

The Influence of Accelerator Pedal Position Control during Transient Laboratory Testing on Heavy Duty Diesel Engines

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ABSTRACT

Pollutants are a major issue of diesel engines, with oxides of nitrogen (NO_x) and airborne total particulate matter (TPM) of primary concern. Current emission standards rely on laboratory testing using an engine dynamometer with a standard test procedure. Results are reported as an integrated value for emissions from a transient set of engine speed and load conditions over a length of time or a set of prescribed speed-load points. To be considered a valid test by the US EPA, the measured engine speed and load are compared to the prescribed engine speed and load and must be within prescribed regression limits. To explore differences in NO_x, TPM, carbon monoxide (CO), total hydrocarbons (THC), and fuel consumption based on the control algorithm used to set the engine speed and load, five diesel engines (1991 DDC S60, 1992 DDC S60, 1999 Cummins ISM, and 2004 Cummins ISM) were operated on the heavy-duty transient FTP cycle with two different engine control settings and a second 1992 DDC S60 incorporated three different engine control settings. From the least to the most aggressive accelerator pedal position control (APPC) studied, the brake-specific emissions of THC, CO, NO_x, and TPM were found to differ up to 14.0%, 33.9%, 2.4%, and 19.6%, respectively. The older engine technology were influenced the most while the 2004 Cummins ISM was influenced the least by the control algorithm due to improved engine control with the variable geometry turbocharger (VGT) reducing turbocharger lag, which causes relatively rich zones inside the cylinder. A wider range of APPC aggressiveness than tested would still

produce valid transient tests and cause variation between test facilities; therefore, tighter regression tolerances are suggested.

INTRODUCTION

The durability, high thermal efficiency, and high fuel efficiency of diesel engines compared to other types of internal combustion engines are the reasons the diesel engine is a widely used power plant. With no reliable cost-effective alternative method of power production with the same advantages, diesel engines will continue to be used in the near future for commercial and industrial applications and may become more popular in the passenger vehicle arena. Pollutants are a major issue from diesel engines, with oxides of nitrogen (NO_x) and airborne total particulate matter (TPM) receiving particular interest. These pollutants and others in diesel exhaust have been identified with adverse health effects [1, 2]. To reduce air pollution, the Environmental Protection Agency (EPA) in the United States, and other regulatory agencies worldwide, have tightened diesel engine emissions standards over the last two decades [3].

Current emission standards rely on laboratory testing using an engine dynamometer with a standard test procedure. Results are reported as an integrated value for emissions from a transient set of engine speed and load conditions over a length of time or a set of prescribed speed-load points. However, on-road heavy-duty diesel engines operate at different conditions and the emissions produced are dependent on the speed,

load, acceleration, and environment [4]. Therefore, researchers that utilize emission results from engine dynamometer testing to predict “real-world” emissions of all diesel engines, such as emission inventories, are therefore bound by the limitations of these tests.

Variability exists between test facilities with coefficient of variations of 16% and 45% for NOx and TPM, respectively [5]. Emissions standards have become tighter and test protocols have improved since the 1989 study by Stein and colleagues [5], but some variability between test facilities will exist. A heavy-duty diesel engine round robin test is presently being performed using a 2007-like engine and it is anticipated that NOx and TPM will have similar, if not higher, variation due to the relatively low levels of these emissions. Emission inventories have historically relied on the emissions results of these test facilities. A better understanding for the variability in the emissions is important to quantify the existing pollutants emitted into the atmosphere.

The objective of this project was to investigate the influence of accelerator pedal position control (APPC) on emissions from transient testing on heavy-duty diesel engines. Five engines, model years 1991 to 2004 were tested with two different APPC algorithms (one engine had three different control algorithms). The control algorithms ranged in the aggressiveness of the APPC. To determine whether stricter control should be placed on determining a valid transient test, the current regression analysis required by the Title 40 CFR Part 86 Subpart N [3] was investigated.

TEST SETUP

To investigate the influence of old (before 2004 emission standards) and newer engine technology on the APPC during transient heavy-duty diesel engine testing, a 1991 S60 engine, two 1992 DDC S60 engines, a 1999 Cummins ISM 370 engine, and a 2004 Cummins ISM 370 engine were tested. One of the 1992 DDC Series 60 engines was acquired by West Virginia University (WVU) in poor condition (actual in-use engine from an over-the-road truck) and was rebuilt from the block up using DDC specified components and is referred as the 1992 DDC

Rebuilt or 1992 DDC R (Figure 1). An engine break-in with over one hundred hours of steady state and transient operation was performed on the engine after the rebuild and before any emissions testing. The 2004 Cummins engine was procured new and only used in the WVU laboratory. All engines are 4-stroke, turbocharged, intercooled, and electronically controlled. The 2004 Cummins engine used cooled exhaust gas recirculation (EGR) and a variable geometry turbocharger (VGT) to meet the 2004 emissions standards. Pertinent engine information is shown in Table 1 for the engines. Note that while fundamental combustion studies use single-cylinder research engines that are tightly controlled, there is limited data available from actual production engines. The selection of these engines provides representative data for actual in-use engines.



Figure 1 WVU Test Cell with 1992 Detroit Diesel Series 60 Engine Mounted

An engine test sequence consisted of a warm-start heavy-duty federal test procedure (FTP, Figure 2) test followed by three hot-start FTP tests; only the hot start FTP results are presented. The FTP cycle is a set of engine speed and load points determined based on the engine’s maximum torque at each engine speed. A proportional–integral–derivative (PID) control algorithm was utilized between the desired and measured engine speed by controlling the dynamometer. The laboratory had a separate PID control algorithm between the desired and measured torque by controlling the accelerator pedal position. The fuel control algorithm

Table 1: Engine Specifications

Engine Manufacturer	Detroit Diesel Corporation	Detroit Diesel Corporation	Detroit Diesel Corporation	Cummins	Cummins
Engine Model, Year	Series 60, 1991	Series 60, 1992	Series 60 (Rebuilt), 1992	ISM 370 ESP, 1999	ISM 370, 2004
Configuration	Inline 6 cylinder	Inline 6 cylinder	Inline 6 cylinder	Inline 6 cylinder	Inline 6 cylinder
Displacement (L)	11.1	12.7	12.7	10.8	10.8
Power Rating (hp)	345 @ 1800 rpm	365 @ 1800 rpm	355 @ 1800 rpm	370 @ 2100 rpm	370 @ 2100 rpm
Torque Rating (ft-lbs)	1335 @ 1200 rpm	1450 @ 1200 rpm	1410 @ 1200 rpm	1350 @ 1200 rpm	1450 @ 1200 rpm
Compression Ratio	16:1	15:1	15:1	16.3:1	16.1:1
Bore X Stroke (mm x mm)	130 X 139	130 X 160	130 X 160	125 X 147	125 X 147
Air Handling	Turbocharged, Aftercooled	Turbocharged, Aftercooled	Turbocharged, Aftercooled	Turbocharged, Aftercooled	Turbocharged, Aftercooled, VGT
Exhaust Gas Recirculation (EGR)	N/A	N/A	N/A	N/A	Cooled EGR
Accelerator Pedal Position Control (APPC)	1,3	1,3	1,2,3	1,3	1,3

and electronic control unit (ECU) on the engine was not changed. A regression analysis was performed after each FTP between the measured and set points for the engine speed, torque, and power. Engine speed, torque, and power are each required to meet certain tolerances for the slope, intercept, coefficient of determination (R^2), and standard error of estimate (SEE) by Title 40 CFR Part 86 Subpart N [3]. It should be noted that the warm start test was used to bring the engine to normal operating conditions. In between each test was a 20 minute soak period used for zero and spanning the analyzers, changing TPM filters, and data collection.

By changing the constants in the PID controller, each engine was operated on two different APPC algorithms for a FTP test sequence. The 1992 DDC R had three different APPC algorithms utilized. The APPC algorithms were numbered in order of least to most aggressive. The aggressiveness of the APPC is similar to the driver-to-driver differences from chassis dynamometer testing [6-9].

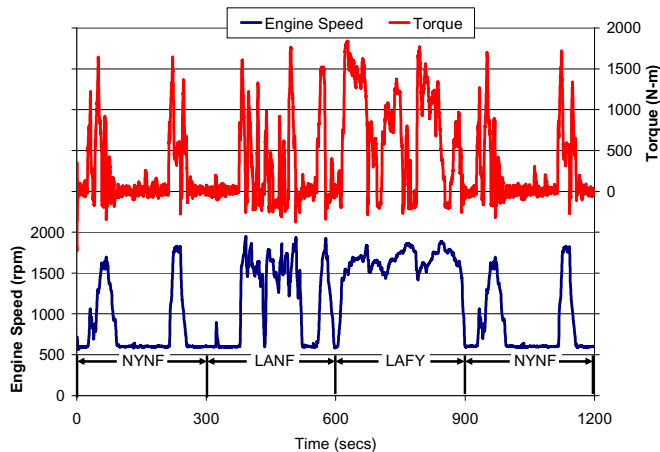


Figure 2 FTP Test Cycle on the 1992 Series 60 DDC

The diesel fuel utilized had a total aromatic content (ASTM D5186, by percent mass) of 34.2, cetane number of 49.2, a hydrogen-to-carbon ratio of 1.8, which is representative of an on-road diesel fuel. The fuel had a

sulfur content of 341 ppmw. Although present United States on-road diesel fuel is required to be ultra-low sulfur (below 15 ppmw), the fuel was a “500 ppmw” low sulfur fuel.

A full scale dilution, constant volume system (CVS) was employed based on Title 40 CFR Part 86 Subpart N requirements [3]. A critical flow venturi was used as the method of measuring the diluted exhaust. The dilute exhaust analyzers consisted of a Rosemount Analytical Model 402 heated flame ionization detector (HFID), Rosemount Model 955 heated, wet chemiluminescent, Horiba Model AIA-210LE non-dispersive infrared (NDIR), and Horiba Model AIA-210 non-dispersive infrared (NDIR) to measure total hydrocarbons (THC), NOx, carbon monoxide (CO), and carbon dioxide (CO₂), respectively. The TPM was gravimetrically measured in accordance with Title 40 CFR Part 86 Subpart N requirements using proportional sampling of the diluted exhaust through a pair of Pallflex 70mm diameter Model T60A20 fluorocarbon-coated glass microfiber filters in series using a secondary dilution tunnel.

RESULTS

The integrated brake-specific results of fuel consumption (BSFC), THC, CO, NOx, and TPM from the hot-start FTP tests are presented in Table 2. The Student's T-test was performed comparing the higher aggressive APPC (APPC 1 and 2) to the least aggressive APPC (APPC 3). The percent increases/reductions are only shown for statistically significant values with a p-value < 0.05. With APPCs 1 and 2, the BSFC had no significant difference or changed minimally (-0.3 to 0.1%) compared to APPC 3. As the aggressiveness of the APPC algorithm increased, the work over the FTP cycle increased (2.3-4.3%). The brake-specific THC with APPC 1 had a significant reduction for the 1991 DDC engine (14.0%), 1999 ISM (3.0%), and 2004 ISM (5.5%) compared to APPC 3; the other engines showed no significant difference. A significant increase in brake-specific CO (4.7-33.9%) was noticed for all engines with APPC 1 compared to APPC 3. The TPM had significant

Table 2: Brake Specific Emission

Engine	APPC	Work		BSFC		CO		NOx		THC		TPM	
		bhp-hr	Diff (%)	lb bhp-hr	Diff (%)	g bhp-hr	Diff (%)	g bhp-hr	Diff (%)	g bhp-hr	Diff (%)	g bhp-hr	Diff (%)
1991 DDC	1	22.8	-	0.381	-	2.45	-	4.61	-	0.0619	-	0.133	-
	3	23.4	2.6%	0.382	*	3.28	33.9%	4.50	-2.4%	0.0532	-14.0%	0.159	19.6%
1992 DDC	1	24.8	-	0.384	-	3.27	-	5.22	-	0.131	-	0.251	-
	3	25.4	2.5%	0.383	*	3.77	15.3%	5.12	-1.8%	0.120	*	0.270	7.3%
1992 DDC R	1	24.8	-	0.374	-	3.50	-	5.20	-	0.114	-	0.249	-
	2	25.4	2.3%	0.374	0.1%	3.94	12.6%	5.12	-1.5%	0.112	*	0.270	8.3%
	3	25.4	2.4%	0.374	*	3.98	13.8%	5.14	-1.1%	0.113	*	0.276	10.9%
1999 ISM	1	26.1	-	0.370	-	0.906	-	4.10	-	0.269	-	0.114	-
	3	26.9	2.9%	0.368	-0.3%	1.04	14.5%	4.08	-0.5%	0.261	-3.0%	0.127	*
2004 ISM	1	24.6	-	0.427	-	0.589	-	2.33	-	0.212	-	0.0717	-
	3	25.6	4.3%	0.424	*	0.616	4.7%	2.35	*	0.200	-5.5%	0.0744	*

* No significant difference using a T-test with p < 0.05