

Effects of Biodiesel Operation on Light-Duty Tier 2 Engine and Emission Control Systems

Marek Tatur, Harsha Nanjundaswamy and Dean Tomazic
FEV Inc.

Matthew Thornton
National Renewable Energy Laboratory

ABSTRACT

Due to raising interest in diesel powered passenger cars in the U.S. in combination with a desire to reduce dependency on imported petroleum, there has been increased attention to the operation of diesel vehicles on fuels blended with biodiesel. One of several factors to be considered when operating a vehicle on biodiesel blends is understanding the impact and performance of the fuel on the emission control system.

This paper documents the impact of the biodiesel blends on engine-out emissions as well as the overall system performance in terms of emission control system calibration and the overall system efficiency.

The testing platform is a light-duty HSDI diesel engine with a Euro 4 base calibration in a 1700 kg sedan vehicle. It employs 2nd generation common-rail injection system with peak pressure of 1600 bar as well as cooled high-pressure EGR. The study includes 3 different fuels (U.S. ULSD –base fuel; and B5 and B20 prepared from soy-derived biodiesel) with two different emission control systems (ECS) (NOx adsorber catalyst (NAC) with a diesel particle filter (DPF) and selective catalytic reduction (SCR) with a DPF). The main focus of this paper is on NAC calibration, regeneration, and desulfurization; DPF regeneration and preliminary emissions, with a focus on oxides of nitrogen (NOx), and fuel economy results. The NAC ECS aged to end of life conditions and showed efficiencies in the mid 80% range, therefore allowing operation within the Tier 2 Bin 5 emission standards for both intermediate as well as useful life conditions.

The development test results from the vehicle chassis tests showed some NOx benefits operating on B20 fuel blends with the NAC ECS. This is a result of the calibration work being performed using the 20% biodiesel fuel blend. The resulting higher exhaust temperatures with ULSD resulted in lower ECS effectiveness with the NAC. The average tailpipe results operating the vehicle on B20 were in the range of 0.03

g/mi, while the emissions with ULSD averaged below 0.05 g/mi with larger cycle-to-cycle variability.

INTRODUCTION

Due to advancements in diesel engine technology light-duty diesel powered vehicle are becoming more popular in the U.S. In addition to the increased interest in light – duty diesel vehicles the anticipation and eventual phasing in of stringent Tier 2 emissions standards for this vehicle class has lead to the necessity of emissions control systems (ECS) on these vehicles. Concurrently, increasing fuel prices have rejuvenated interest in bio-fuels, such as biodiesel, as a means to displace demand for petroleum-derived fuels.

Selective catalytic reduction (SCR) with urea and NOx adsorber catalyst (NAC) are the leading technologies for meeting the Tier 2 NOx emission standards for light-duty diesel vehicles. Extensive research has been conducted over the past decade focusing on the performance and durability of these technologies in conjunction with conventional fuels [1-8]. Little research has been performed with the intent of gaining an understanding of the impact of bio-fuels, or more specifically biodiesel, on these ECSs.

Biodiesel is a renewable fuel derived from vegetable oil, animal fat, or waste cooking oil and consists of the methyl esters of fatty acids. It is typically used as a diesel blending component at levels up to 20 volume percent. A resource assessment indicates that biodiesel has the potential to displace 5% or more of petroleum diesel over the next decade [9], and a life cycle analysis indicates that use of B20 reduces life cycle petroleum consumption by 19% [11]. Although little is known about the potential impacts of these fuel blends on the life and performance of ECSs.

This paper will discuss the emissions performance of the NAC system, combined with a diesel oxidation catalyst

(DOC) and diesel particle filter (DPF), while operating on ultra-low sulfur diesel (ULSD) and a blend of ULSD and 20% biodiesel (B20). A consideration of SCR and NAC chemistry suggests several areas where biodiesel blends may perform differently than pure petroleum-derived fuels. This paper will include an initial look at these potential areas, as well as a discussion of the test bed hardware, ECS specifications, controls and initial emissions results.

Before with the start of the emission control system development, the engine-out emissions were recalibrated to result in required NOx and HC conversion efficiencies of approximately 80% from the emission control system. The achieved target level was in the range of 0.35 g/mile NOx emissions over the FTP75.

Based on the experience gained during the APBF-DEC light-duty vehicle development efforts [1, 2, 4, 7, 8], the development team decided to start the activities with the implementation and calibration of the NAC system. The hardware configuration was defined as close coupled DOC and NAC combination allowing fastest possible catalyst light-off after cold start. The SCR system was designed around the vehicle body constraints with a close-coupled DOC and an underfloor SCR – DPF allowing sufficient mixing length after the point of injection for urea.

TESTING HARD- AND SOFTWARE

The testing was conducted primarily in the engine test cell running steady-state as well as transient test cycles simulation which includes all certification cycles such as the FTP75, HWFET, and US06. This approach allowed investigating the engine and emission control system behavior in great detail under controlled conditions. The results of all development activities were confirmed on a vehicle chassis dynamometer. The U.S. EPA's National Vehicle and Fuel Economy Laboratory (NVFEL) in Ann Arbor, Michigan was used to determine the vehicle emissions performance over the certification cycles after completion and integration of all development activities.

ENGINE HARDWARE

The engine used for this project is an in-line 4 cylinder, turbocharged, common-rail system direct injected engine, producing 106 kW at 4000 rpm and peak torque of 360 Nm at 2000 rpm. The base engine hardware was Euro 4 level configuration and was not modified during the development efforts. It consisted of a high pressure EGR loop with the EGR cooler partially integrated in the cylinder head as well as a VNT turbocharger. All actuators were electronically controlled and utilized electric actuators for their adjustments.

Following Table 1 lists more detailed parameters.

Table 1: Engine Specifications

Engine Power	106 kW @ 4000 rpm
Peak torque	360 Nm @ 2000 rpm
Max engine speed	4700 rpm
Max. BMEP	22 bar
Number & Arrangement of Cylinders	4 cylinder inline
Firing order	1 - 3 - 4 - 2
Valve train	4 Valve DOHC
Displacement	2.15 L
Bore to stroke ratio	1.0034
Compression Ratio	18
Fuel injection system	2nd Generation Common-Rail DI

Figure 1 illustrates the engine's engine-out specific NOx emissions over the entire engine map. The engine operates in conventional Diesel mode without the use of low temperature combustion techniques in certain engine operating regimes.

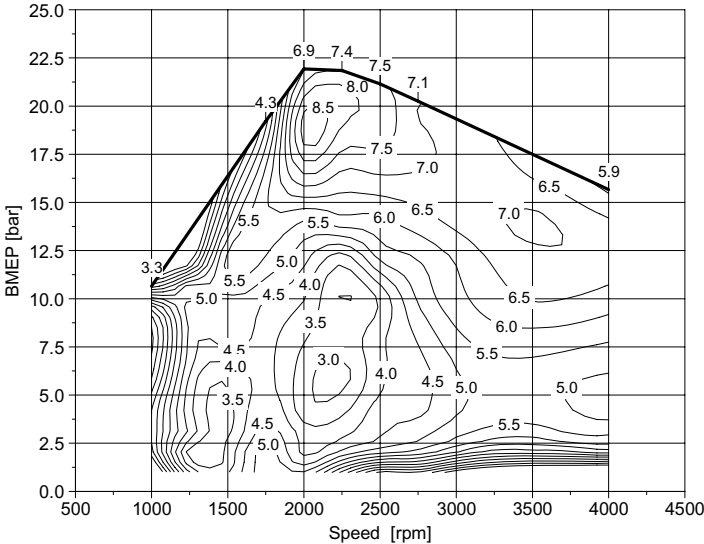


Figure 1: Engine-out NOx [g/kWhr]

VEHICLE SPECIFICATIONS

The vehicle used in this project is a mid-size four door sedan with the base specifications listed in Table 2. No vehicle modifications such as removal of components with the intent to decrease vehicle weight were performed. The only modification was the installation of the required rapid prototyping equipment to control the ECSs and the data acquisition system.

Table 2: Vehicle specifications

Criteria	Unit	Value
Vehicle mass	kg	1700
Air drag coefficient	-	0.29
Frontal surface area	m ²	2.20
Transmission gear ratio	1st	4.99
	2nd	2.82
	3rd	1.78
	4th	1.25
	5th	1.00
	6th	0.82
Tires / Wheels	Axle	2.65
	rear	205/55 R 16 91 H
	front	205/55 R 16 91 H

EMISSION CONTROL HARDWARE

As indicated two different ECSs were subject to evaluation as part of this project. The first system which was developed was a NAC system, an SCR system is also developed and results will be described in a later publication. In both cases a close coupled DOC and an under-floor DPF are included. Catalyst sizes were chosen that allowed manageable packaging on the project vehicle. All catalyst components were connected through dual wall (air gap insulated) piping. The vehicles original muffler remained in place.

NOx Adsorber Catalyst System

The NAC system was comprised of a close-coupled DOC / NAC combination (assembled in one can). This configuration enabled early catalyst light-off after cold start and therefore fast and efficient control of gaseous emissions. The under-floor catalyzed DPF was also utilized to control any breakthrough hydrocarbons.

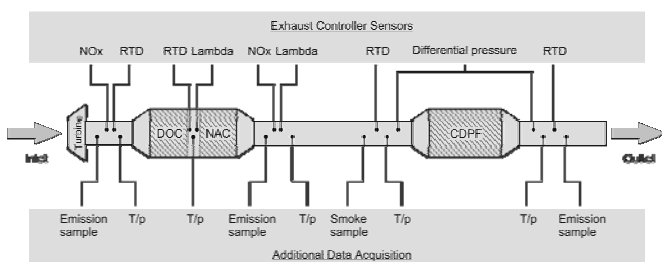


Figure 2: NOx Adsorber Catalyst/DPF Emission Control System

Figure 2 shows the ECS layout and sensor suite used for controls on the top of the schematic and the additional sensor locations on the bottom. In order to provide the highest level of control accuracy and quality a two NOx sensor setup was chosen. The removal of the upstream NOx sensor and its replacement with an engine-out model is possible and was considered however results in some incremental decrease in system effectiveness especially under highly transient conditions and was therefore not utilized.

EMISSION CONTROL SOFTWARE

The design process of the ECS software was aimed to be as modular as possible. Each control module can be easily removed or substituted by an alternative routine. Figure 3 shows the high level structure of the controller which is implemented in the rapid prototyping environment.

The input as well as the output module convert the signals to useful conditions for each side of the controller. The core of the ECS algorithm is within the intervention handler module.

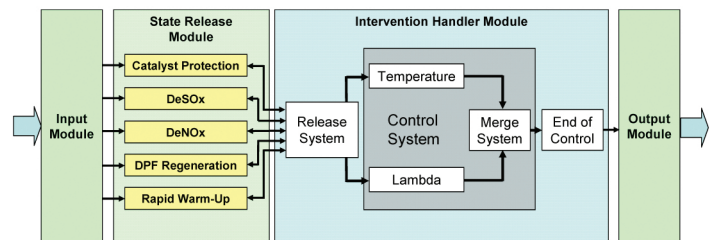


Figure 3: Emission Control Software Structure

The different intervention requests coming from the State Release Module and a release system are transformed into the corresponding output signals through a multi-variable control structure which allows the control of temperature and lambda simultaneously.

FUEL SPECIFICATIONS

Three different fuels were used in this study. The ultra low sulfur Diesel fuel (ULSD) also called the base fuel was used to blend the 5% and 20% by volume blends (blended with soy methyl ester). Table 3 lists the fuel specifications for each tested fuel type. Noteworthy is that the B5 blend used a different base fuel, therefore some differences in the fuel properties are apparent.

Table 3: Fuel specifications

		ULSD	B5	B20
Net Heating Value	MJ/kg	42.534	42.432	41.522
Cetane Number	-	41.4	42.4	45.6
Density @ 293 K	kg/m3	847.5	847.9	852.9
K Viscosity @ 313 K	mm2/sec	2.429	2.335	2.685
Carbon	wt%	87.04	86.48	85.01
Oxygen	wt%	0.00	0.61	2.29
Hydrogen	wt%	12.96	12.91	12.70
H/C	-	1.774	1.779	1.780
O/C	-	0.00	0.01	0.02
Stoichiometric Air/Fuel	-	14.46	14.36	14.04

TEST CYCLES

The project Included the following test cycles:

- 1. FTP-75, performed as two complete UDDS cycles
- 2. US06
- 3. HFET

Table 4 lists all the specifics of the test cycles, including length, average speed, and maximum speed.

Table 4: Test cycles

Cycle	Length	Average Speed	Maximum Speed	Remarks
UDDS	12.07 km 7.5 mi	31.6 km/h 19.6 mi/h	91.8 km/h 56.7 mi/h	Urban driving
US06	12.9 km 8.01 mi	77.9 km/h 48.4 mi/h	129.3 km/h 80.3 mi/h	Aggressive high-speed driving
HFET	16.52 km 10.26 mi	77.8 km/h 48.3 mi/h	96.4 km/h 59.9 mi/h	Highway driving, fuel economy

Figure 4 shows the cycles mentioned above.

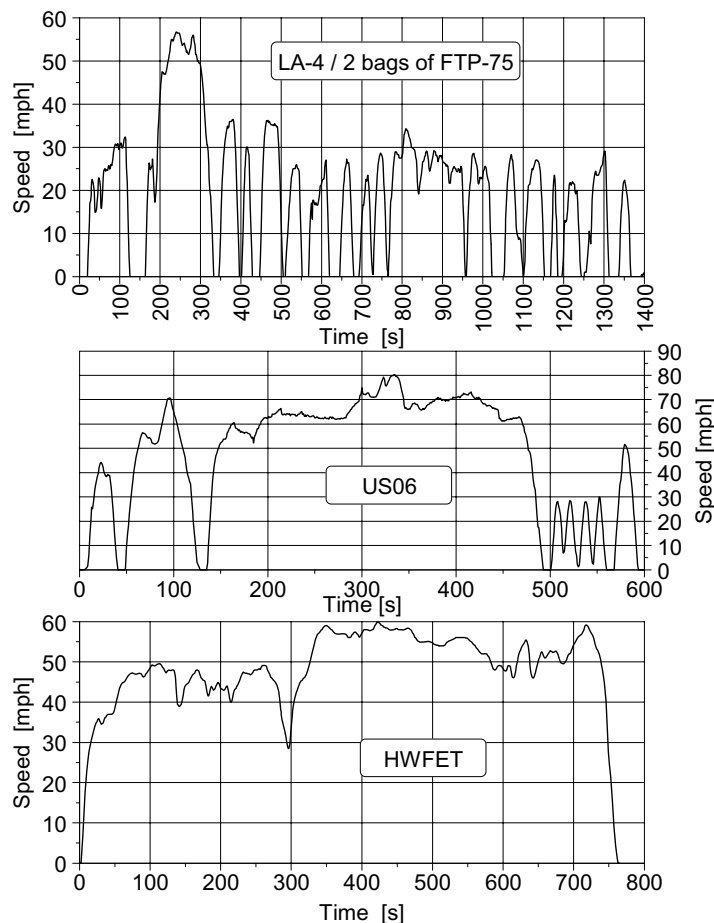


Figure 4: Emissions test cycles

In order to allow direct comparison between the test cell and the vehicle the torque and engine speed profile was programmed into the test cell control system. The base

vehicle data was used to determine the power requirement as result of each cycle's vehicle speed profile. With the transmission gear and axle ratio the transformation into engine speed and torque is performed. Refinement of the cycle results comparing the measured engine speed and commanded fuel quantity result was performed subsequently. The resulting test cycles performed in the test cell are described as *engine dynamometer transient cycle simulations* while the vehicle tests are defined as *vehicle chassis dynamometer tests*.

DEVELOPMENT TEST RESULTS

COMPARISON OF ENGINE TEST CELL WITH VEHICLE RESULTS

To allow for accelerated development activities it was found that the duplication of the chassis dynamometer vehicle test cycles described in the previous section into the engine dynamometer environment provides a benefit to the calibration efforts. It was critical to develop cycles that not only matched the engine speed and load conditions in the same transient way as in the vehicle, but also to obtain the same engine-out emission levels as the vehicle. Figure 5 and Figure 6 show the engine speed and injected fuel quantity (equivalent to load parameter) comparing the two different sites.

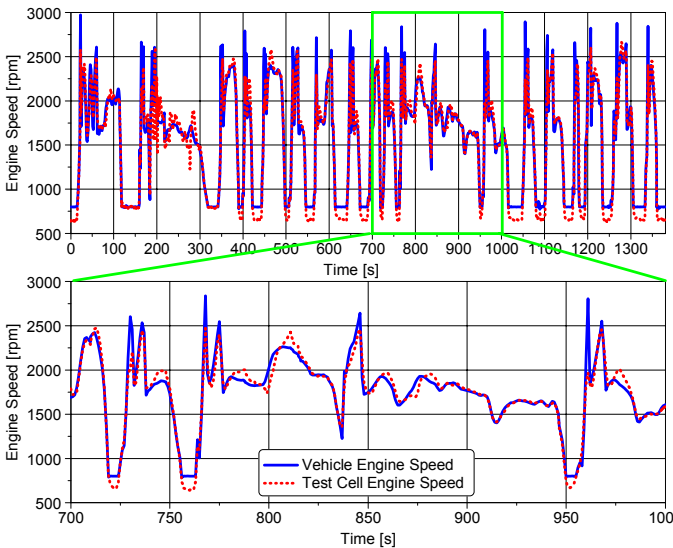


Figure 5: Engine speed comparison test cell and vehicle