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Effect of Air Filter Condition on Diesel Vehicle Fuel Economy

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ABSTRACT

Proper maintenance can help vehicles perform as designed, positively affecting fuel economy, emissions, and overall driveability. This paper addresses the issue of whether air filter replacement improves fuel economy. Described are measured results for increasing air filter pressure drop in turbocharged diesel-engine-powered vehicles, with primary focus on changes in vehicle fuel economy but also including emissions and performance. Older studies of carbureted gasoline vehicles have indicated that replacing a clogged or dirty air filter can improve vehicle fuel economy and, conversely, that a dirty air filter can be significantly detrimental to fuel economy. In contrast, a recent study showed that the fuel economy of modern gasoline vehicles is virtually unaffected by filter clogging due to the closed loop control and throttled operation of these engines. Because modern diesel engines operate without throttling (or with minimal throttling), a different result could be anticipated. The effects of clogged air filters on the fuel economy, acceleration, and emissions of three late model turbocharged diesel-powered vehicles were examined. The vehicles were powered by turbocharged diesel engines with different displacements and engine designs. The results reveal rather low sensitivity of these modern diesel vehicles to air filter condition.

INTRODUCTION

The US Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy and the US Environmental Protection Agency (EPA) jointly maintain a fuel economy website (www.fueleconomy.gov) that helps fulfill their responsibility under the Energy Policy Act of 1992 to provide accurate fuel economy information to consumers. The site provides EPA fuel economy ratings for passenger cars and light trucks from 1984 to the present, information on alternative fuels, driving and vehicle maintenance tips, and other relevant information related to energy use. Under the auspices of this program, the Oak Ridge National Laboratory (ORNL) Fuels, Engines, and Emissions Research Center (FEERC) conducts studies to validate and improve this information. This paper documents a study aimed specifically at the effects of engine air filter condition on the fuel economy of diesel vehicles. A previous (companion) paper detailed results of an investigation of the effects of air filter condition on gasoline vehicles [1].

A vehicle's published EPA fuel economy rating is determined by driving the vehicle over prescribed cycles on a chassis dynamometer. City fuel economy is measured using the Urban Dynamometer Driving Schedule, also known as the Federal Test Procedure (FTP). Highway fuel economy is measured using the Highway Fuel Economy Test (HFET). Another relevant test is the US06, an aggressive (high speed, high load) test used to confirm emissions compliance during aggressive driving. Typically fuel economy results from this test are not reported, but EPA uses results from the US06 and other cycles to adjust the FTP and HFET results [2], and these adjusted fuel economy rates are what are reported on the vehicle manufacturer's window sticker, in the Fuel Economy Guide [3], and on the fueleconomy.gov website. Because of the wide range of loads and speeds encountered in these three driving cycles, they were used for the gasoline vehicle study noted previously [1] and for the current diesel vehicle study.

Proper vehicle maintenance will help a vehicle perform as it was designed, positively affecting fuel economy, emissions, and overall driveability. Past studies have indicated that replacing a clogged or dirty air filter may significantly improve vehicle fuel economy, but these studies examined only gasoline vehicles using carburetors and the open loop control typical of the 1970s [4, 5, 6]. Recent work has shown that modern gasoline engines with closed loop feedback systems are not sensitive to the state of the air filter [1], given that the engine power is controlled by throttling the intake air. Because of this control approach, any additional throttling from a clogged air filter is offset by further opening the throttle (to achieve the same desired manifold pressure); however, maximum engine power is affected by the intake air restriction imposed by a clogged filter. Conventional diesel engines operate largely without throttles. Although throttles are in use in some diesel engines today for active control of exhaust temperature and species, to enhance warm-up, or to control exhaust gas recirculation, these throttles are fully open most of the time. Because the diesel engine is largely unthrottled and airflow is relatively high even at light load, the added restriction from a clogged filter may have measureable effects on fuel economy.

EXPERIMENTAL SETUP

Defining a Clogged Air Filter

Four air filter indicators were examined to determine the pressure drop that would indicate a clogged filter. Two identical air filter indicators for Dodge Ram pickup trucks equipped with 5.9 L diesel engines (one purchased new from a Dodge dealer and another borrowed from a 2006 Dodge Ram pickup) were tested. In addition, an indicator borrowed from a 2001 Chevrolet Silverado with a gasoline engine was tested. These specific vehicles were not tested in this program, but these filter indicators were available and examined to gather preliminary information about the appropriate pressure drop for a clogged filter. A vacuum pump and water manometer were used to determine that about 4.2 kPa of differential pressure (DP) drop would "set" the Dodge Ram indicators and about 5.7 kPa would set the Silverado indicator to show filter replacement was needed. A 2007 Dodge Ram pickup with a 6.7 L diesel engine, which was also equipped with a filter indicator, was tested in this study. Results taken from the actual vehicle test data indicate that the 2007 Dodge Ram air filter indicator sets when a 3.6 kPa or greater DP occurs, as shown in Figure 1.

Figure 1. Air filter indicator from the 2007 Dodge Ram diesel truck. The yellow indicator reaches the red zone at 3.6 kPa differential pressure.

The intake air filter must address numerous functions in addition to filtration for the service life of the filter without allowing engine performance to be affected [7]. In light- and medium-duty applications, the service life is defined as about 48,000 km (30,000 miles) [7, 8, 9], which is typical for normal driving conditions. It is common, however, for servicing to occur when the filter appears dirty. Engine air filters are designed to increase in efficiency by using the initial layer of dust as an added filter layer. Initial filter efficiency is about 98% but increases to more than 99% by the end of the filter service life [9, 10]. Thus, changing an air filter before the useful service life is achieved can result in premature engine wear [8, 9, 10, 11].

In engineering terms, the service life of an air filter is commonly defined as a level of restriction which results in a pressure drop across the filter of about 2.5 kPa (10 in. water) more than the pressure drop of the new or clean filter at the maximum flow rate for the engine [7, 11, 12, 13]. This condition is defined as the "final pressure drop" when conducting tests to investigate filter cleaning procedures [12].

According to Patil, Halbe, and Vora, it is common for air filter service indicators to be set between about 5.0 and 7.0 kPa [9], which corresponds to the setting of the Chevrolet Silverado unit. The 2006 Dodge Ram 5.9 L and 2007 Dodge Ram 6.7 L units were set at a somewhat lower range, possibly due to the vehicles being equipped with diesel engines. As noted previously, while the level of restriction on a closed-loop feedback, throttled, spark ignition engine does not affect fuel economy, the additional pumping loss might be expected to affect an unthrottled diesel engine.

This study used the same method for filter clogging that was used in the gasoline vehicle study [1]. An air filter was considered fully clogged if the pressure drop exceeded about 5.0 kPa at the maximum air flow point, which would likely be realized by wide open throttle (WOT) testing. A pressure drop of this magnitude would be adequate to set a filter indicator and also satisfy the pressure drop criteria in the literature [7, 11, 12, 13].

FEERC Vehicle Laboratory

Vehicle testing was performed at the FEERC vehicle laboratory. The laboratory features a Burke E. Porter 300 hp motor-in-the-middle, two-wheel drive, 48 in., single roll, AC motoring chassis dynamometer. The dynamometer meets requirements of the EPA Specifications for Large Roll Chassis Dynamometers. The laboratory is further equipped with three dedicated emissions benches, each with conventional California Analytical Instruments five-gas analyzers. Two benches routinely measure raw undiluted emissions (e.g., engine-out and tailpipe emissions), and the third bench samples dilute exhaust from a constant volume sampling system (CVS or dilution tunnel). The CVS is equipped with three critical flow venturis, allowing several discrete flow rates ranging from 200 to 1,050 ft^3/min. The CVS bag sampler is equipped with conventional analyzers for CO, CO_2, NO_X, and total hydrocarbons (THC) and can also accommodate more advanced emissions instrumentation for particulate matter, ethanol, aldehyde, and other measurements. The laboratory temperature and humidity are regulated and measured. All continuous modal emissions data and additional sensors and vehicle controller network information can be acquired by an integrated data acquisition system. The FEERC laboratory has been cross-checked against three independent certification laboratories, and results are in excellent agreement for fuel economy and vehicle emissions.

Test Vehicles

The following three turbocharged diesel vehicles were tested.

- 2007 Dodge Ram 2500 Truck-6.7 L inline six (I6) engine with a variable geometry turbocharger system, six speed automatic transmission, medium duty, with a diesel particulate filter (DPF) and lean NO_X trap (LNT) emissions system.
- 2009 Volkswagen Jetta TDI-2.0 L turbocharged inline four cylinder (I4) engine, six speed manual transmission, with a DPF and LNT emissions system.
- 2009 BMW 335d-3.0 L I6 engine with a sequential twin-turbocharger system, six speed automatic transmission, with a DPF and a urea selective catalytic reduction (SCR) emissions system.

The Ram and Jetta were chosen for their differing engine sizes and relatively high sales volumes. Although growing in popularity, diesel vehicle options in the United States are currently limited. Difficulties were experienced with the Ram and Jetta in obtaining results with the same level of consistency found with many other vehicles [1]. This variability was attributed to the regeneration of the LNTs and led to choosing the BMW, which uses a urea SCR system for NO_X control.

VEHICLE TESTING

The initial objective for testing each vehicle was to measure fuel economy and emissions for the FTP, HFET, and US06 driving cycles and also perform a purposeful WOT test to examine the maximum filter pressure drop and changes in acceleration performance. All tests were intended to be performed for a clean air filter and a clogged air filter; for some limited cases a severely clogged filter state was also examined.

Simulating a Clogged Air Filter

During previous testing of gasoline vehicles, a method was developed to obtain a level of air filter clogging that would set a filter indicator and that was beyond the level of air filter pressure drop (~5.0-7.0 kPa at the maximum air flow point, which would likely be realized by WOT conditions) considered acceptable [1]. The same method of adding shop towels across the face of the intake air filter was used for the three diesel vehicles.

Experimental Challenges

The testing of the three diesel vehicles began with the Ram 2500 truck. Difficulties in completing the desired test sequences were quickly encountered but were somewhat predictable. The 6.7 L engine is rated at 350 hp, which is near the maximum capacity of the chassis dynamometer. Furthermore, the full-flow dilution tunnel temperature limitations could be exceeded while testing this vehicle at high loads. Therefore the US06 and WOT tests were omitted for the Ram to avoid damage to laboratory equipment.

Aftertreatment Considerations

The fact that all three vehicles were equipped with DPFs and the Jetta and Ram used LNTs posed additional challenges. Both aftertreatment devices require regeneration, which can cause significant instantaneous increases in fuel consumption. The DPF regenerations were found to be easily detected from the large temperature excursions and a very obvious increase in CO_2 emissions. Fortunately, the DPF regeneration events were fairly infrequent (affecting only 10%-15% of attempted tests). Any test involving DPF regeneration was simply discarded from analysis. LNT regeneration is much more frequent and more difficult to detect. A special preparatory test technique (explained later) was developed for testing the Jetta in an effort to obtain comparable data.

The BMW 335d uses urea SCR for NO_X control; the urea dosing does not introduce fuel consumption variability from the rich exhaust pulses required for the LNT system. Because the NOx treatment technology is not coupled to fuel use, very consistent fuel economy test results were obtained for this vehicle.

Dodge Ram Truck

As mentioned previously, because of equipment limitations only the FTP and HFET tests were performed with the Ram 2500. Although no WOT conditions (maximum air intake flow conditions) were explored, it was obvious that the clogged filter tests had more than sufficient air filter pressure drop to simulate a filter that should be replaced. The maximum air filter DP and cycle-average DP for the air filter are shown in Figure 2 (values are averaged over repeated tests). The air filter indicator (shown in Figure 1) set to the "change" position for every clogged filter FTP test (exceeded ~ 3.6 kPa peak DP), and it set every time during the severely clogged tests for both FTP and HFET test cycles.

The fuel economy results for the Ram truck are shown in Figure 3. Test-to-test variability is higher for this vehicle than the typical ±1% for this laboratory, believed to be due to LNT regeneration. The results do not show any measureable decline in fuel economy due to filter clogging, and any perceived change is attributed to test-to-test variation. The range bars in Figure 3 give the maximum and minimum values obtained, and the columns give the average of the data set.

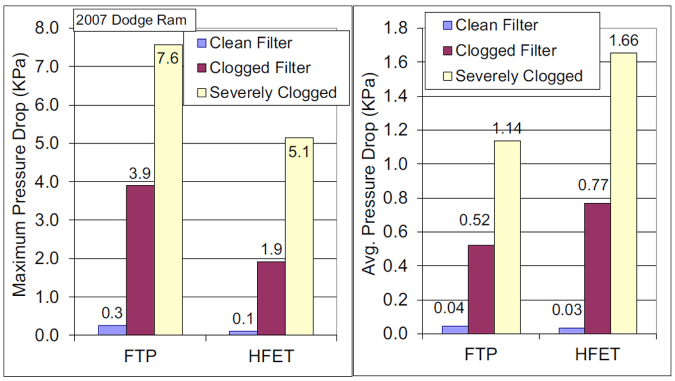

Figure 2. Maximum and average differential pressure across the air filter for the 2007 Dodge Ram truck.

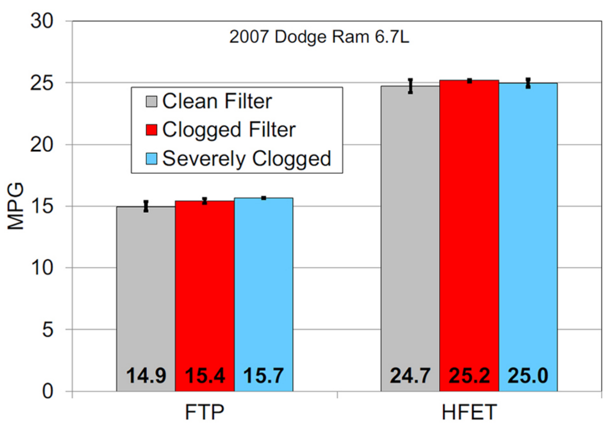

Figure 3. Fuel economy results for the 2007 Dodge Ram truck. Error bars indicate the data range (maximum and minimum values).

Exhaust emissions results for the Ram truck are given in Tables A1 and A2 in the appendix. Filter clogging does not appear to have any measureable effect on emissions. One clean filter test resulted in higher than average NO_X emissions (0.297 g/mile). Reasons for this outlier are not clear but are probably related to the LNT condition at start-of-test.

Volkswagen Jetta

Some of the results of the initial test cycles for the Volkswagen Jetta were sufficiently erratic to prompt a revised approach. Fuel economy results for the HFET and the USO6 cycles appeared to be particularly erratic and almost bimodal even after disregarding all data involving DPF regeneration. It appeared that the LNT was being regenerated significantly more in some tests than others due to the condition of the LNT at start-of-test. To start each HFET and US06 test with the vehicle and the LNT in a similar state, a special preparatory cycle was developed. When the vehicle was driven at a steady 50 mph for 10 min just before starting each HFET and US06 test, the results were found to be much more consistent. All HFET and US06 test results for the Jetta presented here were collected using this method.

The FTP tests were found to be fairly consistent, so no revised test procedures were deemed necessary. Preparation for the FTP tests consisted of the previous day's tests, which included a minimum of an FTP, HFET, and USO6. Furthermore, the average airflow and air filter pressure drop are lowest for the FTP cycle and should be the least sensitive to air filter state.

The severely clogged case was dropped for the HFET and US06 cycles because of time and resource constraints (but had been performed for the FTP cycle).

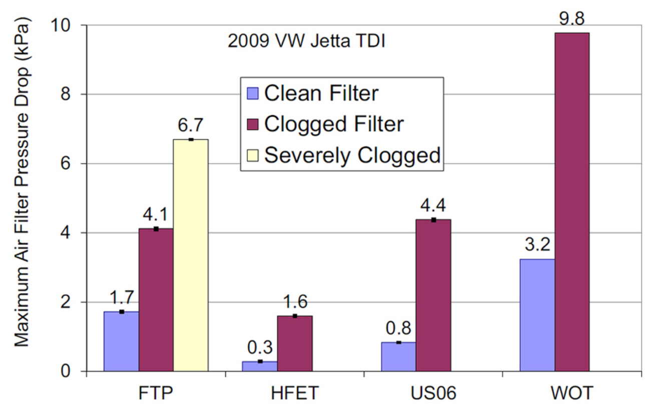

Figure 4. Maximum intake air filter differential pressure for the Volkswagen Jetta test cycles.

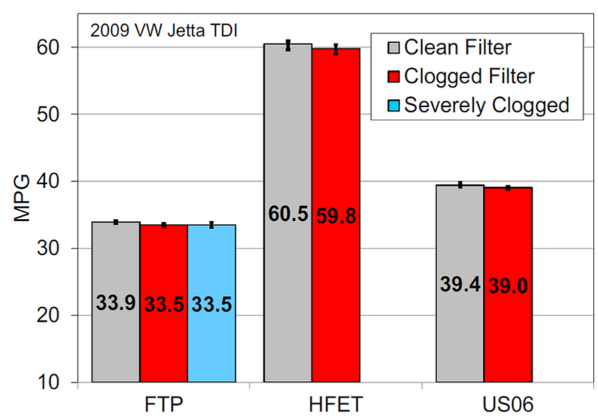

Figure 5. Fuel economy results for the Volkswagen Jetta. Error bars indicate the data range (maximum and minimum values).

Air filter maximum DP results for the Jetta tests are shown in Figure 4. The WOT test reveals that the clogged filter DP is well beyond the earlier criteria for a filter needing to be changed. Fuel economy results are summarized in Figure 5; no change in fuel economy is seen beyond the bounds of typical test variation. Results for 20-80 mph acceleration times for the WOT test are given in Figure 6, showing a small but measureable performance drop due to the clogged filter.

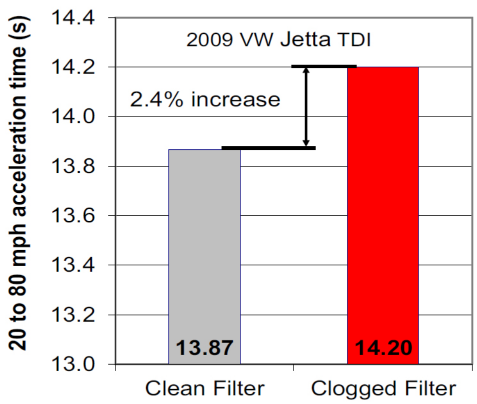

Figure 6. Volkswagen Jetta wide open throttle acceleration time from 20 to 80 mph.

Exhaust emissions results for the Jetta are presented in Tables A3, A4, A5 in the appendix. The FTP results in Table A3 show high NO_X emissions for the clean filter case and then NO_X emissions dropping with the degree of filter clogging. Although this appears to be a trend, possibly caused by air filter pressure drop, evidence suggests this result is caused mainly by variations in LNT function and the sample set being small. When observing the chronology of the tests, it was found that an LNT desulfurization event occurred just before the FTP tests with the severely clogged filter. It occurred during a (discarded) HFET test, which had very high CO emissions (almost all other HFET tests had no measureable CO) during relatively steady cruising, indicating rich operation typical of LNT desulfation. The newly desulfurized LNT would at least explain why very low NOx values are measured for the two severely clogged air filter FTP tests. A number of tests immediately following the LNT desulfation event had relatively low NOx emissions.

No emission trends are observed for the Volkswagen Jetta HFET and US06 tests.

BMW 335d

The testing campaign for the BMW 335d produced more consistent results than those for the LNT-equipped vehicles. The air filter DP results, shown in Figure 7, indicate that the clogged filter DP is well beyond the criteria for a filter requiring replacement. A severely clogged case was included for the HFET and US06 cycles and the WOT tests. Fuel economy results, summarized in Figure 8, show no measureable change in fuel economy due to the air filter condition. Results for 20-80 mph acceleration times for the WOT test are given in Figure 9, showing a small but measureable performance drop due to the clogged filter.

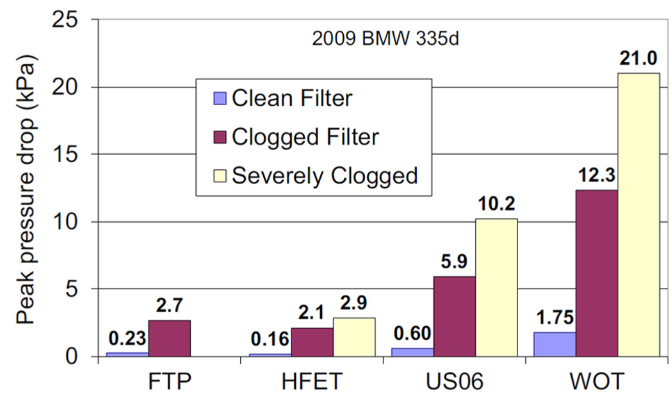

Figure 7. Maximum intake air filter differential pressure for the BMW 335d test cycles.

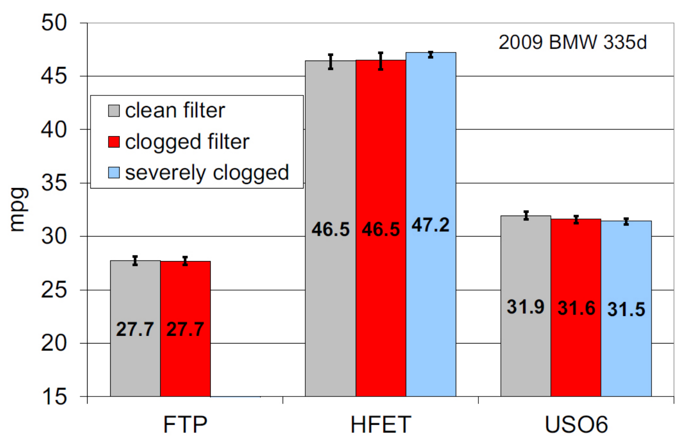

Figure 8. Fuel economy results for the BMW 335d. Error bars indicate the data range (maximum and minimum values).

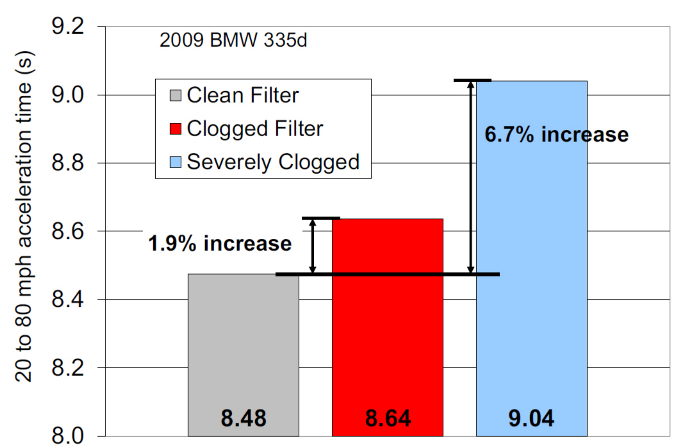

Figure 9. Time comparison for wide open throttle accelerations from 20 to 80 mph for the BMW 335d.

Tables A6, A7, A8 in Appendix A show the BMW emission results, and again, no obvious trends are noted. In Table A8 and Figure A1, NO_X emissions on the US06 test appear to decrease with the degree of filter clogging. The decrease in lambda with filter clogging may contribute to decreased NO_X. The US06 cycle-average lambda value and lowest measured lambda values are shown in Figure 10. This small change in lambda may influence NO_X produced by the engine and cause the apparent NO_X trend. However, it is important to note that this trend could also be contributed to or caused by the urea SCR system.

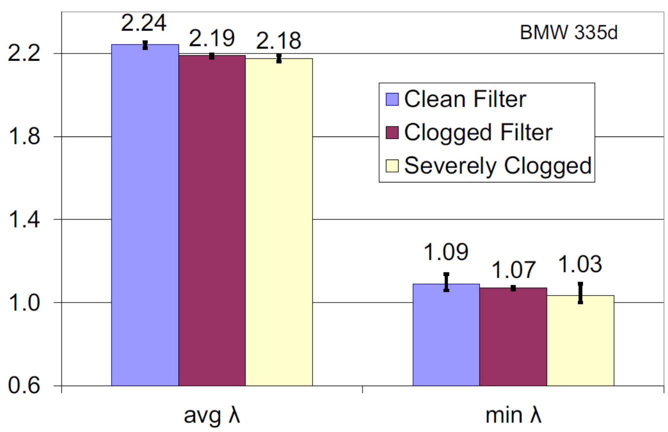

Figure 10. BMW 335d average lambda value over US06 cycles and minimum lambda values for the US06 tests (average of like tests). Error bars indicate the data range (maximum and minimum values).

ESTIMATE OF INCREASED PUMPING WORK

The engine mass air flow rate and the air filter DP traces were recorded for the BMW drive cycle tests as shown in Figure 11. These measurements allow the pumping power required to pull air through the filter to be estimated. The average pumping power calculated for the US06 cycle was estimated to be about 5 W for the clean filter case, and 52 and 98 W for the clogged and severely clogged air filter cases. For the severely clogged case, about 58 kJ of work (energy) is required over the US06 cycle (97.7 W × 596 s = 58.2 kJ). Diesel fuel has a lower heating value of about 42.5 kJ/g; therefore, 58 kJ represents about 1.36 g of fuel on an equivalent energy basis or about 4.5 g of fuel burned at an assumed engine efficiency of 30%. This 4.5 g of fuel represents less than 0.6% of the total fuel burned during a US06 test, which is just beyond the sensitivity of chassis dynamometer testing. Using the same logic, the estimate for the US06 clogged filter case would be 2.4 g of fuel or about 0.3% of the total fuel for the test. The cumulative pumping work required for the BMW 335d US06 and HFET cycle tests depending on the filter state is shown in Figure 12.

The US06 cycle proved to be the "worst case" of the cycles examined, and similar calculations for the FTP and HFET tests imply the effect is less than half of that estimated for the US06 in terms of estimated percent fuel penalty. This result is due to the high power demand (and high air flow rates) for the US06 cycle compared to the other cycles.

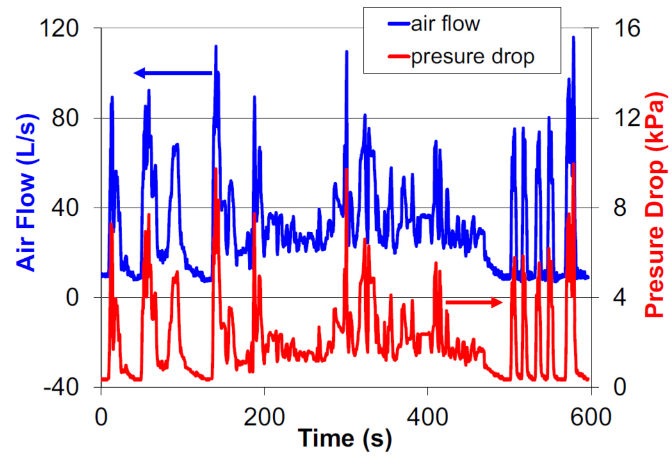

Figure 11. BMW 335d engine intake air flow and pressure drop across the air filter for the US06 cycle.

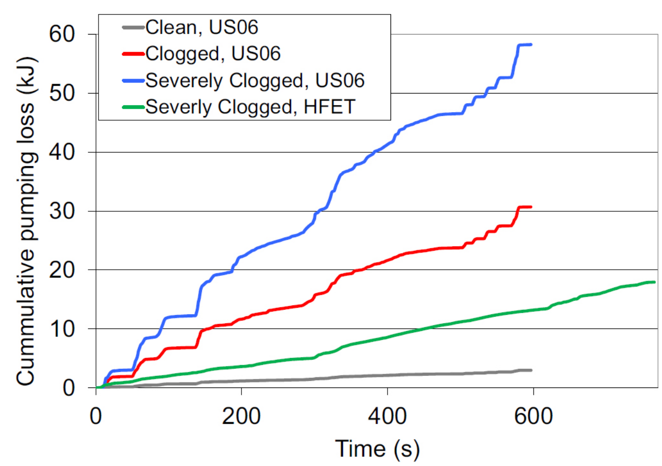

Figure 12. Cumulative pumping work required for selected BMW 335d cycle tests.

SUMMARY/CONCLUSIONS

The main goal of this study was to explore the effects of a clogged intake air filter on the fuel economy of diesel powered vehicles operating over prescribed test cycles. Three late model turbocharged diesel vehicles were tested, including a 2.0 L I4, a 3.0 L I6 and a 6.7 L I6 engine. For two vehicles, the FTP, HFET, and US06 were used to examine the effects of the air filter state, and a WOT test was conducted to quantify the air filter pressure drop and assess the change in acceleration performance. The Dodge Ram truck was not tested using the US06 and WOT tests due to equipment limitations, although significant pressure drops were realized in the clogged filter test cases over the FTP and HFET.

Results for a high level of air filter clogging indicated the effect on fuel economy was small and was less than the sensitivity of standard dynamometer vehicle testing. A small effect on exhaust emissions was noted in some circumstances.

Analysis of pumping work energy consumption for the BMW gave further evidence that only a small effect on fuel consumption would be expected even when filter clogging was far beyond the point of recommended filter replacement.

Other possible powertrain effects due to a clogged air filter (change in engine control, exhaust gas recirculation, etc.) could not be ruled out, but they were small enough to not be detected by the cycle testing in this study.

The two sedans did show a modest loss in acceleration performance due to filter clogging, showing measureable effects at WOT conditions.

For consumer advice, the authors conclude that changing the air filter more often than the vehicle manufacturer's recommendation will be of little or no value (driving conditions should be taken into account and are normally discussed in the vehicle owner's manual).

There was evidence that the presence of an LNT system for NO_X control confounded repeatability for some experiments. Regeneration of the DPF was infrequent but observed for all three vehicles during the testing campaigns and seemed quite obvious when occurring.

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DISCLAIMER

DEFINITIONS/ABBREVIATIONS

CVS - constant volume sampling

DOE - US Department of Energy

DP - differential pressure

DPF - diesel particulate filter

EPA - US Environmental Protection Agency

FEERC - Fuels, Engines, and Emissions Research Center (ORNL)

FTP - Federal Test Procedure (EPA)

HFET - Highway Fuel Economy Test (EPA)

I4 - inline four

I6 - inline six

lambda - Actual air:fuel/stoichiometric air:fuel (rich < 1.0; lean > 1.0)

LNT - lean NOX trap

ORNL - Oak Ridge National Laboratory

SCR - selective catalytic reduction

THC - Total hydrocarbons (uncorrected FID hydrocarbons)

US06 - high speed, high load drive cycle (part of supplemental FTP)

WOT - wide open throttle

APPENDIX A. EMISSIONS DATA

Tables A1, A2, A3, A4, A5, A6, A7, A8 are presented here, as called out in the body of the paper.

Table A1. Dodge Ram 6.7 L turbo-diesel FTP cycle emissions summary

Air filter state	Clean			Clogged			Severely clogged		
	Avg. of 4	Max.	Min.	Avg. of 2	Max.	Min.	Avg. of 2	Max.	Min.
CO (g/mile)	0.20	0.24	0.17	0.21	0.22	0.21	0.24	0.24	0.20
CO_2 (g/mile)	681	695	665	659	667	651	649	650	648
NO_X (g/mile)	0.160	0.297	0.098	0.099	0.110	0.088	0.095	0.102	0.089
Total hydrocarbons (g/mile)	0.243	0.317	0.140	0.271	0.320	0.222	0.275	0.283	0.268
Fuel economy (mpg)	14.9	15.3	14.6	15.4	15.6	15.2	15.7	15.7	15.6

Table A2. Dodge Ram 6.7 L turbo-diesel HFET cycle emissions summary

Air filter state	Clean			Clogged			Severely clogged		
	Avg. of 4	Max.	Min.	Avg. of 3	Max.	Min.	Avg. of 2	Max.	Min.
CO (g/mile)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO_2 (g/mile)	412	420	404	404	406	403	408	413	402
NO_X (g/mile)	0.064	0.090	0.044	0.056	0.068	0.039	0.079	0.090	0.069
THC (g/mile)	0.073	0.099	0.056	0.063	0.072	0.057	0.065	0.066	0.064
Fuel economy (mpg)	24.7	25.3	24.2	25.2	25.3	25.1	25.0	25.3	24.7

Table A3. Volkswagen Jetta 2.0 L turbo-diesel FTP cycle emissions summary

Air filter state	Clean			Clogged			Severely clogged		
	Avg. of 2	Max.	Min.	Avg. of 3	Max.	Min.	Avg. of 2	Max.	Min.
CO (g/mile)	0.15	0.24	0.07	0.31	0.40	0.21	0.16	0.16	0.16
CO_2 (g/mile)	299	301	298	303	306	301	303	307	300
NO_X (g/mile)	0.102	0.131	0.072	0.057	0.071	0.050	0.009	0.010	0.009
THC (g/mile)	0.139	0.157	0.122	0.189	0.213	0.177	0.162	0.170	0.153
Fuel economy (mpg)	33.9	34.1	33.8	33.5	33.7	33.2	33.5	33.9	33.1

Table A4. Volkswagen Jetta 2.0 L turbo-diesel HFET cycle emissions summary

Air filter state	Clean			Clogged		
	Avg. of 6	Max.	Min.	Avg. of 3	Max.	Min.
CO (g/mile)	0.00	0.00	0.00	0.00	0.00	0.00
CO_2 (g/mile)	168	171	167	170	172	169
NO_X (g/mile)	0.065	0.110	0.022	0.106	0.165	0.011
THC (g/mile)	0.011	0.035	0.001	0.011	0.018	0.005
Fuel economy (mpg)	60.5	60.9	59.6	59.8	60.4	59.0

Table A5. Volkswagen Jetta 2.0 L turbo diesel US06 cycle emissions summary

Air filter state	**Clean**			**Clogged**		
	Avg. of 3	**Max.**	**Min.**	**Avg. of 3**	**Max.**	**Min.**
CO (g/mile)	0.00	0.00	0.00	0.00	0.00	0.00
CO_2 (g/mile)	258	260	255	260	262	259
NO_X (g/mile)	0.700	0.778	0.657	0.778	0.851	0.690
THC (g/mile)	0.088	0.093	0.085	0.093	0.108	0.064
Fuel economy (mpg)	39.4	39.8	39.2	39.0	39.2	38.8

Table A6. BMW 335d FTP cycle emissions summary

Air filter state	**Clean**			**Clogged**		
	Avg. of 5	Max.	Min,	Avg. of 3	Max.	Min.
CO (g/mile)	0.08	0.09	0.07	0.11	0.13	0.10
CO_2 (g/mile)	368	373	362	368	373	363
NO_X (g/mile)	0.046	0.054	0.039	0.040	0.045	0.037
THC (g/mile)	0.055	0.058	0.051	0.067	0.073	0.063
CH_4 (g/mile)	0.049	0.052	0.047	0.057	0.060	0.054
Nonmethane hydrocarbons (g/mile)	0.007	0.010	0.005	0.010	0.012	0.006
Particulate matter (g/mile)	0.0007*			0.0006	.0007	.0005
Fuel economy (mpg)	27.7	28.1	27.3	27.7	28.1	27.3

*Measured for one test only.

Table A7. BMW 335d HFET cycle emissions summary

Air filter state	**Clean**			**Clogged**			**Severely clogged**		
	Avg. of 5	**Max.**	**Min.**	**Avg. of 3**	**Max.**	**Min.**	**Avg. of 3**	**Max.**	**Min.**
CO (g/mile)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO_2 (g/mile)	220	223	217	219	224	216	216	218	216
NO_X (g/mile)	0.009	0.011	0.008	0.014	0.021	0.002	0.007	0.008	0.004
THC (g/mile)	0.015	0.018	0.012	0.018	0.020	0.017	0.017	0.018	0.016
CH_4 (g/mile)	0.014	0.016	0.012	0.017	0.020	0.016	0.015	0.016	0.014
Nonmethane hydrocarbons (g/mile)	0.002	0.004	0.000	0.001	0.001	0.0001	0.001	0.002	0.000
Fuel economy (mpg)	46.5	47.0	45.7	46.5	47.2	45.6	47.1	47.3	46.8

Table A8. BMW 335d US06 cycle emissions summary

Air filter state	**Clean**			**Clogged**			**severely clogged**		
	Avg. of 6	**Max.**	**Min.**	**Avg. of 3**	**Max.**	**Min.**	**Avg. of 3**	**Max.**	**Min.**
CO (g/mile)	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.06	0.00
CO_2 (g/mile)	319	323	315	323	327	320	324	328	322
NO_X (g/mile)	0.124	0.150	0.106	0.070	0.073	0.067	0.053	0.058	0.044
THC (g/mile)	0.010	0.0130	0.008	0.010	0.011	0.009	0.011	0.012	0.009
CH_4 (g/mile)	0.008	0.009	0.006	0.009	0.010	0.009	0.009	0.010	0.007
Nonmethane hydrocarbons (g/mile)	0.002	0.007	0.000	0.001	0.002	0.000	0.002	0.004	0.000
Fuel economy (mpg)	31.9	32.3	31.6	31.6	31.9	31.2	31.5	31.7	31.1

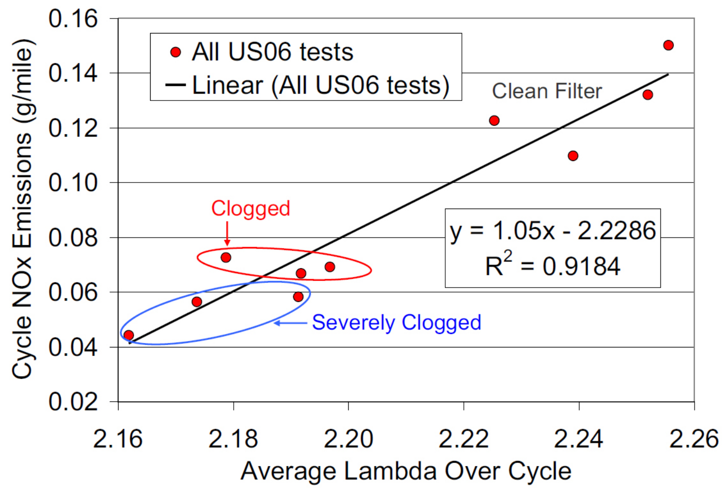

Figure A1. BMW 335d NOX emissions versus average lambda for the US06 cycle tests.

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