

Effect of B20 and Low Aromatic Diesel on Transit Bus NO_x Emissions Over Driving Cycles with a Range of Kinetic Intensity

Michael P. Lammert, Robert L. McCormick, Petr Sindler and Aaron Williams
National Renewable Energy Laboratory

ABSTRACT

The objective of this research project was to compare the emissions of oxides of nitrogen (NO_x) from transit buses on as many as five different fuels and three standard transit duty cycles to establish if there is a real-world biodiesel NO_x increase for transit bus duty cycles and engine calibrations. Prior studies have shown that B20 can cause a small but significant increase in NO_x emissions for some engines and duty cycles. Six buses spanning engine build years 1998 to 2011 were tested on the National Renewable Energy Laboratory's Renewable Fuels and Lubricants research laboratory's heavy-duty chassis dynamometer with certification diesel, certification B20 blend, low aromatic [California Air Resources Board (CARB)] diesel, low aromatic B20 blend, and B100 fuels over the Manhattan, Orange County and UDDS test cycles. The buses selected represented the majority of the current national transit fleet as well as including hybrid and selective catalyst reduction (SCR) systems that are increasing penetration in the fleet.

The engine emissions certification level had the dominant effect on NO_x, with the kinetic intensity of the tested duty cycle being the secondary driving factor. The biodiesel effect on NO_x emissions was not statistically significant for most buses and duty cycles for blends with certification diesel, with the exception being a 2008 model year bus. CARB fuel had many more instances of a statistically significant effect of biodiesel increasing NO_x. SCR systems proved effective at reducing NO_x to near the detection limit on all duty cycles and fuels, including B100. A hybrid system proved to significantly increase NO_x emissions over a same model year bus with a conventional drivetrain and the same engine. As all but one test bus were equipped with diesel particulate filter aftertreatment PM emissions were negligible and trends could not be drawn. On the oldest sample bus without aftertreatment PM emissions were reduced with B20 blends. Fuel economy was not significantly changed by engine certification level except that the 2008 conventional bus had the best performance on all cycles while all other buses had very similar results on each cycle. All buses had lower fuel economy with increased kinetic intensity of the cycle.

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INTRODUCTION

Biodiesel is an important petroleum displacement fuel that is produced from various fats, oils, and greases. It consists of fatty acid methyl esters produced from the various feedstocks by transesterification with methanol. Biodiesel used in the United States must meet the quality requirements of ASTM Specification D6751. Over 1 billion gallons of biodiesel were produced in the United States in 2011 [1]. Typically, biodiesel is used as a blend with petroleum diesel at levels ranging from 2% to 20% by volume (B20). Energy content per gallon is slightly lower for B20, resulting in a small reduction in peak torque and fuel economy, but no change in thermal efficiency [2].

Early studies revealed that blending biodiesel into diesel fuel caused emissions of oxides of nitrogen (NO_x) to increase in many engines [2,3]. It was also shown that biodiesel from unsaturated feedstocks (having more double bonds) caused a larger increase in NO_x [4]. Several different hypotheses have been presented for the cause of this NO_x increase [5]. Mueller and coworkers have shown that the primary cause is shifting of the combustion stoichiometry to be less rich at ignition and in the standing premixed autoignition zone near the flame liftoff-length [6]. However, Eckerle and coworkers demonstrated that engine control systems could respond to the lower energy content of biodiesel in ways that compensated for the NO_x increase under some engine

operating conditions [7]. Yanowitz and McCormick reviewed all available data and tried to relate differences in the effect of biodiesel on NO_x to specific engines and fuel injection technologies [8]. They concluded that biodiesel could increase or reduce NO_x emissions depending upon engine technology and driving cycle, and that there were inadequate data to determine an average effect. Transit buses represent a large niche market with a specific engine calibration. Therefore, it is important to determine if using biodiesel blends could increase emissions in this application. The objective of this research project was to evaluate the NO_x emissions of a range of transit buses on as many as five different fuels and three standard transit duty cycles to establish if there is a discernible real-world biodiesel NO_x increase for transit bus duty cycles and engine calibrations.

BACKGROUND AND METHODS

Bus Selection

An analysis of the 2009 American Public Transportation Association transit authority survey [9] was used to select buses to test based on the prevalence of different models in the nation's transit fleet. Figure 1 shows the population by model year of different engine makes. Beyond representing the current population, an effort was made to represent up and coming technologies such as hybrid powertrains and newer emissions control systems. While Detroit Diesel Engines used to dominate the market, in the late 1990s and early 2000s Cummins Engines began to dominate the transit bus market. Also of note is the distinct rise in hybrid powertrains starting in 2003. Table 1 breaks down the percent of the transit population represented by each engine for each engine certification period. Table 2 lists the actual buses tested to represent the biggest categories and those increasing in percent of bus population. Two Colorado transit agencies, Denver Regional Transportation District (RTD) and the Roaring Fork Transportation Authority (RFTA), loaned buses for these tests.

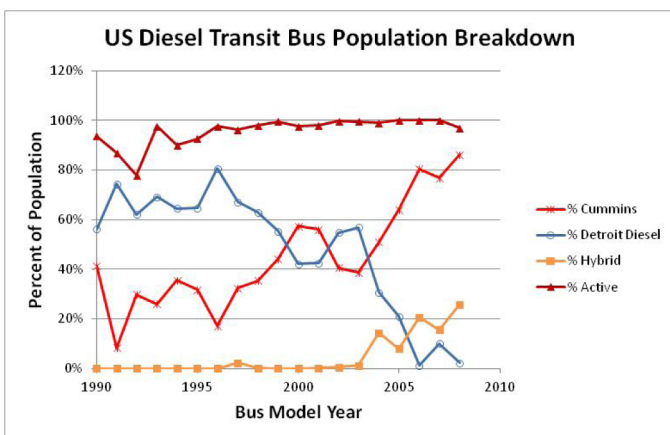


Figure 1. U.S. transit bus population.

Table 1. Population Breakdown of Current U.S. Transit Bus Fleet.

Transit Bus Population by Emissions Model Year				
Model Years	% of Active Fleet	Cummins Engine	Detroit Diesel Engine	Hybrid Powertrain
'98-'01	39%	19%	19%	0%
'02-'06	44%	24%	15%	3.8%
'07-'08	17%	14%	1%	3.5%

Table 2. Selected Test Buses.

Tested Transit Buses					
Bus Model Year	Bus MFR	Engine MFR	Engine Model	Emissions Equipment	Transit Agency
1998	Neoplan	Detroit Diesel	Series 50	none	RFTA
2005	Gillig	Cummins	ISM	EGR, aftermarket DPF	RTD
2008	Gillig	Cummins	ISL	EGR, DPF	RTD
2008	Gillig	Cummins	ISL	EGR, DPF (Hybrid)	RTD
2010	Gillig	Cummins	ISL	EGR, DPF, SCR	RFTA
2011	Gillig	Cummins	ISL	EGR, DPF, SCR	RFTA

DPF = diesel particulate filter, EGR = exhaust gas recirculation, SCR = selective catalyst reduction

Fuel Selection

The purpose of this study was to identify the effect on NO_x emissions from different buses on different duty cycles and using different fuels. U.S. Environmental Protection Agency certification diesel, a nominally 10% aromatic Tier 2 certification diesel meeting requirements for CARB diesel, a B100 derived from soy oil, and B20 blends of each diesel with the biodiesel were used. The CARB diesel has a lower aromatic content (8.5% vs. 29.9%) and a higher cetane number (48.7 vs. 42.5) than the certification diesel and was included in addition to the certification diesel both because CARB has great interest in NO_x emissions and because the low-aromatic fuel has been shown to reduce NO_x emissions [10]. Additionally, early results suggested that the effect of biodiesel on NO_x may be greater for lower aromatic, higher cetane diesel fuels [3]. The biodiesel was typical of soy biodiesel. Detailed fuel properties are provided in the Appendix.

Test Cycle Selection

Dynamometer test cycles representative of common U.S. transit bus usage were desired to best represent real in-use emissions. Also taken into consideration was that the cycles chosen should be common enough that data from other researchers could be compared. The Manhattan Bus (MANB)

Orange County Transit Authority (OCTA), and Urban Dynamometer Driving Schedule (UDDS) cycles were chosen. These cycles are also being used as part of the Altoona new bus testing program at Pennsylvania State University [11]. Table 3 shows some of the representative statistics for the cycles, and Figures 2,3,4 show the speed-time traces of the cycles. “Average speed” is the average speed over the full time a bus engine is on and is commonly used to describe transit routes while “average driven speed” does not consider zero speed time and is more indicative of the intensity of a duty cycle. Stops per mile is another metric that is commonly used to describe transit routes. The kinetic intensity metric [12] reflects the nature of energy consumption along a given drive cycle. A large kinetic intensity value corresponds to drive cycles where the energy consumed is more strongly influenced by vehicle acceleration rather than vehicle driving speed. Similarly a small kinetic intensity value corresponds to drive cycles where vehicle speed dominates acceleration with regards to energy consumption. Lower average speeds and higher kinetic intensity and stops per mile tend to indicate a duty cycle that has more aggressive transient conditions typical of a heavy traffic urban environment and typically gets lower fuel economy than duty cycles with higher average speeds and lower kinetic intensity and stops per mile. The Manhattan Bus cycle represents transit bus operating conditions in a very dense urban environment. Of the three drive cycles, it has the most stops, lowest speed, and highest kinetic intensity. The OCTA cycle represents urban transit bus operation in the Los Angeles area and is characterized by higher driving speeds and less frequent stops than the MAN cycle. The UDDS cycle has the highest operating speeds and lowest kinetic intensity. This cycle represents generic urban and suburban operating conditions for heavy-duty vehicles and is the basis for the heavy-duty engine dynamometer federal test procedure cycle.

Table 3. Selected Representative Statistics of Chosen Dynamometer Test Cycles.

	MAN	OCTA	UDDS
Cycle Time (min)	18.2	31.8	17.7
Cycle Distance (mile)	2.1	6.5	5.6
Avg Speed (mph)	6.8	12.3	18.9
Avg Driven Speed (mph)	10.7	15.7	28.2
Maximum Speed (mph)	25.3	40.6	58.0
Stops per Mile	9.7	4.7	2.5
Kinetic Intensity (1/mile)	9.1	3.6	0.6

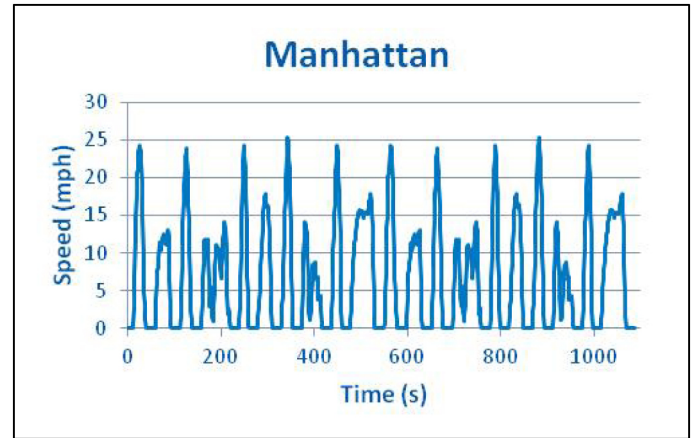


Figure 2. MAN chassis dynamometer test cycle.

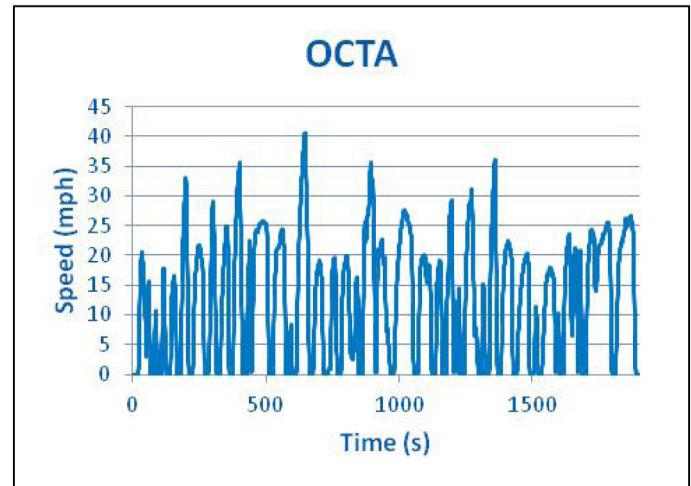


Figure 3. OCTA chassis dynamometer test cycle.

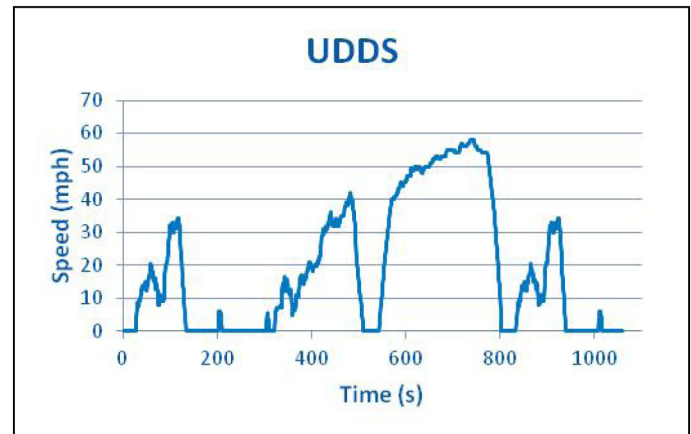


Figure 4. UDDS chassis dynamometer test cycle.

Laboratory Chassis Dynamometer Testing Procedures

When tested, the vehicle is secured to the dynamometer with the drive axle(s) over the rollers. The vehicle is exercised by a driver following a prescribed speed trace on the test aid monitor. Test weight was determined by assuming half the rated passenger load and a driver with an average weight of 150 lbs per person in addition to the curb weight. Vehicle weights are given in [Table 4](#). A large fan is used to evacuate the space behind the vehicle where the hot air tends to accumulate. The engine exhaust stream is collected by the emissions measurement system for analysis, and various vehicle parameters are monitored and logged by the data acquisition system.

Table 4. Test Bus Weight.

Test Bus	Curb Weight (lbs)	Gross Vehicle Weight Rating (lbs)	Test Weight (lbs)
1998 Neoplan / DDC Series 50	30,300	40,600	33,640
2005 Gillig / Cummins ISM	28,540	39,600	31,315
2008 Gillig / Cummins ISL	27,890	39,600	30,780
2008 Gillig / Allison Hybrid / Cummins ISL	29,160	39,600	32,060
2010 Gillig / Cummins ISL	28,340	39,600	31,415
2011 Gillig / Cummins ISL	26,960	39,600	29,850

To assure the accuracy and consistency of road load simulation, the dynamometer is subjected to various procedures and checks. From a practical perspective, the daily testing routine consists of following steps. In the morning the vehicle is lifted off the rollers and the dynamometer is subjected to its warm-up procedure until the parasitic losses stabilize. Then the unloaded coastdown procedure is used to verify that the parasitic losses did not change from the previous test due to component failure and that the load cell calibration has not drifted. Following this verification, the vehicle is dropped on the rollers and driven for roughly 20 minutes to warm up. After the warm-up, a conditioning test run is performed to stabilize the vehicle temperature for a given test cycle. At this point, the system is ready to either set or verify correct road load simulation through a loaded coastdown procedure. The following test runs are considered usable in terms of data validity provided the road load simulation proves consistent. This is verified after each test to ensure that changing conditions (e.g., test facility temperature) are not affecting vehicle loading. To maximize the chances of consistency, the soak period between one test end and following test start is kept at 20 minutes.

Emissions measurement

The emissions measurement system is based on recommendations in Code of Federal Regulations Section 40, Part 86, Subpart N. It consists of a full flow dilution tunnel with a constant volume sampling system for mass flow measurement. The tunnel flow rate is measured and controlled using critical flow venturis. The dilution and engine combustion air is supplied by an air handling unit that maintains the desired air temperature of 20°C and dew point of 12°C.

The diluted engine exhaust was sampled for gravimetric PM analysis and by a Horiba MEXA 7100 series system for gaseous analysis including total hydrocarbons, NO_x, carbon monoxide, and carbon dioxide. The gas analytical system was verified prior to the beginning of the testing period including linearization checks and NO_x efficiency test. The analyzers were zero and span calibrated on a daily basis, and each test was bracketed by zero and span response reading used for corrections. The emissions measurement data were then reduced to distance-specific mass results using the Code of Federal Regulations-recommended calculations, including humidity, dry to wet, zero, span and background corrections.

Fuel consumption measurement

The fuel consumption measurement in this project relied on a gravimetric approach. The engine fuel supply and return lines were connected to a fuel container placed on a scale. The scale mass measurements were recorded in real time along with all the test data. The difference between the beginning and the end test mass measurement indicated the mass of fuel consumed during the test. Prior to testing the scale calibration was verified with a known calibration weight. The instrument used for this test was a Sartorius Midrics MAPP1U-60ED-L. The fuel consumption measurement was also backed up using the carbon balance method back-calculating the mass of fuel consumed from measurement of exhaust emissions constituents.

RESULTS

Bus NO_x Emissions

1998 Neoplan / DDC series 50 NO_x emissions

A 1998 model year Neoplan 40-ft bus with a Detroit Diesel Series 50 275 HP engine from RFTA was selected to represent the pre Heavy Duty Diesel Engine Consent Decree engine certification period that included no EGR or exhaust aftertreatment. [Figure 5](#) shows the NO_x g/mile results of each test cycle and fuel. Note that individual run data for NO_x emissions, PM emissions, and fuel economy are provided in the [Appendix](#). The B20 blend with certification diesel showed no statistically significant effect on NO_x emissions on any cycle. The B20 blend with CARB diesel showed a 3% to 5% increase in NO_x on the OCTA and UDDS cycles, but no increase on the MAN cycle (the most kinetically intense cycle). The test cycle had a larger effect with the UDDS cycle



producing 50% less NO_x than the MAN cycle on certification diesel. The B20 blends demonstrated a 24% reduction in particulate emissions (PM) on the UDDS cycle with certification diesel and a 19-38% reduction with CARB diesel. Figure 6 shows the PM g/mile results of each test cycle and fuel.

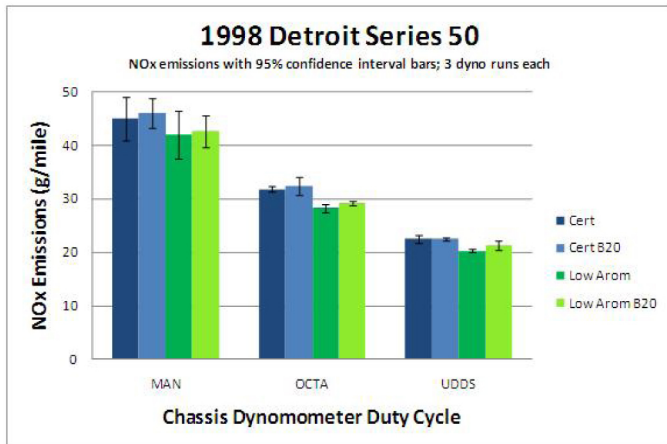


Figure 5. NO_x emissions from a 1998 transit bus.

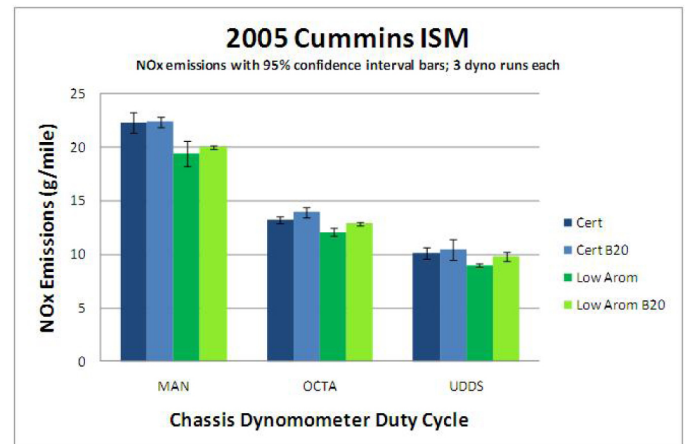


Figure 7. NO_x emissions from a 2005 transit bus.

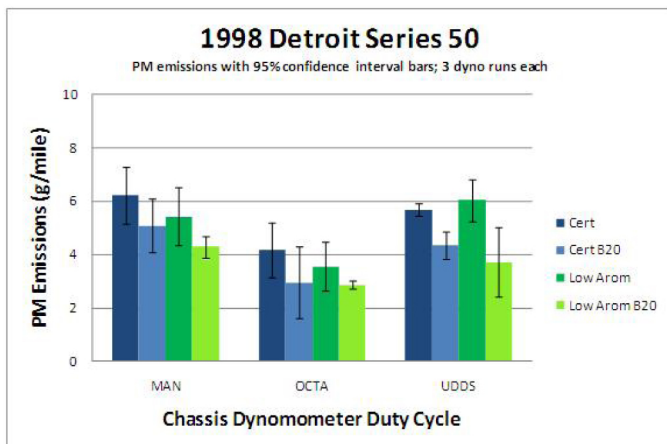


Figure 6. PM emissions from a 1998 transit bus.

2008 Gillig / Cummins ISL NO_x emissions

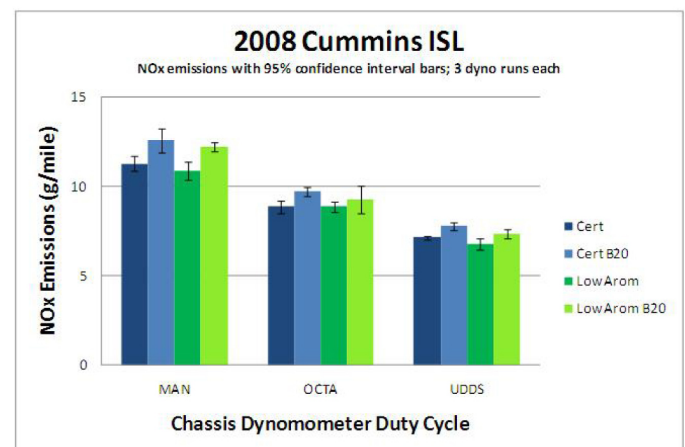


Figure 8. NO_x Emissions from a 2008 transit bus.

2005 Gillig / Cummins ISM NO_x emissions

A 2005 model year Gillig 40-ft bus with a Cummins ISM 280 HP engine from Denver RTD was selected to represent the post Heavy Duty Diesel Engine Consent Decree engine certification period that included EGR but not DPF units. However, Denver RTD, like most transits, had installed aftermarket DPF units on its buses that did not have active regeneration, and particulate emissions were below detection limits. Figure 7 shows the NO_x g/mile results of each test cycle and fuel. Note that NO_x emissions for this bus were approximately 50% lower than observed for the 1998 model year bus. The B20 blend with certification diesel showed no effect on NO_x for the MAN and UDDS cycles and a 5% increase in NO_x on the OCTA cycle as compared to

certification diesel. The B20 blend with CARB diesel showed no increase in NO_x on the MAN cycle, but a 3% to 5% increase on the OCTA and UDDS cycles as compared to CARB diesel. CARB diesel showed a 9% to 13% reduction in NO_x as compared to certification diesel. The test cycle had a larger effect with the UDDS cycle producing 55% less NO_x than the MAN cycle on certification diesel.