Evaluation of on road emissions from transit buses during revenue service

Douglas C. Lambert, Michal Vojtisek-Lom and P. Joshua Wilson
Clean Air Technologies Inc., 819 East Ferry St., Buffalo NY 14211, USA, tel. (716) 893-5800
e-mail: dlambert@cleanairt.com, michal@cleanairt.com, pjwilson@cleanairt.com

ABSTRACT

Eight transit buses were tested over a period of two weeks during regular service on revenue routes in Buffalo, NY using a portable emissions monitoring system. The series of buses tested included both stock buses and buses with rebuilt motors, retrofitted with Johnson Matthey CCT Cam Converter kits under the EPA's voluntary retrofit program. Second-by-second mass emissions data were successfully collected during scheduled bus runs with passengers on-board. Emissions were reported in grams per mile and preliminary results indicate significantly lower CO and PM associated with the rebuilt, retrofitted buses. The study provided insight into measurement methodology and data analysis techniques for in-use fleet vehicles. Experience from this project will inform the design of test plans for future studies.

INTRODUCTION

Diesel engines are a primary source of vehicle emitted particulate matter and nitrogen oxides. As a result, there has been considerable interest in reducing emissions originating from diesel internal combustion engines. Efforts aiming to reduce diesel emissions include stricter standards for new and newly rebuilt engines, mandated or voluntary engine retrofits, advanced exhaust aftertreatment devices, reformulated and low-sulfur diesel fuel and alternative fuels, or inspection and maintenance programs. As significant costs are often associated with these efforts, the impact of each strategy on emissions needs to be quantified.

Because diesel transit bus engines operate primarily in heavily populated areas, are in-use for comparatively large portion of the day, and are often controlled by government agencies, they have been an imporatant target for heavy-duty vehicle emissions reductions. The Urban Bus Retrofit Program, mandated by the Clean Air Act Amendments of 1990, required larger metropolitan transit authorities to use certified emissions reduction technologies as part of all standard engine overhaul procedures. Today, voluntary programs paired with regional emissions credits continue to encourage reduction of emissions in transit bus fleets.

Due to the large amount of resources being invested in emissions reductions technologies, verification of the effectiveness of competing technologies, and more generally, accurate quantification of bus fleet emissions is important. Currently, heavy-duty vehicle emissions testing consists primarily of engine dynamometer tests of new engines, and of a limited amount of testing of in-use vehicles on chassis dynamometers. At the same time, emissions are known to vary among even otherwise identical vehicles, over the vehicle lifetime, and as a result of varying environmental and operating conditions [1,2]. Transit bus operation, with operating parameters involving complex interactions with traffic and passengers, poses especially daunting challenges for understanding emissions from laboratory testing under simulated conditions.

To address the need for emissions testing of a relatively large number of vehicles under a variety of operating conditions, during the real-world, everyday operation of the vehicle, portable, on-board vehicle exhaust emissions monitoring systems have been developed [3-7]. Previous studies conducted at the University of Pittsburgh demonstrate that portable, on-board systems can be designed, installed and operated on commuter vanpool vans and shuttle buses during their regular revenue service with passengers on board, without a significant interference to the vehicle operation or a safety hazard [8].

In this study, a simlar approach – using portable, on-board emissions monitoring system to test emissions on a relatively large number of vehicles in their regular revenue service – was demonstrated on a fleet of Niagara Frontier Transit Authority urban transit buses operating in Buffalo, NY region. The goal of the study was to develop in-service test methods and to determine the feasibility of in-service testing for transit buses. A secondary goal was to assess the effectiveness of a Johnson-Matthey Cam Converter Technology emissions reduction retrofit kit.

EXPERIMENTAL

Buses

The Niagara Frontier Transportation Authority (NFTA) transit bus fleet services the Buffalo / Niagara Falls region, with a ridership of 22.3 million in 2000. Eight buses of similar age, use and maintenance history were selected for this study. All buses were 1992 Motor Coach Industries transit buses with, with 267-336,000 miles. All buses were equipped with 1992 Detroit Diesel 6V92TA 2-cycle diesel engines with DDEC II electronic control systems, 4-speed Allison automatic transmissions, and were based since their purchase at the Cold Springs garage and randomly assigned to various routes. None of the buses were operated with air conditioning. The buses were intermediate in age and typical of the buses used in the fleet. On four of the buses, the engine had been rebuilt and retrofitted with a Johnson-Matthey Cam Converter Technology (CCT) upgrade kit as part of the EPA's Urban Bus Program. The remaining four buses received no rebuild or retrofit.

The CCT upgrade kit consists of modified cam shafts, a catalytic exhaust muffler, and emissions-related engine rebuild parts and engine settings, partly designed to retard injection timing. The kit is certified specifically for this model engine and is certified to reduce emissions of particulate matter by 33%, carbon monoxide by 40% and hydrocarbon by 50%, and no reduction claims are made regarding nitroxogen oxide emissions. The kits are warrantied for 150,000 miles.

All eight buses were tested in July 2001. Data from three buses, however, was deemed insufficient to warrant further analysis: On two buses, this was due to operator errors and equipment malfunction, primarily due to the temperatures inside of the bus exceeding 100F. On one bus, this was due to a fuel leak discovered during the testing. Only data from the five remaining buses will be therefore discussed. For each of the five buses, the bus number, mileage, and where applicable, the date of and mileage since the rebuilt are listed in Table 1.

Table 1. Mileages and rebuild dates of buses tested

Bus #	Mileage(k)	Date of Rebuild	Mileage since Rebuild (k)
401	280	N/A	N/A
409	281	N/A	N/A
412	267	N/A	N/A
403	336	5/2000	29
413	287	6/2000	33

Instrumentation

A portable on-board vehicle mass exhaust emissions monitoring system manufactured by Clean Air Technologies International [6] was used to measure the mass emissions of CO, CO_2, NO_x and PM, and to collect vehicle and engine operating parameters. The system was installed under a seat in the rear of the bus and powered from the bus electrical system. The system samples undiluted, raw exhaust from the tailpipe using a sample probe clamped to the tailpipe, and a 1/4" diameter sample line attached to the vehicle by clamps and duct tape. Concentrations were measured on a second-by-basis, with CO and CO_2 measured using NDIR, and NO_x and PM were measured by electrochemical cell and laser light scattering, respectively. Exhaust flow is determined computationally on a second-by-second basis from the engine operating data obtained through the engine control unit diagnostic port, and from the known exhaust gas and fuel composition. Mass emissions rates in grams of pollutants per second are then calculated from the concentration and flow data. Additionally, the unit included an internal global positioning system for recording vehicle location and speed.

The system was installed in the rear of the bus, with the main unit being strapped to a seat and the separate PM unit sitting under the same seat. A sample probe was inserted into the exhaust pipe, and sample lines were routed through a rear window to the instruments. The engine control module was accessed from a port under the dashboard at the front of the bus, and its cable taped under seats and routed to the instruments at the rear of the bus. The instruments were run entirely on vehicle power which was accessed from the vehicle power control panel at the rear of the bus, with power being taken either from 12 VDC or 24 VDC terminals. When 24 VDC power was used, a power converter was incorporated to supply 12 VDC power to the instruments (see discussion). The GPS antenna was routed out a bus window and taped to the vehicle roof. Analyzed exhaust gases were also exported out the same window.

Before in-use testing began, the system was installed on a bus and presented to the NFTA operations manager and technical staff to allow for input regarding safety or operation concerns. They expressed concern that no batteries, pressurized gases, open flames, or explosive materials would be present, and that no exhaust discharges would happen inside of the bus. None of these concerns were relevant to the installed equipment, and the NFTA personel requested no modification to the installation as it was originally presented. It is noted, though, that when it was suggested that power might need to be accessed directly from the vehicle battery under the side of the bus and routed into the vehicle through a window, the NFTA personel felt that this would be a safety concern. This may be an issue in future in-use testing on vehicles that do not provide power access inside the vehicles. Fortunately, this series of bus had easily accessed power terminals inside the bus.

Routes, drivers and testing

NFTA route no. 12 was chosen as it was convenient, offered multiple repetitions of the same route in the same day, and was typical of other routes in Buffalo. This route involved about six back and forth cycles in a single day of testing. The route is an east west route entirely within the city of Buffalo, and on level terrain. It serves as a feeder from urban residential neighborhoods to a central north-south subway located approximately mid-way in the route.

A single bus was tested each day on the bus route using two drivers. This is not typical operation for a bus in this fleet, as usually buses switch between routes randomly several times a day as drivers take breaks or switch shifts. Most of the testing was done with two drivers, one in the morning and one in the afternoon. The drivers had been assigned to the route previously and were familiar with the route. Their assignment to our project was random and based only on their previous scheduling.

One day prior to the testing, agreement was made as to which bus would be tested the following day. On the day of the testing, the monitoring equipment was intalled on the bus in the garage parking lot. Testing took place during the day, starting in the morning and ending as the day shift ended for the bus depot. At the end of the day, the equipment was removed during a driver change, and the bus resumed its normal service. Typical installation and removal times were 15-20 and 5-10 minutes, respectively.

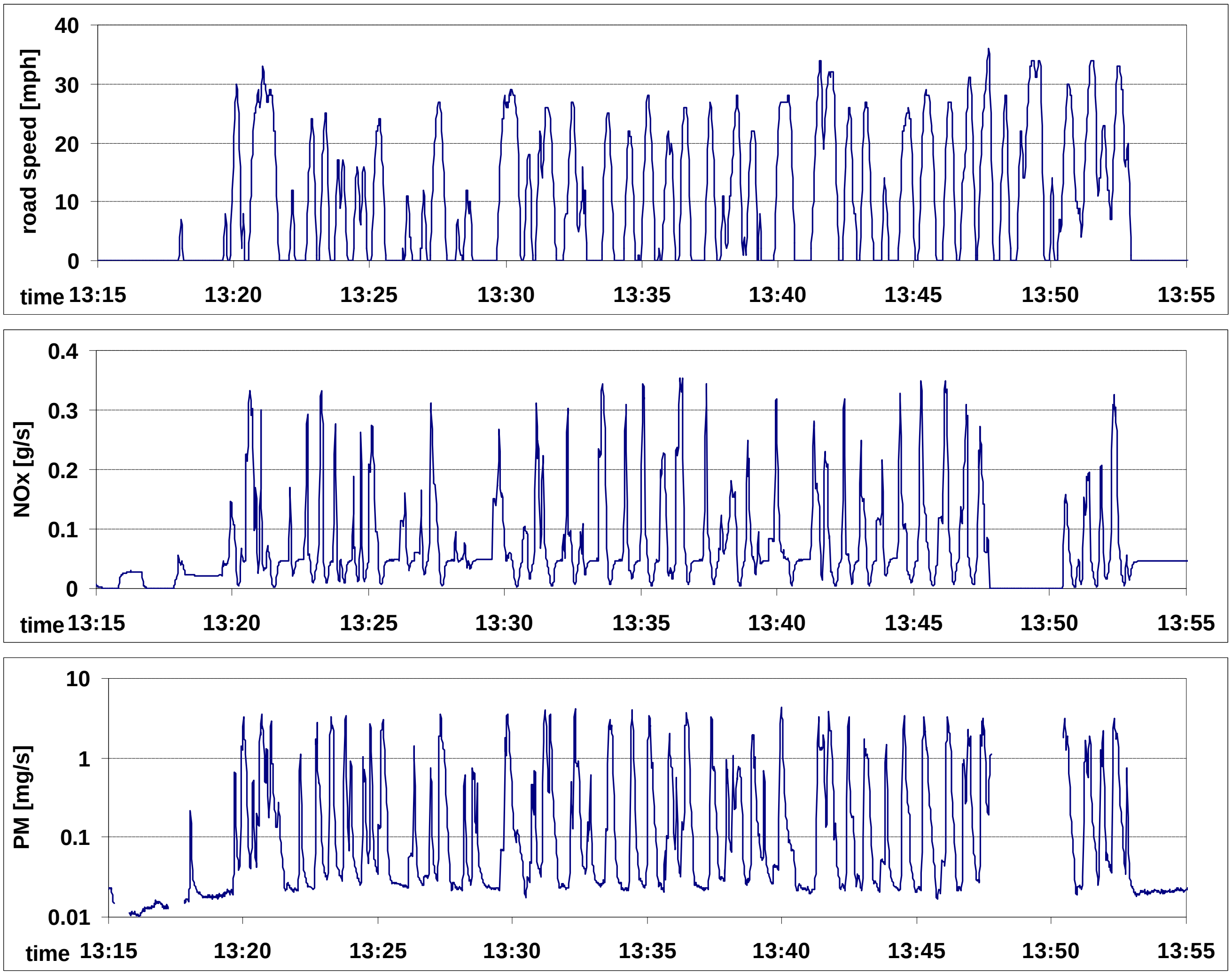
RESULTS

Over the course of eight test days, approximately 35 hours of test data was collected. During that time, no complaints, accidents, unsafe or potentially unsafe conditions were reported. Both the drivers and the passengers were cooperative, occassionally showing interest in the equipment. An example of road speed and emissions data is shown in Figure 1.

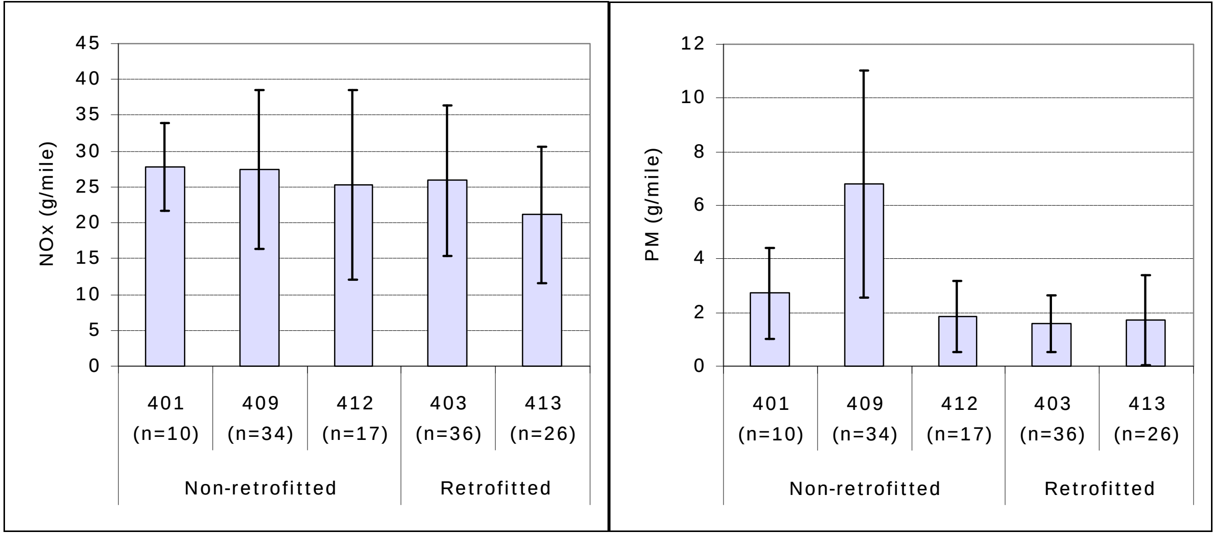
The raw test data included driver rest periods during which the engine was shut off, and time during which the data was incomplete due to periodic (every 30 minutes) gas analyzer zero calibration, or due to miscellaneous operator and equipment malfunctions, which are addressed in detail in the discussion section. Using the GPS position data, several segments of the route were defined, and total emissions calculated for each segment for which complete and valid data was available for the entire length of the segment. A total of 9.6 hours of segmented data was used for the further analysis.

A high degree of variability was observed in all of the tests. Figures 2 through 5 respectively show NO_x, PM, CO and CO_2 emissions per mile for each bus. Two standard deviations are shown by error bars. These charts show the average of all the segments tested, weighted by segment. Two of the non-retrofitted buses appear to have substantially higher PM and CO emissions relative to the other buses. No major differences in NO_x and CO_2 emissions among the buses were observed.

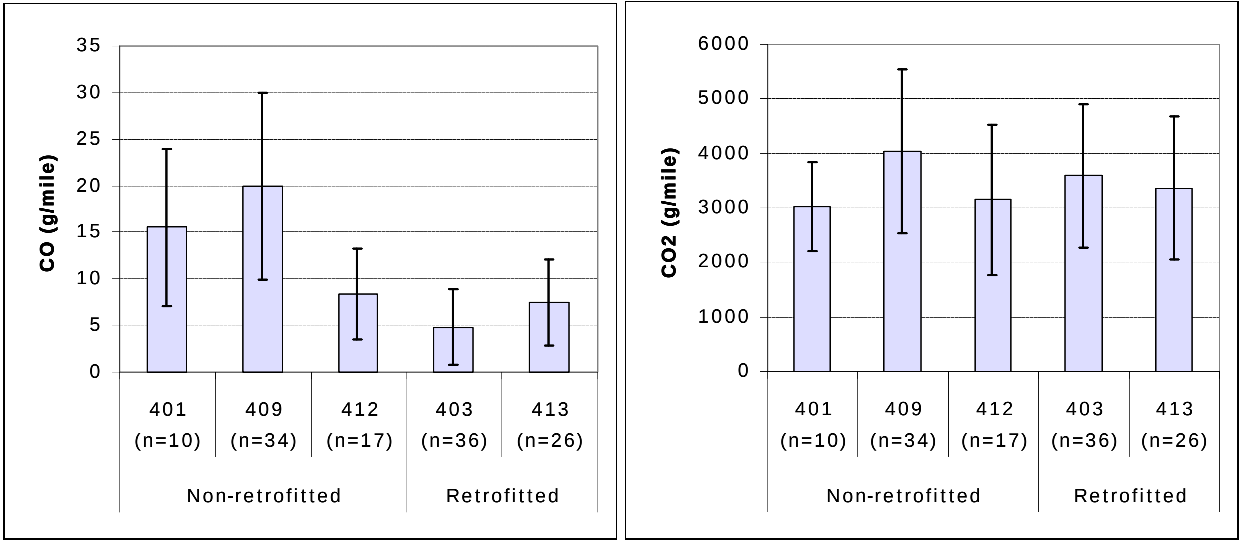
Figure 1. Example data: Road speed, NO_x and PM emissions during an early afternoon run of the route 12 with bus no. 403.



Figures 2 and 3. Average NO_x and PM emissions in grams per mile for all segments. Bars indicate 2 standard deviations, 'n' indicates sample size.

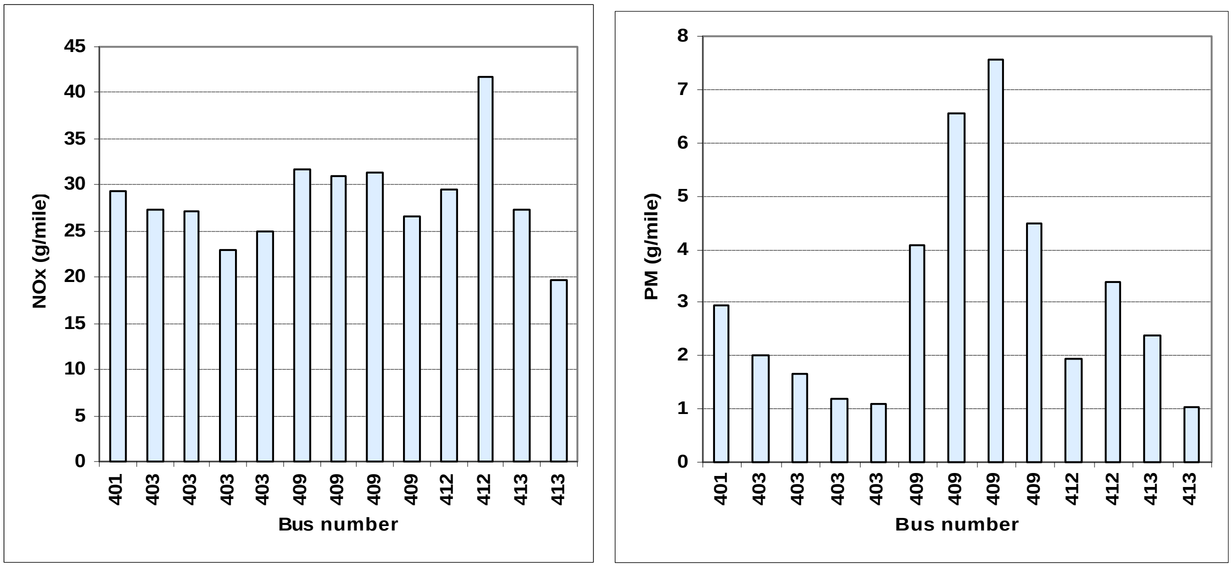


Figures 4 and 5. Average CO and CO_2 emissions in grams per mile for all segments. Bars indicate 2 standard deviations, 'n' indicates sample size.



The high observed variability for individual buses did not apear to depend on systematic factors measured in the study. Figures 6 and 7 show NO_x and PM emissions for every run of a single segment. In this case we see that even within a single segment there is a high degree of variability. As expected, some amount variance is due to the differences amoung individual buses, but relatively large variances are observed even within a single segment for the same bus.

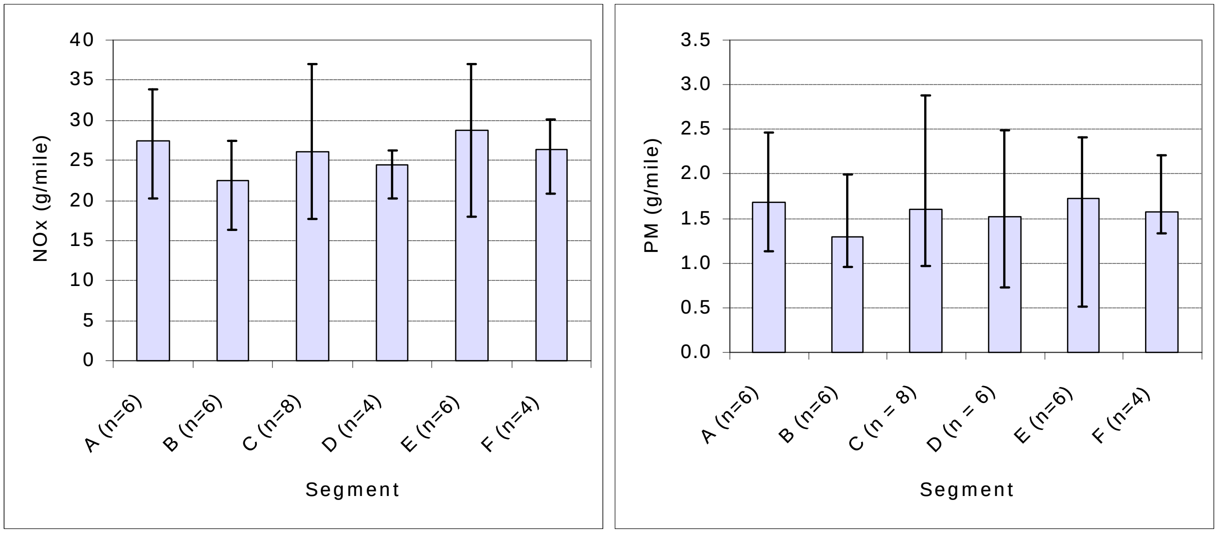
Figures 6 and 7. NOx and PM per mile for individual runs on a single segment (Segment A).



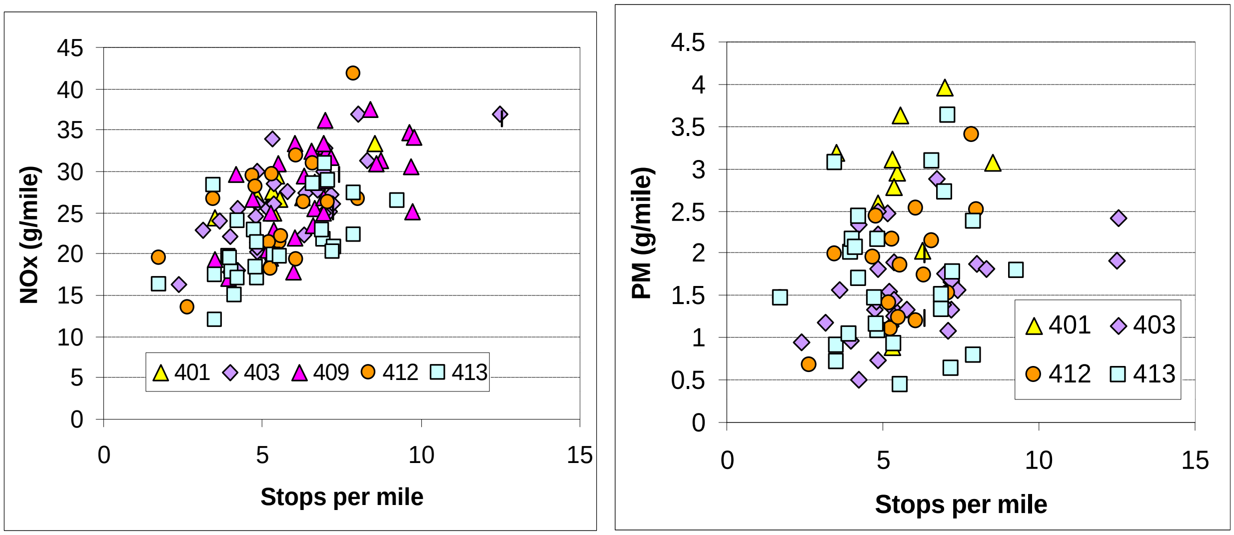
Variances in emissions for a single bus are shown in Figures 8 and 9 in order to demonstrate that the different segments do not appear to be the cause of the variability observed.

Figures 10 through 13 show NO_x and PM plotted against stops per mile and average speed. For NO_x there is clearly a dependence on number of stops and average speed. Bus 409 with relatively high PM emissions is omitted from the PM charts in order to show the other buses in better detail.

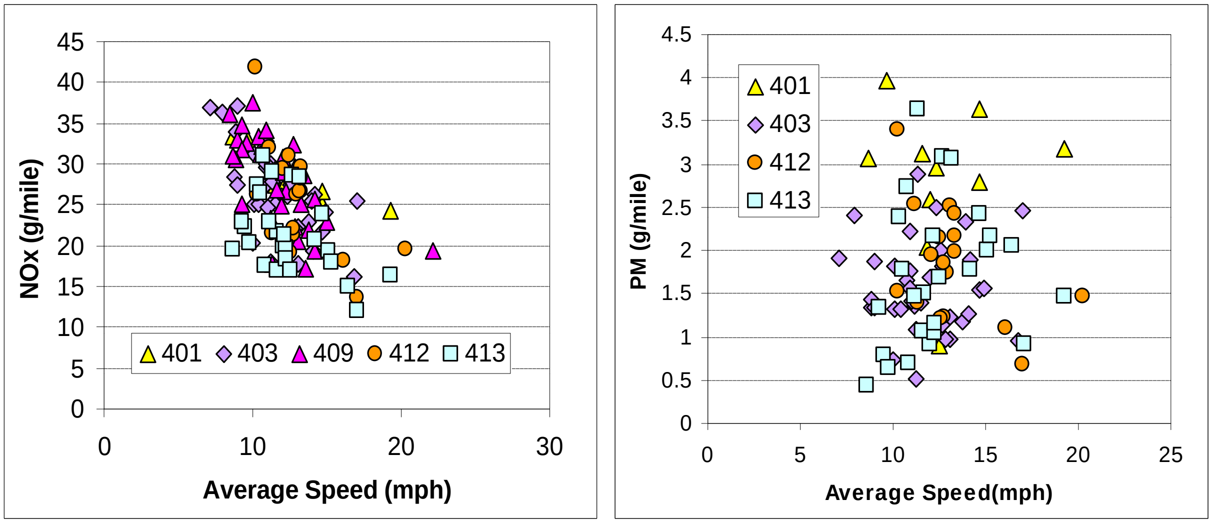
Figures 8 and 9. NO_x and PM in grams per mile by segment for Bus 403. Bars indicate the range of results.



Figures 10 and 11. NO_x and PM per mile versus stops per mile.



Figures 12 and 13. NO_x and PM per mile versus average speed.



DISCUSSION

Testing generally proceeded smoothly and allowed for the collection a significant amount of in-use emissions data with very little overall expense or interference to the fleet or to the bus operator. The bus was removed from service for approximately 30 minutes (for the installation and removal of the test equipment), but this was conducted during regularly scheduled stops, and did not interfere with the bus operation. The presence of the equipment and test technician reduced the bus carrying capacity by 2-3 passengers, which was deemed acceptable. The overall experience with the test equipment and methodology was positive.

Difficulties were limited to the loss of data caused by operator error, equipment malfunction, and general lack of experience with the bus fleet operation and the specific requirements of the project. The equipment malfunctions were attributed to several principal factors: (a) installation of the equipment on a bus without air conditioning, on a hot summer day, near the engine, with ambient temperatures at the equipment location exceeding 100° F, resulting in equipment overheating; (b) use of 12 VDC electrical circuit to power the equipment - on several buses, the actual voltage available fell below 11.5 VDC, instead of customary 13.5-14 VDC, (c) software failures attributed to newly developed engine control unit interface. As of the writing of this paper, these problems were resolved by actively cooling the instruments, by using 24 VDC circuit and a 24 VDC-to-12 VDC converter to power the system, and by fine-tuning the software. The monitoring system has been also automated to provide continuous measurements, without interruptions for gas analyzer zero or span calibrations. In a recent study, instruments routinely conducted eight-hour tests without interruption [9].

The two dominant observations that can be made from this study are that it is very practical and efficient to measure emissions of buses while in-service, and that the emissions from buses while on the road, and in-service have a large amount of variability. The source of this variability extend beyond differences between buses and routes, as will be described here.

Variability was large throughout the data. Some of this variability can be attributed to differences between individual buses, as can be seen in Figures 2 though 5. In particular, unrebuilt and unretrofitted buses 401 and 409 have levels of PM and CO emissions that are substantially higher than those of the other buses, including the third unretrofitted bus, 412. Generally, though, differences among buses are difficult to quantify because of the variability within the measurements for each bus.
For a given vehicle, emissions are known to vary by test route. The segments defined in this study were relatively similar to each other: All of the segments were flat and traveled through similar urban residential neighborhoods with similar traffic and bus stop patterns. Operation typically involved acceleration from stop to 20 to 35 mph, followed by a very short cruise at constant speed, followed by deceleration to stop, as shown in Figure 1. Figures 8 and 9 show that for bus 403 the differences in emissions among the segments were comparable to the differences in multiple measurements within each segment; thus, no difference attributable to the test segment is apparent. This observation was typical for all of the buses tested.

The frequency of accelerations possibly had a significant effect on the emissions differences within segments. This can be seen in figures 10 and 12 for NO_x. Figure 10 shows that increasing the number of stops per mile correlates with an increase in NO_x emissions. Figure 12 shows that with increasing average speed for a segment there is a correlation with decreasing NO_x. Both of these effects were also observed for CO_2 emissions, and hence for fuel consumption. In fact, NO_x and fuel consumption patterns are closely correlated, and when NO_x was expressed in grams per gallon of fuel consumed rather than grams per mile, no correlation between stops or average speed and NO_x was evident and the grams per gallon of fuel NO_x emissions were relatively consistent between vehicles. The correlation between gram per mile NO_x or CO_2 and stops and average speed is not surprising as it would be expected that a higher number of stops in a segment and lower average speed (which is to some extent correlated with the number of stops in city environment) would require more power output from the engine therefore more fuel consumption and emissions. Correspondingly, if the vehicle has a higher average speed, it is likely to have less acceleration events and to spend more time in low emissions, low fuel consumption cruise mode.

On the other hand, there is no apparent correlation between PM and either stop density or average speed, as shown in Figures 11 and 13, respectively. This observation is inconsistent both with the popular belief that PM emissions are high during transient and high load operation, as well as with the strong correlation of high PM levels and accelerations apparent from the visual observation of the second-by-second data (see Figure 1).

One possible explanation is that there are other factors influencing the PM emissions. Recently, this research team confirmed that vehicle history can have a significant impact on diesel PM emissions, as well as on gaseous emissions from vehicles equipped with catalytic converters. For example, prolonged idling was found to cause significantly elevated PM emissions levels during subsequent operation [9]. On Bus 409, the PM emissions were high in the morning, and followed a decreasing trend throughout the day. A similar pattern, though less pronounced, was observed on three other buses, but not on the one remaining bus. While the equipment was installed on each bus before it has been driven that day, the operation of the bus in the later part of the previous day (including any extended idling at the garage) was not controlled or recorded, and could have had the influence on PM "drift" during the test.

Another possible argument is that on-road testing using a portable on-board system cannot yield consistent, repeatable results. In a recent study using similar instrumentation and vehicles, much smaller test-to-test variances (generally less than 5% for NO_x and CO_2) were observed when a vehicle was driven on a test track using a chassis dynamometer driving cycle [11]. It is concluded that the high variability within each bus is caused by a combination of not well understood or quantified factors encountered in the real world. Aside from the factors specific to the vehicle, these factors include individual driving style of each driver, ambient conditions, traffic conditions, passenger load, frequency and duration of stops, both current and in the recent past. As the effects of these and other factors are compounded together, real-world driving is likely to remain difficult to quantify or reproduce, and subject to high variability.

While the variability between test vehicles can be reduced by operating the vehicle under more controlled conditions (such as on a chassis dynamometer or on a test track), doing so raises concerns about choosing the conditions which are not representative of actual vehicle operation. For example, Niemeier reports that for light duty vehicles, discrepancies between standard laboratory drive cycles and drive cycles specifically designed to simulate a specific region's unique traffic patterns can have a large effect on measures emissions [12]. Reducing the variability by narrowing the range of the vehicle operating conditions may thus not be desirable if real world emissions are to be determined.

The vehicle-to-vehicle variability also remains one of the key factors. The widely circulated understanding that a relatively small portion of the vehicles can be responsible for a disproportionately large portion of the total fleet emissions was confirmed in this study for CO and PM emissions, where one bus was found to have much higher emissions than the four others.

Another often-raised question is how the on-road emissions data would compare to laboratory measurements. The emissions results from this study were compared to a relatively extensive set of emissions data from comparable buses (1992 model with a 6V92TA engine and a 4-speed automatic transmission) tested on a chassis dynamometer [10]. CO, CO_2 and NO_x emissions measured during this study fell well within the ranges observed during chassis dynamometer testing using a CBD driving cycle, which follows a somewhat similar pattern to the actual driving observed in this study. (CBD cycle is approximately a 2-mile, 10-minute driving cycle consisting of 14 accelerations from stop to 20 mph, and subsequent cruise at 20 mph.) PM emissions observed in this study were somewhat higher than those observed on the chassis dynamometer (significant variances in data prevent a meaningful statistical comparison; visual observation suggests 50-100% higher). It should be noted that the chassis dynamometer tests were conducted on lower mileage buses. These tests took place up to 1997, meaning that the buses tested were no more than five years old, compared to the uniform age of nine years of the buses tested in this study.

As this is, to the author's best knowledge, the first study to attempt to measure emissions of a transit bus in-service, some discussion is necessary as to the merits of this methodology. In-service testing is much less expensive than laboratory testing, keeping the vehicle in it regular revenue operation, and avoiding the cost of transport to the laboratory. This allows for a much larger sample of vehicles to be tested. In-service testing also allows for measurement of emissions on the actual routes for which the bus would typically be employed, avoiding errors associated with simulating actual operation of a vehicle in a laboratory. It is likely that transit bus operation, with its inherently complex set interactions with passengers (HVAC, doors, lifts, varying loads, etc.), would create additional challenges for laboratory simulation. Some of the variability added by testing in-service is mitigated by the error eliminated by testing on the actual routes for which the bus is operated on.

At the minimum, in-service testing of transit buses should be employed to determine the representativeness of laboratory testing to real world vehicle operation. In addition to determining the impact of various emission reduction strategies, driving cycles are used in laboratories to create mobile emission factors, and these factors in turn are used to estimate mobile source inventories. It is therefore desirable to estimate the real-world emissions from a fleet of vehicles as accurately as possible.
It follows that for in-service testing a large number of vehicles needs to be tested under a variety of operating conditions for a relatively long time, on the order of hours, to reliably reduce the effect of variances and obtain a reliable emissions result for individual vehicles. While variances within each vehicle can be explained and controlled to a good extent in the future, variances among different vehicles are likely to be difficult to predict; thus, the need to test a large number of vehicles is not likely to be reduced. It can therefore be suggested that portable, on-board emissions monitoring systems should be considered as a viable, cost-effective method to collect emissions data on a large number of vehicles operated in their regular revenue service.

CONCLUSIONS

This study provides the first example of the application of portable emissions monitoring instrumentation to in-service testing of urban transit buses. It was found that in-service emissions measurement during revenue service was a very feasible approach to transit bus emissions measurement, with very little cost and inconvenience to the fleet. The instrument installation caused no safety problems, there was minimal interference with vehicle operation, and no complaints were received regarding the testing.

High variability was observed both among the buses and within the measurements for each bus, suggesting that testing of a large number of vehicles for a relatively long time might be necessary to understand and characterize emissions from a particular fleet of vehicles. This is not unusual as real-world driving is not controlled or repeatable.

Average, per mile emissions have been reported for five buses. Buses with rebuilt engines and emissions reduction retrofits were found to have significantly lower PM and CO emissions than two of three buses without the rebuild and retrofit. NO_x and CO_2 emissions were comparable on all buses. Increasing per mile NO_x and CO_2 emissions correlated with increasing stop density and decreasing average speed for a particular segment, while PM emissions appeared to be independent of both stop density and average speed.

Data collected in actual vehicle operation can be used to evaluate the effect of various emissions reduction strategies such as emissions regulations and standards, alternative fuels, hybrid-electric drive systems, advanced catalytic converters and particulate traps, fleet inspection and maintenance programs, driver training, or route optimization. This data can also be used to develop emissions factors specific for a given fleet and region, to create more accurate emission models, and to provide better understanding of heavy-duty vehicle emissions in general.

REFERENCES

1. Deaton, M.L., Winebrake, J.J.: “Comparing Lifetime Emissions of Natural Gas and Conventional Fuel Vehicles” J. Air & Waste Manage. Assoc., 50: 162-168.
2. Clark, N.N. et al.: “Factors Affecting Heavy-Duty Diesel Vehicle Emissions” J. Air & Waste Manage. Assoc., 52: 84-94.
3. Butler, J. et al.: “Dynamometer Quality Data Onboard Vehicles for Real-World Emissions Measurements.” Proceedings of the 9th CRC On-road Vehicle Workshop, San Diego, CA, April 20-22, 1998.
4. Ikonen, M.: “On-Road Emissions and Fuel Consumption Measurements for Transit Buses Powered by Diesel Fuel, CNG and LPG.” Proceedings of the 11th CRC On-road Vehicle Workshop, San Diego, CA, April 2001.
5. Gautam, M. et al.: Measurement of In-Use, On-Board Emissions from Heavy-Duty Diesel Vehicles: Mobile Emissions System.” SAE tech. Paper 2001-01-3643, 2001.
6. Vojtisek-Lom, M. and Allsop, J.E.: “Development of Heavy-Duty Diesel Portable, On-Board Mass Exhaust Emissions Monitoring System with NOx, CO2 and Qualitative PM Capabilities.” SAE tech. paper 2001-01-3641, 2001.
7. Weaver, C.: “Development of RAVEM Ride-Along Vehicle Emissions Measurement System.” Proceedings of the 11th CRC On-road Vehicle Workshop, San Diego, CA, April 2001.
8. Vojtisek-Lom, M. and Cobb, J.T.: “Quantitative On-board On-Road Emission Measurement of Vehicles in Pittsburgh.” Proceedings of the A&WMA/EPA Emissions Inventory Conference, Raleigh, NC, October 25-28, 1999.
9. Lambert, D.C., Vojtisek-Lom, M., Wilson, P.J.: “Extended Idling Emissions Study. Analysis and final report for testing on heavy-duty diesel vehicles performed in Knoxville, TN.” Report submitted to Idle Aire Technologies, Knoxville, TN, December 2001.
10. Prucz, J.C., Clark, N.N., Gautam, M., Lyons, D.W.: “Exhaust Emissions from Engines of the Detroit Diesel Corporation in Transit Buses: A Dedcade of Trends.” Environ. Sci. Technol., 35, 1755-1764, 2001.

11. Vojtisek-Lom, M., Lambert, D.C., Wilson, P.J.: “Reproducing Driving Cycles On The Road Using Portable, On-Board Emissions Monitoring Systems.” Accepted for presentation at the 12th CRC On-road Vehicle Workshop, San Diego, CA, April 15-17, 2002.
12. Niemeier, D.A.: “Spatial Applicability of Emission Factors for Modeling Mobile Emissions.” Environ. Sci. Technol., 36: 736-7431, 2002.

KEY WORDS
On-road emissions, real-world emissions, in-use emissions, portable on-board emissions monitoring system, emissions in revenue service, fleet emissions, transit bus emissions, vehicle emissions variability