the associated influence of each variable on emission concentrations, a multivariate statistical analysis using Minitab® software is used. A similar kind of analysis has been conducted by Vijayan and Kumar [16] on public transport buses.

RESULTS AND DISCUSSION

The measured vehicle emissions have been analyzed in detail and in order to understand the measurement variation and the influence of operational variables on exhaust emissions, a sensitivity analysis and a statistical analysis are carried out on the measured data. The experimental analysis is divided into two sections: real-world on-road emission characterization and idle-engine emission characterization.

1. Sensitivity Analysis for Exhaust Emissions

In order to understand the measurement variation of the analyzed data, repeat tests are performed and the test-to-test variations are observed for the same vehicle. Two buses equipped with MBE engine (Bus No. 504 and 505), and two with ISB engine (Bus No. 300 and 301), fuelled with B10, are tested for the idle and on-road emissions.

During idle-engine testing, the buses are fuelled with B10 and each bus was tested three times on different idle modes. The emission trends of each pollutant measured under hot-start conditions with all the accessory loadings disabled are discussed here. The standard deviations of the average emissions are presented in Fig. (**1**). It is clear from the error bars in this figure that the measured concentrations are reproducible apart from the CO and NO_x having slightly high variation.

A comparison of second-by-second emission data (not shown in Fig. **1**) showed that all the monitered pollutants followed a similar trend for the three tests. The variation between the repeat tests was not much except for CO (Bus No. 300 and 504) and NO_x (Bus No. 300, 301, 504, and 505). Also, the fuel consumption pattern for all the three tests followed similar trends with a 5% and 3% difference for MBE and ISB engines. Nearly the concentrations of all the monitored pollutants are overlapping, which ensured that the same readings are reproduced. The slight variation in emission results could have occurred due to the change in ambient temperature that is uncontrollable. The same results are obtained for all the other modes and are not discussed in this paper.

The test-to-test variation of real-world on-road emissions are conducted on the same route with the same driver and at the same time of testing, but on different days. These on-road emissions primarily rely on uncontrallable conditions such as traffic patterns, ambient conditions, driver vari-ability, passengers on-board, and vehicle operation status. In this study two buses with MBE engine (Bus No. 504 and 505), and two with ISB engine (Bus No. 300 and 301), fuelled with B5, are tested two times each on successive days.

The average emission data of each pollutant with their respective standard deviations are presented in Fig. (**2**). Not much variation has been observed between the tests in most cases. The standard deviation was high from test-to-test for CO (Bus No. 300 and 301) and NO_x (Bus No. 505). Second-to-second data when observed (not shown in Fig. **2**), the variation was huge due to frequent accelerations and decelerations. But when the average emissions of the total route are observed, the results are almost similar (see Fig. **2**). Note that the literature suggests that real-world on-road emissions cannot be reproduced.

2. Real-World On-Road Emission Characterization

Tests are conducted in order to understand the effect on exhaust emissions using biodiesel blends. The real-world on-road exhaust emission concentrations from the transit buses equipped with MBE and ISB engines and fuelled with B0, B5, B10, and B20 are measured. The emission variation of

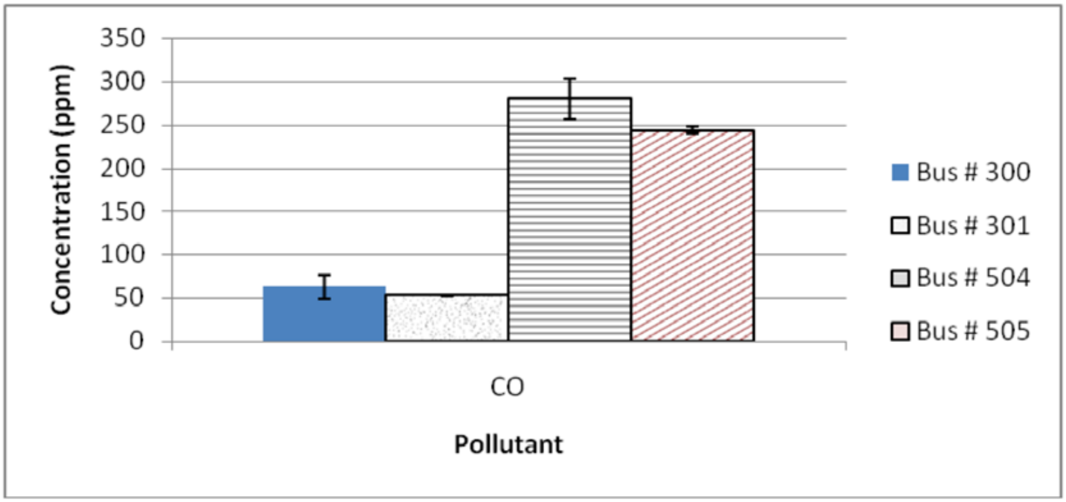

Fig. (1a). Average idle-engine CO emissions using B10 with error bars showing (+/-) standard deviation.

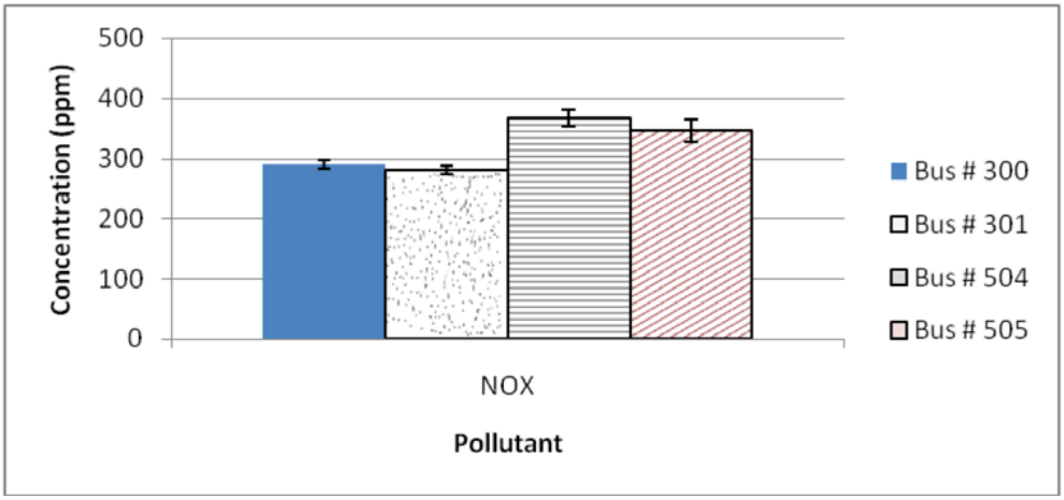

Fig. (1b). Average idle-engine NO_x emissions using B10 with error bars showing (+/-) standard deviation.

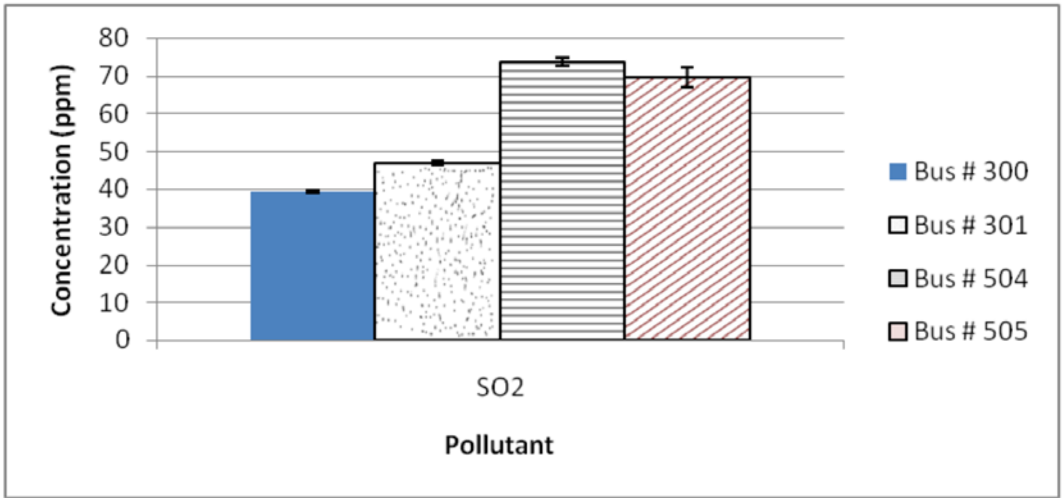

Fig. (1c). Average idle-engine SO_2 emissions using B10 with error bars showing (+/-) standard deviation.

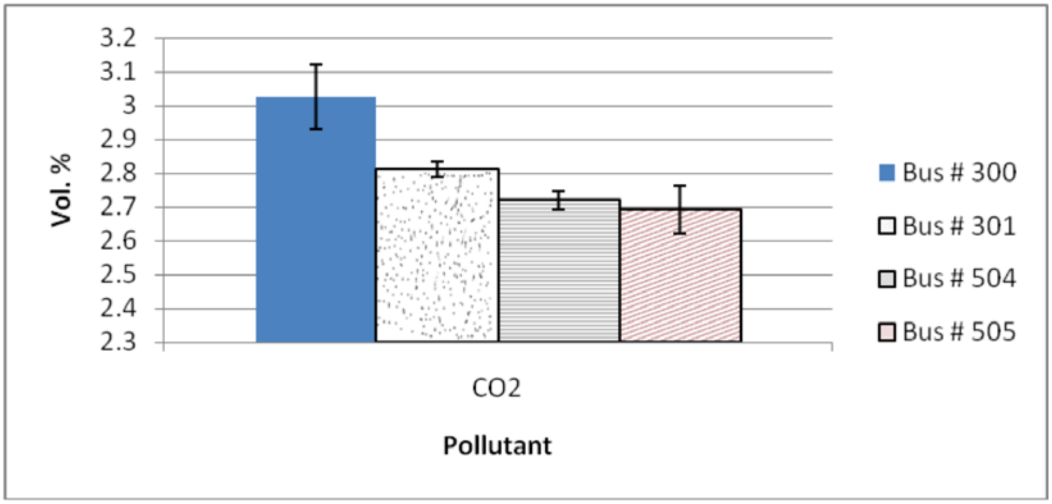

Fig. (1d). Average idle-engine CO_2 emissions using B10 with error bars showing (+/-) standard deviation.

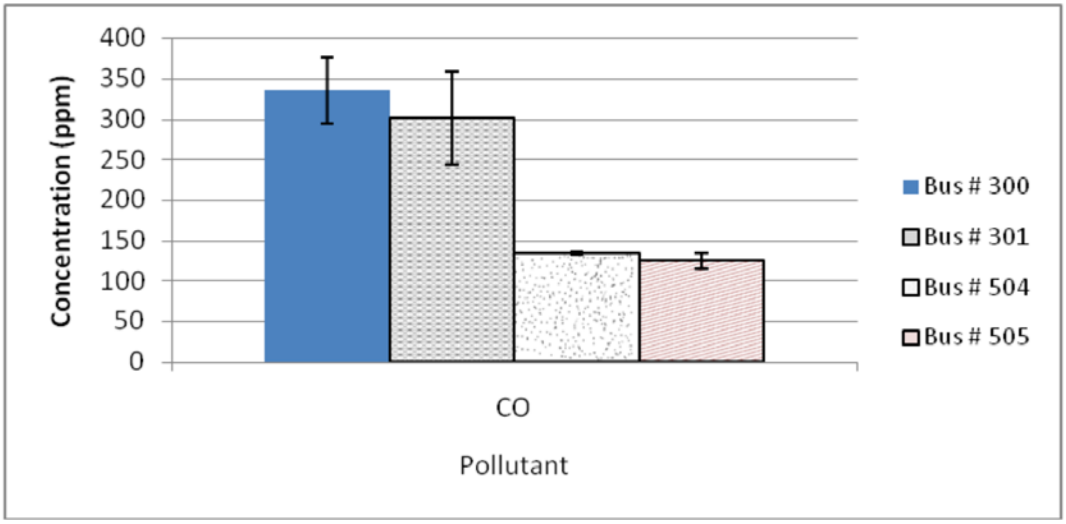

Fig. (2a). Average on-road CO emissions using B5 with error bars showing (+/-) standard deviation.

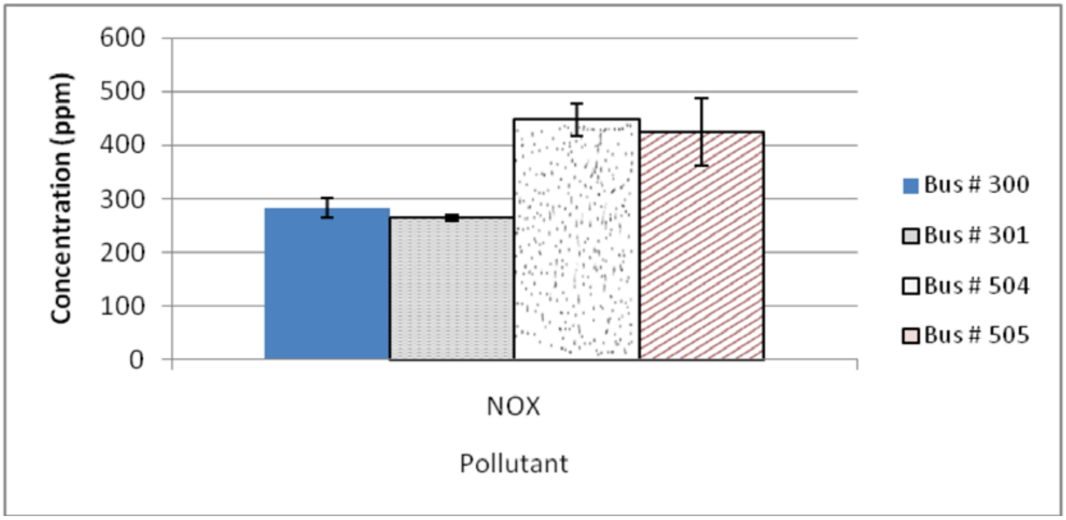

Fig. (2b). Average on-road NO_X emissions using B5 with error bars showing (+/-) standard deviation.

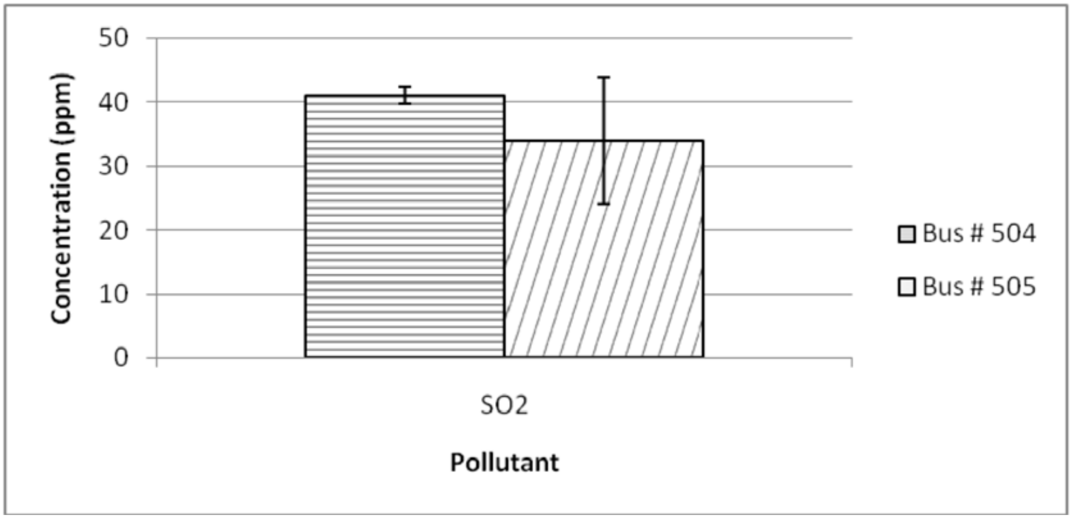

Fig. (2c). Average on-road SO_2 emissions using B5 with error bars showing (+/-) standard deviation.

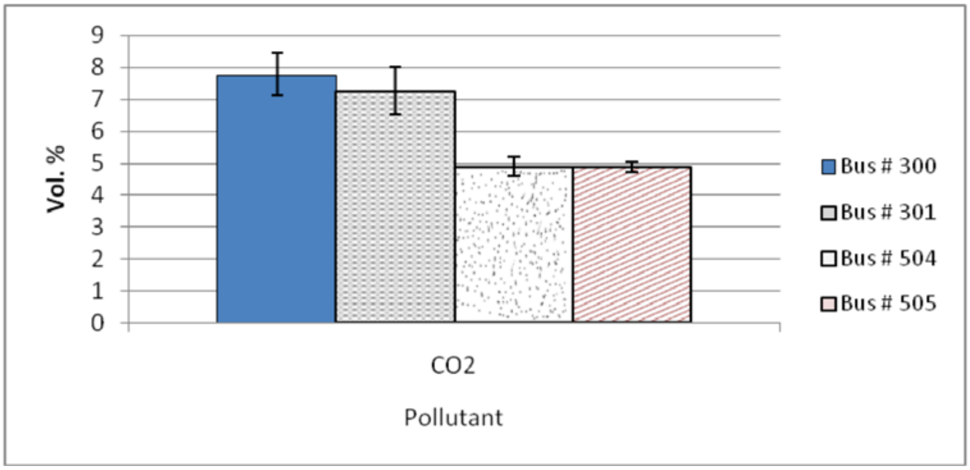

Fig. (2d). Average on-road CO_2 emissions using B5 with error bars showing (+/-) standard deviation.

the pollutant concentrations with biodiesel blends are shown in Fig. (**3**).

It is known that CO from vehicles is released due to the incomplete combustion of a fuel containing carbon. The reduction of CO was linear and was inversely proportional to the percent of biodiesel in the base fuel. A decrease of 38% for MBE engines from B0 to B20 and a 22% of decrease for ISB engines from B5 to B10 was observed. Similar observations were found by Shandilya and Kumar [17] and Graboski *et al*. [18]. They commented that CO reduction is linear with biodiesel concentration in the substrate. The reasons for CO reduction in biodiesel blended buses could be credited to the additional oxygen content in the fuel that enhances a complete combustion of the fuel and the increased cetane number. The higher the cetane number, the lower the probability of fuel-rich zones formation, usually related to CO emissions. Nerella and Kumar [19] provide a detailed discussion on the emission variation of pollutants with respect to the type of engine.

A correlation equation between percent of biodiesel blend (BX) and the percent (%) change in CO emissions for this data-set with BX ranging between 0 and 20 is given below.

$$\%\ Change\ in\ CO\ emissions = \{exp^{[0.101662*BX]-1}\} * 100 \quad (1)$$

NO_x concentrations are the calculated concentrations of NO and NO_2 obtained directly from the analyzer. NO is the dominant pollutant as measured by the analyzer. The increase was up to 15% from B0 to B20 for MBE engines. In the case of ISB engines, the increase was up to 10% from B5 to B10. Schumacher *et al*. [20] commented that as the concentration of biodiesel in a base fuel increase, the amount of NO_x released increase. This increase in NO_x emissions can be attributed to the higher oxygen availability in the combustion chamber when using biodiesel, which could promote NO formation. The percent change in NO_X emissions with biodiesel blend using the data-set obtained from this study is presented below.

$$\%\ Change\ in\ NO_X\ emissions = \{exp^{[0.090602*BX]-1}\} * 100 \quad (2)$$

The CO_2 emission variation for MBE and ISB engines followed opposite trends with the increase of biodiesel con-

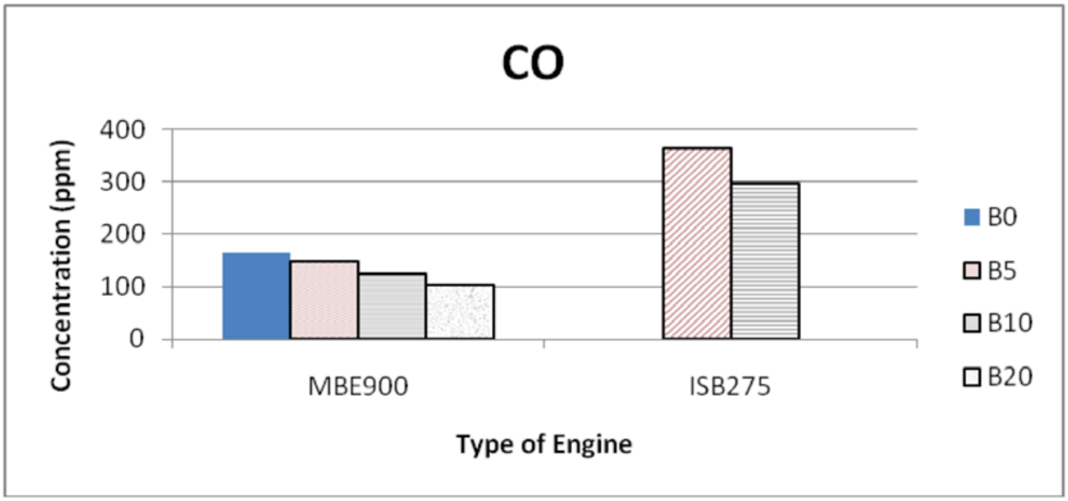

Fig. (3a). Biodiesel impacts on CO concentrations from different engines during on-road tests.

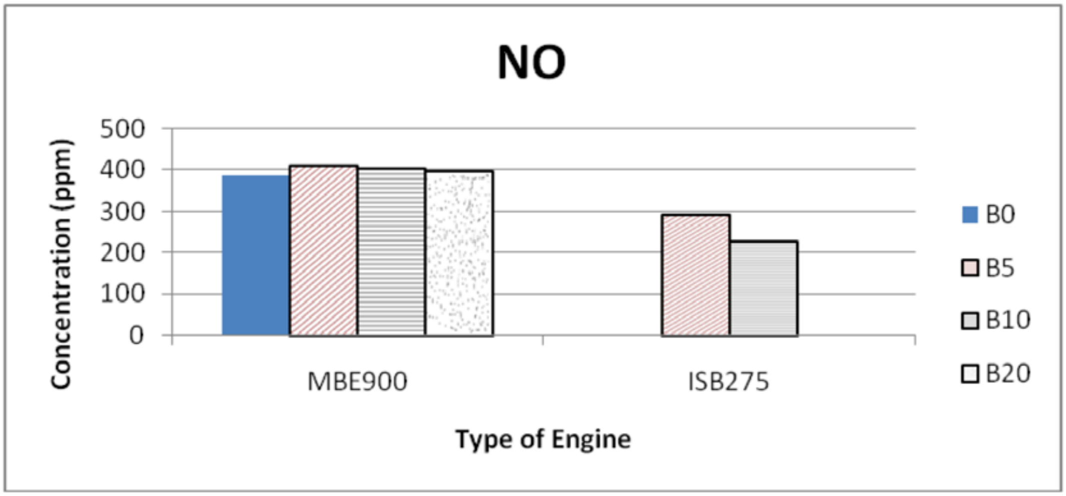

Fig. (3b). Biodiesel impacts on NO concentrations from different engines during on-road tests.

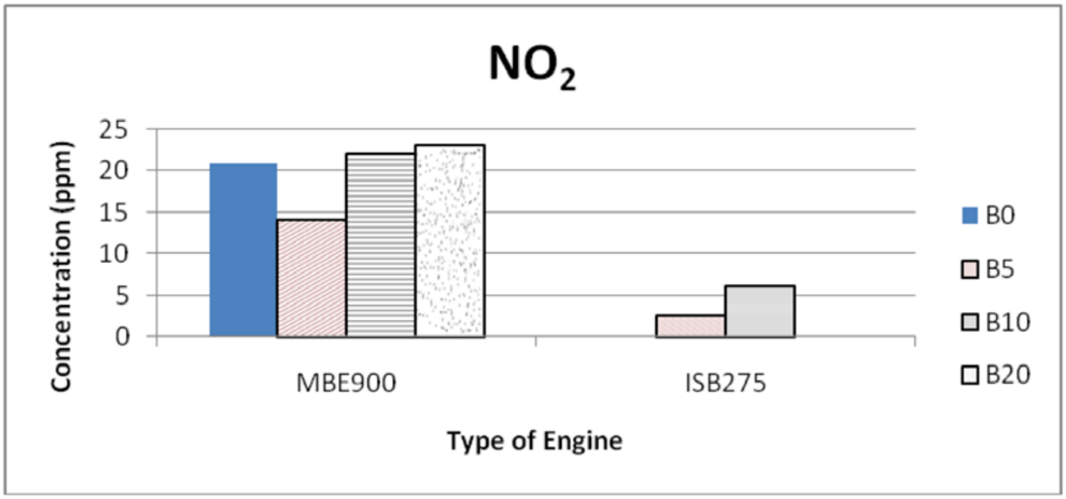

Fig. (3c). Biodiesel impacts on NO_2 concentrations from different engines during on-road tests.

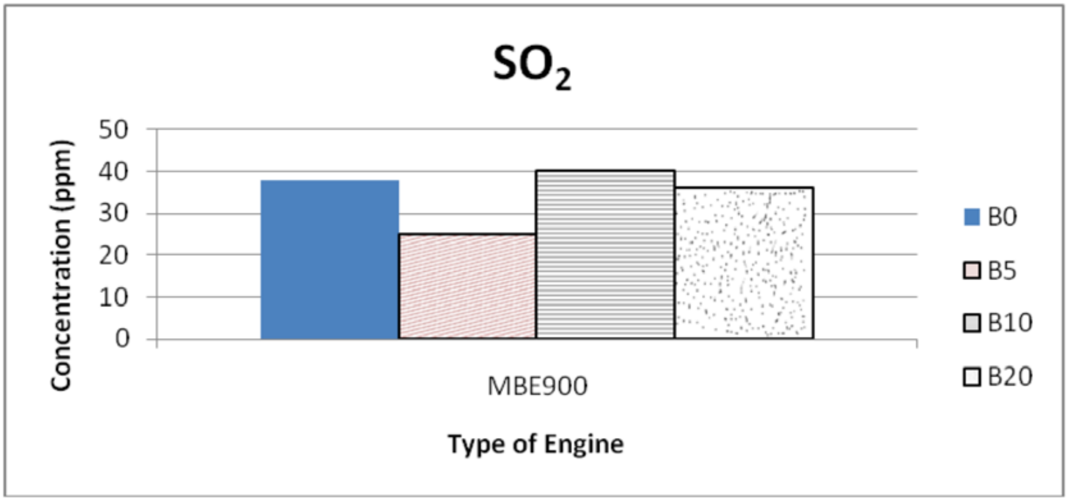

Fig. (3d). Biodiesel impacts on SO_2 concentrations from different engines during on-road tests.

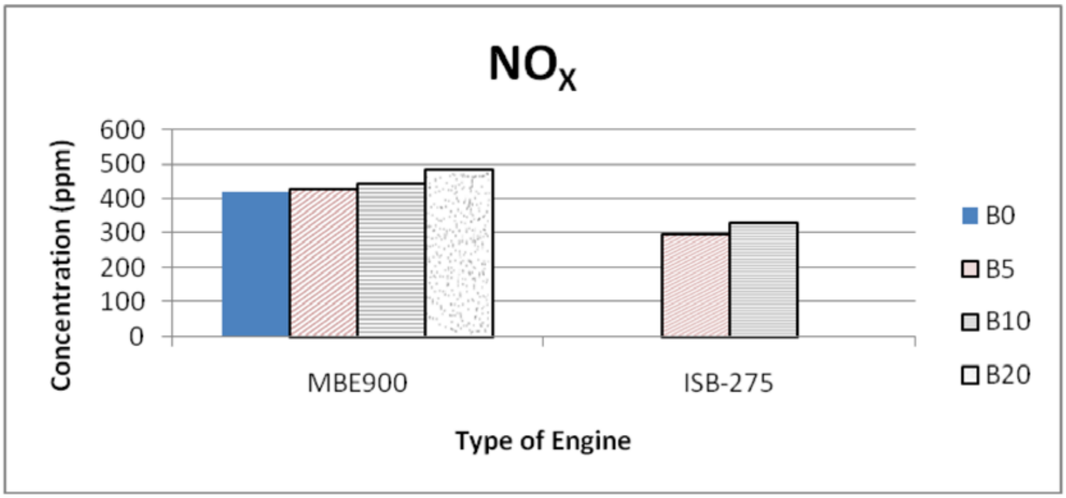

Fig. (3e). Biodiesel impacts on NO_X concentrations from different engines during on-road tests.

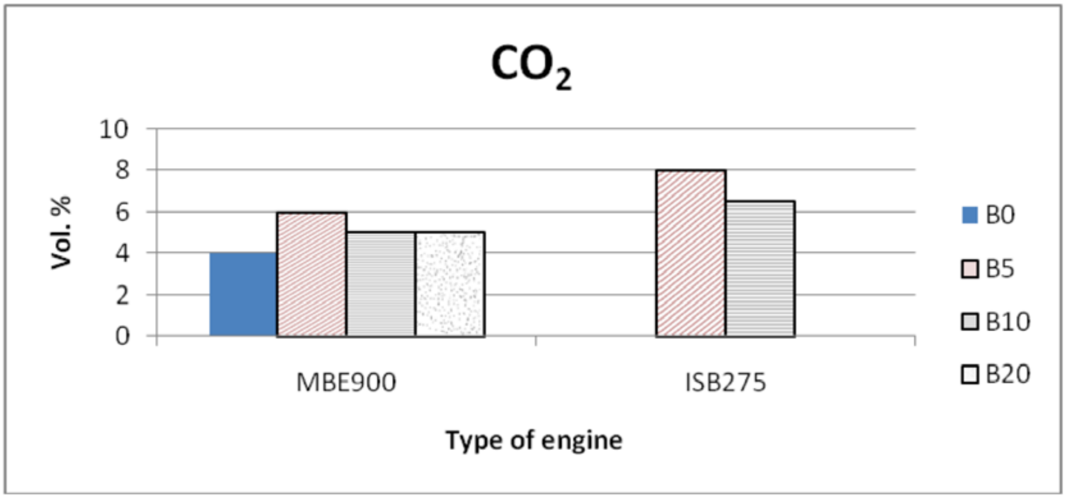

Fig. (3f). Biodiesel impacts on CO_2 concentrations from different engines during on-road tests.

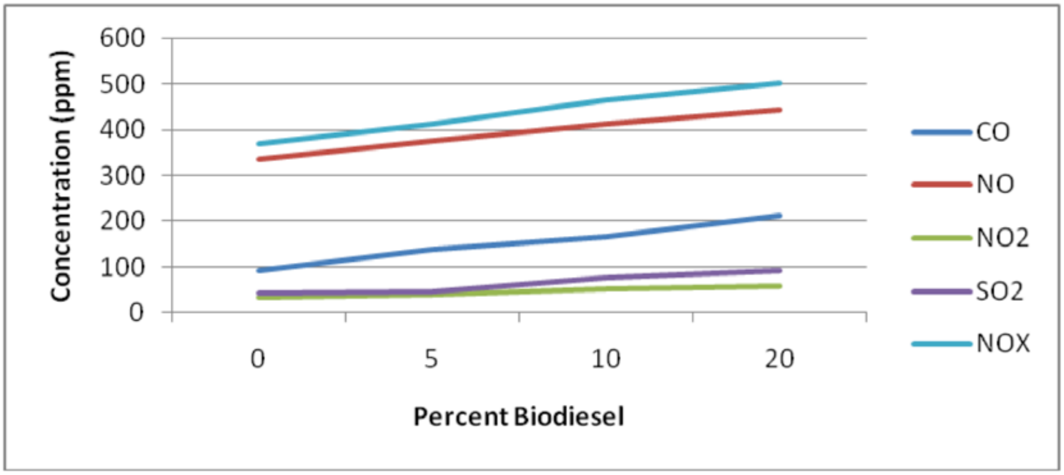

Fig. (4a). Effect of biodiesel on pollutant concentrations during idle-engine.

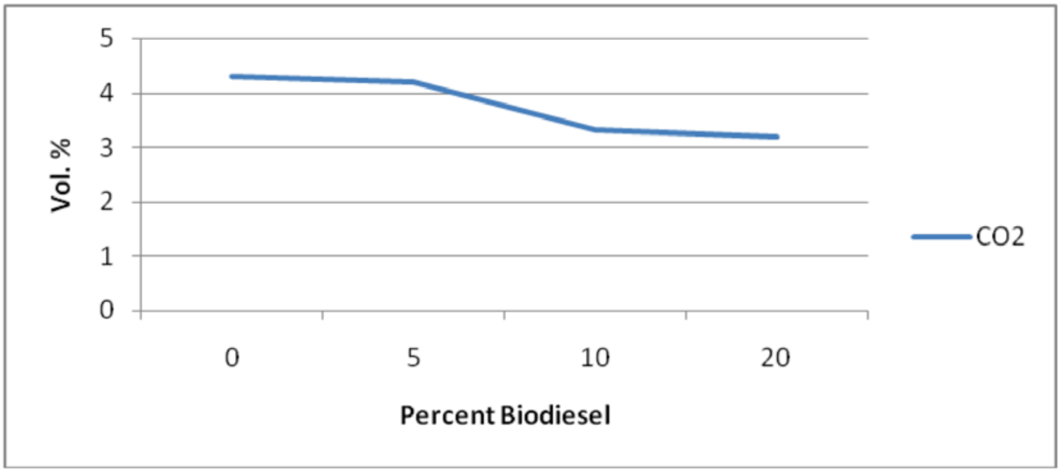

Fig. (4b). Effect of biodiesel on CO_2 concentrations during idle-engine.

centration in the base fuel. The concentrations of CO_2 reduced up to 11% from B0 to B20 for MBE, whereas the CO_2 concentrations increased up to 23% from B5 to B10 for ISB engines. A significant portion of the carbon in biodiesel is based upon biomass from soy beans, which in turn is based upon CO_2 taken by the soybean plant from the atmosphere. Therefore, if the life cycle of biodiesel was considered, net CO_2 emissions released from biodiesel fuel would be curtailed significantly. The percent change in CO_2 emissions with biodiesel blend is given below.

$$\%\ Change\ in\ CO_2\ emissions = \{exp^{[0.086208*BX]-1}\} * 100 \quad (3)$$

SO_2 is released from the combustion of fuels containing sulfur. The reduction of SO_2 was observed to be minimal as the sulfur content in both the fuels (ULSD and Biodiesel) is less than the diesel fuel. The emissions are found to be decreased by 5% from B0 to B20 for buses equipped with MBE engines. Pure biodiesel is free from sulfur, hence biodiesel blended buses are observed to produce lesser SO_2 emissions. The correlation equation for the percent change in CO_2 emissions is given below.

$$\%\ Change\ in\ SO_2\ emissions = \{exp^{[0.089059*BX]-1}\} * 100 \quad (4)$$

3. Idle-Engine Emission Characterization

a. Effect of Biodiesel Concentrations (B0, B5, B10, and B20)

This portion of study was conducted to evaluate the influence of biodiesel on exhaust pollutants when the bus is idle with the engine turned-on. The idle-engine emissions of MBE engine, fuelled with B0, B5, B10, and B20, are measured and analyzed. The emission variation of the monitored pollutants, with respect to the biodiesel concentration, are shown in Fig. (**4**).

All the monitored pollutants, expect CO_2, are observed to increase in proportion to the biodiesel concentration in the base fuel. The CO and SO_2 results are contradicting with the on-road emissions. For the same biodiesel blend, the emission concentrations of CO and SO_2 are observed to decrease for on-road testing and increase for idle-engine testing. Vijayan *et al.* [15] commented that for the same amount of time in operation, vehicles in idle mode produced higher pollutant concentrations than in on-road mode.

The reduction of CO_2 was proportional to the percent of biodiesel in the base fuel. Not much reduction of CO_2 was observed from B0 to B5 (2% redction). However, the reduction was significant from B5 to B10 (21%) and from B10 to B20 the reduction was only 4%. The emission concentrations of CO (128%) and SO_2 (121%) have increased drastically from B0 to B20.

From the above results, it is observed that idle-engine emission concentrations increase with the increase of percent of biodiesel in the base fuel. These observations show the significant impact of idle-engine emissions on the environment and the necessity to reduce idling time of the vehicles.

b. Effect of Engine Temperature

The two MBE buses are tested for 'cold-start' and 'hot-start' modes fuelled with B5, B10, and B20. The results show that the cold-start CO emissions, for B5 and B20 decreased upto 28% and 40%. The change for B10 was observed to be minimal. It was also observed that the remaining monitored pollutants, NO_x, SO_2, and CO_2, increased during cold-start for all the tested blends (see Fig. **5**). The NO_x emissions increased upto 44% for B5, 24% for B10, and 42% for B20. The SO_2 emissions increased up to 10% (B5), 12% (B10), 17% (B20), and the CO_2 emissions increased up to 28% (B5), 7% (B10), 42% (B20). These results show that, irrespective of biodiesel blend, the cold-start emissions of NO_x, SO_2, and CO_2 would be higher than the hot-start emissions, due to the initial warm-up phase of the engine, and the cold-start CO emissions would be less than the hot-start emissions.

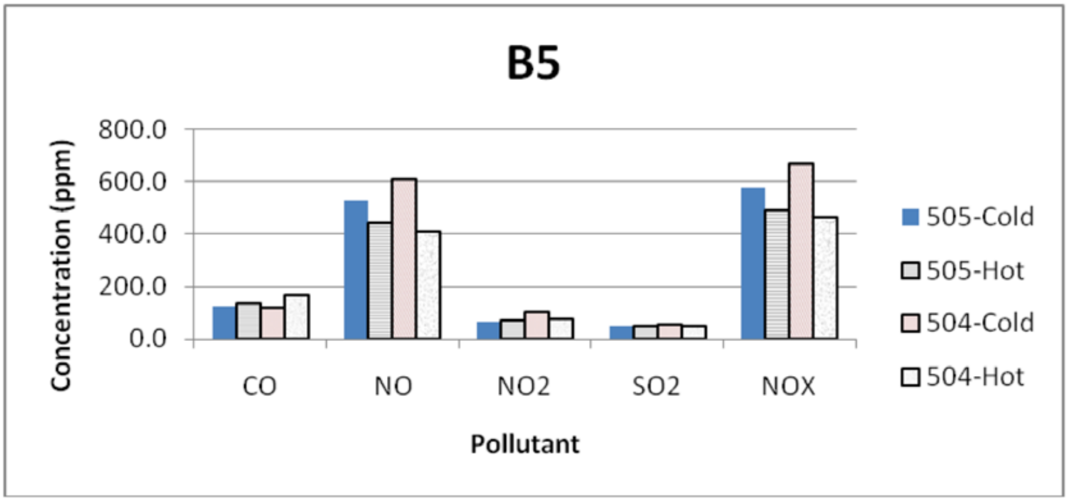

Fig. (5a). Effect of engine temperature on pollutant concentrations of B5.

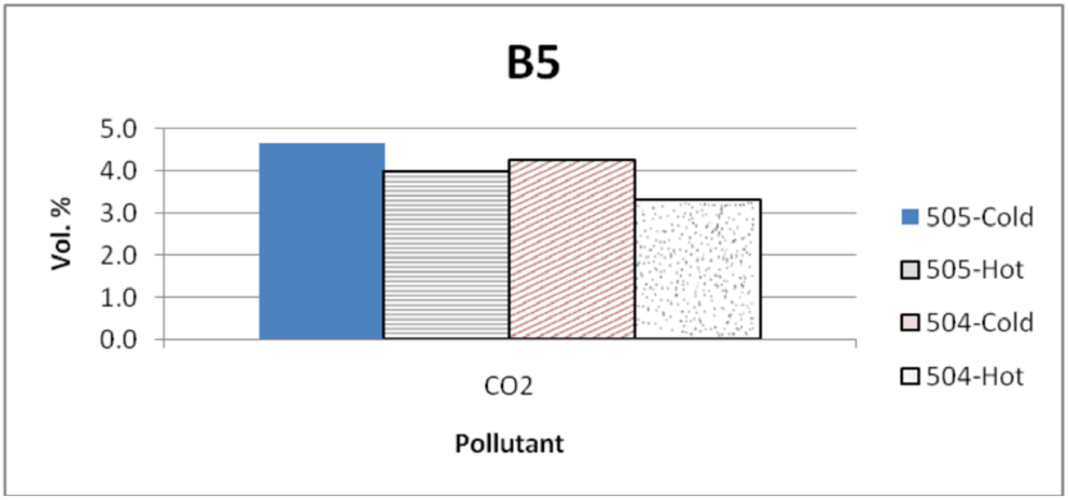

Fig. (5b). Effect of engine temperature on CO_2 concentrations of B5.

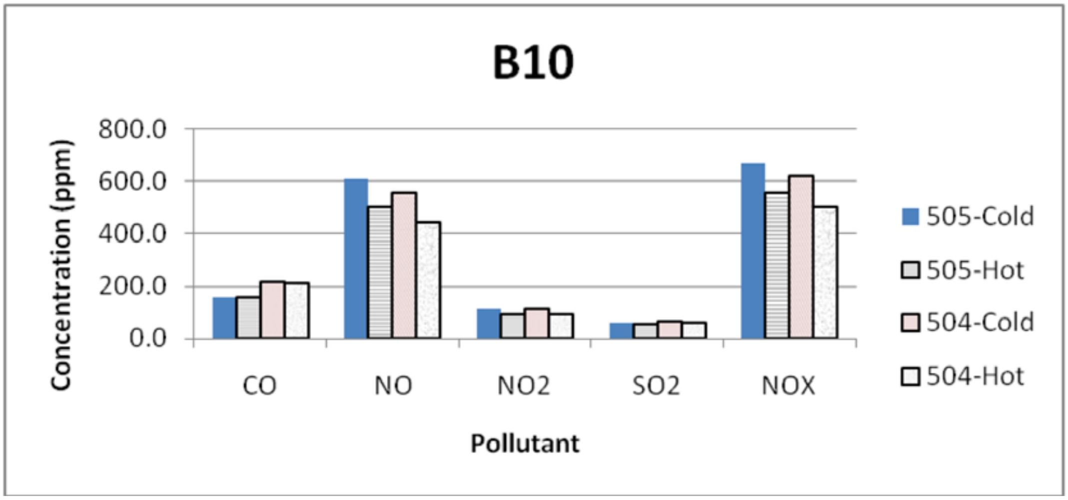

Fig. (5c). Effect of engine temperature on pollutant concentrations of B10.

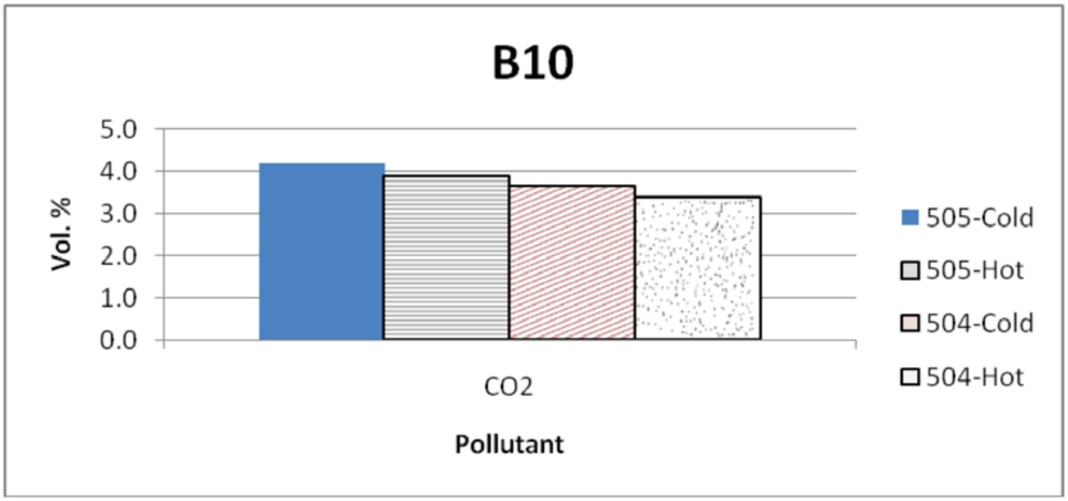

Fig. (5d). Effect of engine temperature on CO_2 concentrations of B10.

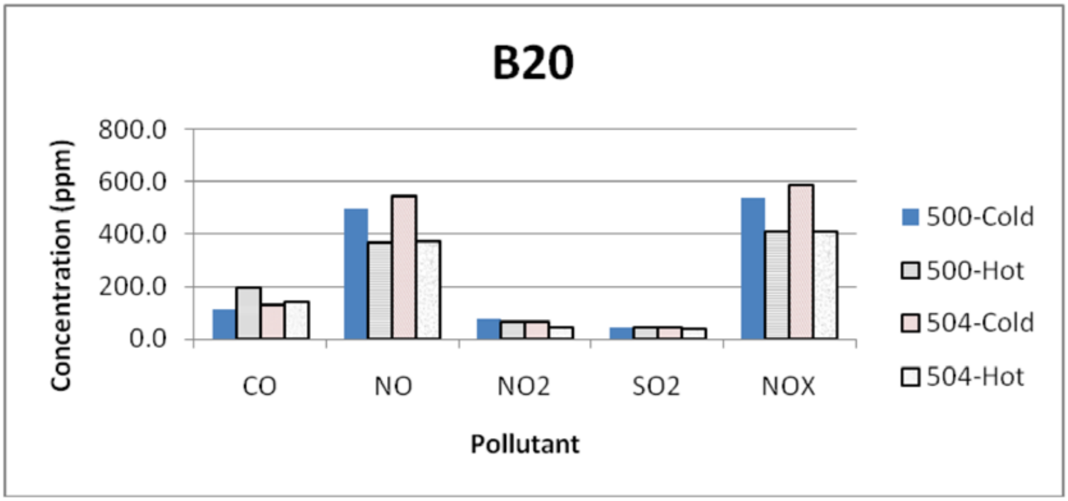

Fig. (5e). Effect of engine temperature on pollutant concentrations of B20.

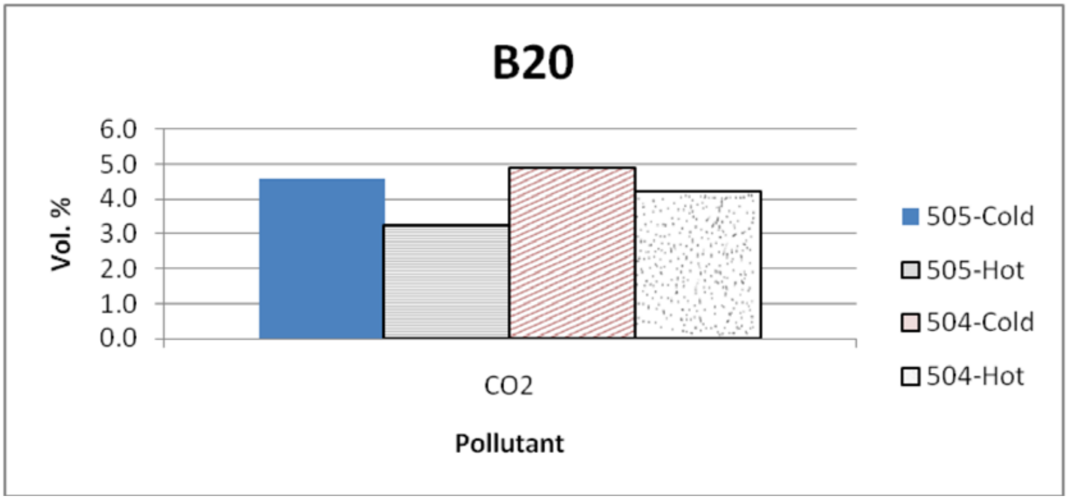

Fig. (5f). Effect of engine temperature on CO_2 concentrations of B20.

Table 3. Important Factors Affecting Pollutant Concentrations in the Exhaust of a B20 Bus During On-Road Testing

Contaminants	Positive Influential Factors	Negative Influential Factors
O_2	Output Torque and Acceleration	Vehicle Speed, Fuel Rate, Engine Load, and Ambient Temp.
CO	Ambient Temp., Engine Load, Exhaust Temp., and Vehicle Speed.	Acceleration and Engine speed.
NO	Ambient Temp., Engine Coolant Temp., Acceleration, and Fuel Rate.	Exhaust Temp., Engine Load, and Output Torque
SO_2	Fuel Rate, Acceleration, and Engine Speed.	Boost Pressure, vehicle Speed, Engine Coolant Temp., Exhaust Temp., Engine Load, and Ambient Temp.
NO_2	Engine Speed, Acceleration, and Fuel Rate	Boost Pressure, Vehicle Speed, Exhaust Temp., Engine Load, Engine Temp., and Ambient Temp.
NO_x	Fuel Rate, Boost Pressure, Acceleration, Engine Coolant Temp., and Ambient Temp.	Exhaust Temp. and Output Torque.
CO_2	Engine Coolant Temp., Fuel Rate, Engine Load, and Engine Speed.	Exhaust Temp. and Output Torque.

4. Influence of Various Engine Parameters

The data set contains various independent variables that influence the pollutant concentrations and it is important to identify the significant variables that can explain the emission behavior of the pollutants. The observations made in this section are from the results obtained using the best subset and multiple regression techniques of Minitab® software. The emission models developed assist in identifying the dependence of pollutant concentrations on different parameters such as engine load, engine speed, acceleration, etc. The regression models for each pollutant are developed for buses fuelled with B5, B10, and B20. The factors affecting pollutant concentrations are summarized in Tables **3**, **4**, and **5** in the order of their significance for the respective biodiesel blend. The positive influential factors tend to increase the pollutant concentrations where as the negative influential factors tend to decrease.

Using the best subset regression technique, the important variables that must be included for regression modeling are identified and the multiple regression technique helps in developing the model with the identified variables. The best model with significant variables effecting the pollutant concentrations are identified based on the higher R^2 and adjusted R^2 with Mallows coefficient close to or less than the number of predictors, and with lower standard deviation. R^2 explains the percentage of variation of the model and adjusted R^2 is the correction of R^2 that handles the overestimating nature of R^2.

a. Real-World On-Road Emission Models

Using the best subset regression and multiple regression analyses on-road instantaneous emission models are developed for pollutants from the exhaust of a bus (see Appendix-**A**). The development of emission models are restricted to B20 as the engine data for B5 and B10 were difficult to record due to the difficulty in maintaing the OBD connections on the day of test. These models help in identifying the on-road emission behavior of the public transport buses and the influence of each operating variable on pollutant concentrations. The R^2 and the adjusted R^2 explains the predictability of a model. The more R^2 and the adjusted R^2 the higher the predictability of a model. All the models showed a good predictability with R^2 and adjusted R^2

Table 4. Important Positive Influential Factors Affecting Pollutant Concentrations in the Exhaust of a B5, B10, and B20 Buses During Idle-Engine

	O_2	CO	NO	SO_2	NO_2	NO_X	CO_2
B5	Engine Speed, Engine Load, Engine Coolant Temp., and Exhaust Temp.	Engine Speed and Boost Pressure	Fuel Rate, Output Torque, and Boost Pressure	Fuel Rate, Output Torque, and Boost Pressure	Fuel Rate, Output Torque, Ambient Temp., and Boost Pressure	Fuel Rate, Output Torque, and Boost Pressure	Fuel Rate, Output Torque, Ambient Temp., and Boost Pressure
B10	Engine Speed, Engine Load, Exhaust Temp., and Boost Pressure.	Engine Speed, Exhaust Temp., Engine Load, and Boost pressure	Ambient Temp., Fuel Rate, and Output Torque.	Ambient Temp., Fuel Rate, and Output Torque.	Ambient Temp., Fuel Rate, Output Torque, and Exhaust Temp.	Ambient Temp., Fuel Rate, and Output Torque.	Ambient temp., Output Torque, Engine Coolant Temp., and Fuel Rate.
B20	Engine Load and Exhaust Temp.	Ambient Temp. and Output Torque.	Engine Speed, Ambient Temp., Fuel Rate, Output Torque, and Boost Pressure.	Engine Speed, Ambient Temp., Fuel Rate, Engine Coolant Temp., Boost Pressure, and Output Torque.	Output Torque, Engine Speed, Ambient Temp., Fuel Rate, Engine Coolant Temp., and Boost Pressure.	Engine Speed, Ambient Temp., Fuel Rate, Output Torque, and Boost Pressure.	Engine Speed, Ambient Temp., Fuel Rate, Engine Coolant Temp., Boost Pressure, and Output Torque.

Table 5. Important Negative Influential Factors Affecting Pollutant Concentrations in the Exhaust of a B5, B10, and B20 Buses During Idle-Engine

	O_2	CO	NO	SO_2	NO_2	NO_X	CO_2
B5	Boost Pressure, Output Torque, and Fuel Rate.	Engine Coolant Temp., Exhaust Temp., Output Torque, and Fuel rate.	Exhaust Temp., Engine Coolant Temp., Engine Load, and Engine Speed.	Exhaust Temp., Ambient Temp., Engine Coolant Temp., Engine Load, and Engine Speed.	Engine Speed, Engine Load, Engine Coolant Temp., and Exhaust Temp.	Exhaust Temp., Engine Coolant Temp., Engine Speed, and Engine Load.	Engine Speed, Engine Load, Engine Coolant Temp., and Exhaust Temp.
B10	Output Torque, Fuel Rate, and Ambient Temp.	Output Torque, Fuel Rate, Engine Coolant Temp., and Ambient Temp.	Boost pressure, Engine Coolant Temp., Exhaust Temp., Engine Load, and Engine Speed.	Boost Pressure, Exhaust Temp., Engine Coolant Temp., Engine Load, and Engine Speed.	Engine Speed, Engine Load, Engine Coolant Temp., and Boost Pressure.	Boost pressure, Engine Coolant Temp., Engine Load, and Engine Speed.	Boost Pressure, Engine Load, Exhaust Temp., and Engine Speed.
B20	Output Torque, Boost pressure, Engine Speed, Fuel Rate, and Ambient Temp.	Boost Pressure, Fuel Rate, and Engine Speed.	Exhaust Temp. and Engine Load.	Exhaust Temp. and Engine Load.	Exhaust Temp. and Engine Load.	Exhaust Temp. and Engine Load.	Exhaust Temp. and Engine Load.

between 81-98 and 62-95, except CO_2 with R^2 and adjusted R^2 of 71.3 and 59.8.

b. Idle-Engine Emission Models

Similar to the on-road emission modeling, the models for predicting the pollutant concentrations are developed for idle-engine conditions (cold-start and hot-start). The emission models are developed for B5, B10, and B20 (see Appendix-**A**). Tables **4** and **5** illustrate that the influence of the selected variables is different for each fuel in the developed models.

O_2 concentrations indicated a steady negative correlation with the fuel rate and a positive correlation with engine speed and engine load for all the fuels studied. The R^2 values for B5, B10, and B20 are 98.9, 97.6, and 98.4; while their adjusted R^2 values are 97.4, 94.3, and 96.8 respectively. The results showed that an increase in engine load and engine speed would always increase the O_2 concentrations.

CO concentrations showed a consistent positive correlation with the engine speed and a consistent negative correlation with output torque and fuel rate for all the tested fuels. The R^2 values for B5, B10, and B20 are 99.5, 99.0, and

95.1; while their adjusted R^2 values are 98.9, 96.9, and 92.4 respectively.

NO concentrations showed a consistent negative correlation with the exhaust temperature for all the selected fuels. The engine coolant temperature, engine speed, and engine load showed a negative correlation and the fuel rate showed a positive correlation for B5 and B10, but the effect of these variables on NO concentrations was different for B20 fuel. The R^2 values for B5, B10, and B20 are 99.3, 99.2, and 99.4; while their adjusted R^2 values are 98.2, 97.5, and 98.9 respectively.

SO_2 concentrations showed a consistent negative correlation with exhaust temperature and engine coolant temperature for all the fuels studied. For B5 and B10 fuels the engine speed and engine load showed a negative correlation and the fuel rate and output torque showed a positive correlation. The R^2 values for B5, B10, and B20 are 98.9, 99.3, and 98.4; while their adjusted R^2 values are 96.6, 97.8, and 96.3 respectively.

NO_2 concentrations showed a consistent negative correlation with engine load and a consistent positive correlation with fuel rate for all the tested fuels. Exhaust temperature, engine coolant temperature and engine speed showed a negative effect for B5 and B10, but did not effect the NO_2 concentrations of B20. The R^2 values for B5, B10, and B20 are 98.3, 99.1, and 98.1; while their adjusted R^2 values are 95.0, 97.9, and 91.3 respectively.

CO_2 concentrations indicated a positive correlation with ambient temperature and fuel rate and a negative correlation with exhaust temperature and engine load. It is important to observe that as the fuel rate increase the CO_2 concentrations increase, due to the incomplete combustion caused by fuel rate. Engine speed had a negative correlation and output torque had a positive correlation for B5 and B10. The R^2 values for B5, B10, and B20 are 98.7, 97.9, and 98.1; while their adjusted R^2 values are 96.1, 93.6, and 95.6 respectively.

The affecting variables on the emission concentrations are different for on-road and idle-engine emission models as shown in Tables **3** to **5**. Unlike the on-road emission models, all the idle-engine emission models for B5, B10, and B20 showed good predictive ability.

CONCLUSIONS

The experimental results showed that the on-road exhaust emissions decreased with the increase in biodiesel blend level for CO, SO_2, and CO_2 while the increase in NO_X was found. On the contrast, the idle-engine emissions showed a substantial increase in CO, SO_2, and NO_x with the increase in biodiesel blend level. This finding shows the importance of reducing the idling duration of vehicles on-road. The emission concentrations of cold-start NO_x, SO_2, and CO_2 are higher than hot-start because of the initial warm-up phase of the engine, irrespective of the biodiesel blend level. The multivariate statistical analysis (on-road and idle-engine) helped in identifying the important variables affecting pollutant concentrations from the exhaust of a biodiesel bus blended with B5, B10, and B20. This will assist the operators of biodiesel fleets in selecting the appropriate operating variables for emission control strategies in their area.

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Appendix-A

In the models presented below, A is the accelerator pedal position measured in %, FR is the fuel rate measured in gal/hr, T is the output torque measure in ft.lb, L is the percent engine load measured in %, ES is the engine speed measured in rpm, Ta is the ambient temperature measured in °F, Tf is the exhaust temperature measured in °F, S is the vehicle speed measured in mph, BP is the boost pressure measured in psi, and CT is the engine coolant temperature measured in °F.

On-road emission models for B20:

$$O_2\,(\%) = 69.8 + 0.123\,A - 2.95\,FR + 0.0816\,T - 0.261\,L - 0.167\,S - 0.629\,Ta \ldots (A1)$$

$$CO\,(ppm) = -11560 - 31.5\,A - 0.584\,ES + 38.1\,L + 22.6\,S + 1.23\,Tf + 136\,Ta \ldots (A2)$$

$$\begin{aligned} NO\,(ppm) = {} & -7478 + 20.0\,A + 9.78\,CT + 98.1\,FR - 3.97\,T - 9.59\,L - 0.504\,Tf \\ & + 79.3\,Ta \ldots (A3) \end{aligned}$$

$$\begin{aligned} SO_2\,(ppm) = {} & 2257 + 5.39\,A - 12.8\,BP - 1.27\,CT + 0.246\,ES + 30.0\,FR - 9.70\,L - 4.64\,S \\ & - 0.592\,Tf - 22.2\,Ta \ldots (A4) \end{aligned}$$

$$\begin{aligned} NO_2\,(ppm) = {} & 1718 + 1.90\,A - 6.91\,BP - 1.61\,CT + 0.141\,ES + 17.9\,FR - 4.49\,L - 2.28\,S \\ & - 0.349\,Tf - 16.1\,Ta \ldots (A5) \end{aligned}$$

$$\begin{aligned} NO_X\,(ppm) = {} & -6931 + 17.0\,A + 29.7\,BP + 8.22\,CT + 50\,FR - 5.07\,T - 0.633\,Tf \\ & + 75.9\,Ta \ldots (A6) \end{aligned}$$

$$CO_2\,(\%) = -7.0 + 0.0765\,CT + 2.66\,FR - 0.0817\,T + 0.182\,L + 0.0902\,S - 0.00921\,Tf \ldots (A7)$$

Idle emission models for B5:

$$O_2\ (\%) = -1505 + 0.0101\,Tf - 3.22\,BP + 0.0991\,CT + 1.49\,ES - 7.63\,FR + 0.722\,L - 0.0536\,T \ldots (A8)$$

$$CO\ (ppm) = -14181 - 0.411\,Tf + 30.0\,BP - 0.820\,CT + 14.6\,ES - 64.0\,FR - 0.546\,T \ldots (A9)$$

$$NO\ (ppm) = 181769 - 0.66\,Tf + 418\,BP - 15.1\,CT - 178\,ES + 738\,FR - 84.9\,L + 6.23\,T \ldots (A10)$$

$$SO_2\ (ppm) = 33978 - 0.115\,Tf - 0.63\,Ta + 84.6\,BP - 2.78\,CT - 33.1\,ES + 142\,FR - 18.1\,L + 1.32\,T \ldots (A11)$$

$$NO_2\ (ppm) = 21398 - 0.0547\,Tf + 0.54\,Ta + 44.1\,BP - 1.27\,CT - 21.0\,ES + 96.3\,FR - 11.7\,L + 0.933\,T \ldots (A12)$$

$$NO_X\ (ppm) = 201982 - 0.72\,Tf + 462\,BP - 16.4\,CT - 197\,ES + 836\,FR - 96.5\,L + 7.12\,T \ldots (A13)$$

$$CO_2\ (\%) = 1280 - 0.00865\,Tf + 0.057\,Ta + 3.02\,BP - 0.0884\,CT - 1.26\,ES + 6.63\,FR - 0.657\,L + 0.0486\,T \ldots (A14)$$

Idle emission models for B10:

$$O_2\ (\%) = -265 + 0.302\,ES - 5.89\,FR + 0.313\,L - 0.0311\,T + 4.86\,BP + 0.0758\,Tf - 0.434\,Ta \ldots (A15)$$

$$CO\ (ppm) = -2039 - 1.64\,CT + 3.51\,ES - 151\,FR + 7.84\,L - 1.61\,T + 131\,BP + 5.09\,Tf - 22.1\,Ta \ldots (A16)$$

$$NO\ (ppm) = 45490 - 2.87\,CT - 48.9\,ES + 1163\,FR - 56.9\,L + 4.62\,T - 1420\,BP - 9.4\,Tf + 81.5\,Ta \ldots (A17)$$

$$SO_2\ (ppm) = 8402 - 0.908\,CT - 9.08\,ES + 214\,FR - 10.8\,L + 0.687\,T - 261\,BP - 0.79\,Tf + 16.1\,Ta \ldots (A18)$$

$$NO_2\ (ppm) = 4200 - 0.454\,CT - 4.48\,ES + 98.2\,FR - 5.28\,L + 0.257\,T - 140\,BP + 0.16\,Tf + 6.89\,Ta \ldots (A19)$$

$$NO_X\ (ppm) = 44475 - 4.31\,CT - 48.2\,ES + 1123\,FR - 49.8\,L + 3.79\,T - 1533\,BP + 79.6\,Ta \ldots (A20)$$

$$CO_2(\%) = 261 + 0.00373\,CT - 0.276\,ES + 6.00\,FR - 0.300\,L + 0.0263\,T - 6.06\,BP - 0.0788\,Tf + 0.398\,Ta \ldots (A21)$$

Idle emission models for B20:

$$\mathrm{O_2\ (\%) = 77 - 1.12\,BP - 0.005\,ES - 12.8\,FR - 0.0096\,T + 0.295\,L + 0.00231\,Tf - 0.607\,Ta} \ldots \mathrm{(A22)}$$

$$\mathrm{CO\ (ppm) = 2208 - 26.8\,BP - 2.96\,ES - 35.7\,FR + 0.061\,T + 11.4\,Ta} \ldots \mathrm{(A23)}$$

$$\mathrm{NO\ (ppm) = -30931 + 72.0\,BP + 24.2\,ES + 1294\,FR + 1.34\,T - 20.1\,L - 0.524\,Tf + 74.7\,Ta} \ldots \mathrm{(A24)}$$

$$\mathrm{SO_2\ (ppm) = -8163 + 18.4\,BP + 0.397\,CT + 6.75\,ES + 229\,FR + 0.178\,T - 3.35\,L - 0.116\,Tf + 15.0\,Ta} \ldots \mathrm{(A25)}$$

$$\mathrm{NO_2\ (ppm) = -3704 + 10.5\,BP + 0.318\,CT + 3.13\,ES + 106\,FR + 0.022\,T - 1.78\,L - 0.0552\,Tf + 6.14\,Ta} \ldots \mathrm{(A26)}$$

$$\mathrm{NO_X\ (ppm) = -33319 + 84.8\,BP + 26.0\,ES + 1413\,FR + 1.32\,T - 23.1\,L - 0.552\,Tf + 82.0\,Ta} \ldots \mathrm{(A27)}$$

$$\mathrm{CO_2\ (\%) = -171 + 0.828\,BP + 0.0125\,CT + 0.124\,ES + 11.5\,FR + 0.00696\,T - 0.235\,L - 0.00307\,Tf + 0.513\,Ta} \ldots \mathrm{(A28)}$$

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