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Evaluation of the Effectiveness of Diesel Particulate Filter Cleaning Methods and their Effect on Fuel Consumption

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Abstract

The negative effects of long-term exposure to soot and particulate matter emissions from diesel exhaust on the human health have been widely acknowledged due to the harmful substances that exhaust gas contains. Regulators have established strict programs to determine the performance and reliability of emissions after-treatment systems and devices. Tests were conducted to evaluate the efficacy of three diesel particulate filter (DPF) cleaning methods: 1) thermal and pneumatic cleaning, 2) ultrasonic cleaning, and 3) aqueous cleaning methods. A novel non-destructive method to quantify soot and ash deposits in the filters was developed, validated and used to determine the effectiveness of the identified cleaning methods. Given the number of different cleaning methods available, testing against a set of standard parameters provided accurate comparative results. Test results showed at least satisfactory ratings for all cleaning systems that were evaluated, while two systems stood out with very good ratings, with up to 96% of deposits removed by one cleaning system. Fuel consumption tests based on SAE J1321 and TMC RP 1102A Fuel Consumption Test Procedure – Type II were also performed to determine the effect of diesel particulate filter cleaning methods on fuel consumption. The tests were conducted on a high-speed test track at a constant speed of 105 km/h (65 mph). Test results showed that excluding the fuel consumed during passive regeneration, the level of obstruction of the diesel particulate filter showed little impact on fuel consumption. Results comparing the fuel consumption of a cleaned DPF versus that of a used DPF ranged from 0.65% to 1.43%.

Introduction to Diesel Particulate Filters

Particulate matter (PM) is a major environmental and health concern due to the damage it causes to the environment as to human health [1]. The negative effects of long-term exposure to soot and PM emissions from diesel exhaust on the human health have been widely acknowledged due to the dangerous and harmful substances that exhaust gas contains. Table 1 describes the various types of emissions from heavy duty diesel engines [2].

A diesel particulate filter (DPF) is a device which eliminates diesel exhaust PM emissions. Once installed in the exhaust stream of a diesel engine, exhaust gases are directed through porous cell walls in the filter, which trap PM. The filters can be made of several materials such as ceramic and silicon carbide, fiber wood cartridges, wire mesh, and sintered metal structures [3]. The filter is usually an extruded cylindrical part made of a ceramic honeycomb structure combined with precious metals that traps soot particles in the exhaust gas [4]. The ceramic honeycomb structure has channels that are sealed on one end to force the exhaust gas through the permeable wall to be filtered [1].

A typical DPF would have hundreds of cells per square inch of filter space. Modern diesel after-treatment systems have exhaust gas flow through a diesel oxidation catalyst prior to entering the DPF. The particles get trapped in the DPF and accumulate over time, causing a pressure differential across the DPF, called back pressure. A high-pressure differential is an indication that the DPF needs to be cleaned to remove the accumulated particles [5, 6]. Thus, the DPF needs to provide a way of removing PM that has been collected in the filter. This process is called regeneration, where the filter burns the soot it has collected [1].

Regeneration is activated when the pressure sensors detect that the back pressure is above set limit, which is an indication that the filter is clogged. At this point, fuel is placed on the catalyst and oxidized, which creates heat to turn the trapped soot to ash. This ash remains in the filter until it is removed by an external cleaning process. Soot generated by diesel combustion can be fully regenerated with no ash remnants, however, soot from additives in the fuel, lubricants in the oil, and engine wear cannot be fully regenerated, leaving ash as the regeneration residue [6, 1].

TABLE 1 Common Pollutants Emitted by Diesel Engine Combustion [2].

Emissions	Description
Oxides of nitrogen (NO and NO_2)	NO_x is used to commonly refer to a variety of nitrogen oxides. NO_2 is produced from burning fuel from various types of vehicles, power plants and off-road equipment [2].
Carbon monoxide (CO)	CO is produced from fuel combustion and is colorless and odorless and can be harmful when inhaled in large quantities [2].
Hydrocarbons (HC)	The term total hydrocarbons (THC), or total petroleum hydrocarbons (TPH), refer to chemical compounds made from hydrogen and carbon that come from crude oil [2].
Particulate matter (PM)	PM is the solid content in the exhaust gas, mostly made up of soot, which is combustible matter (carbon), and ash, which is incombustible matter from compounds in lubricating oil residue [2].

FIGURE 1 Vertical cross-section of a clogged DPF.

Regeneration produces ash, which accumulates after several regeneration events and reduces the filtration area, thereby increasing the frequency of active regenerations, increasing back pressure, and hence, fuel consumption [5]. Ash build-up changes the channel geometry in the DPF and reduces the capacity of the DPF to trap soot, thereby obstructing exhaust flow. As the vehicle continues to be operated in this condition, the effective volume of the DPF decreases, which increases back pressure from the DPF, resulting in engine performance degradation and increase in fuel consumption. This can be avoided by periodically removing the DPF and cleaning it [1]. Figures 1 to 4 show the amount of deposits (soot and ash) in a used DPF that was cut open and the extent of the damage to the DPF. Note that damage to the DPF could be due to excessive heat from multiple regenerations of a heavily clogged filter.

FIGURE 2 Excessive ash build-up in a DPF.

FIGURE 3 Melted DPF substrate.

FIGURE 4 Cracking in the DPF core.

Similarly, Gasoline Particulate Filters (GPF) are built with a honeycomb structure with inlet and outlet channels. The basic difference between a DPF and a GPF is that the GPF is more porous, allowing easier flow through the substrate. As well, GPF regeneration is passive, which means high exhaust temperatures are not required during the process [7, 8]. Given

TABLE 8 Weather conditions during fuel consumption testing – temperature and air density variation

	Temperature				Air density variation	
	Average		Mean variation			
Test	°C	°F	°C	°F	kg/m³	%
Baseline segment	11.71	53.08	2.39	4.30	0.021	1.65
Test segment 1	8.77	47.79	1.11	2.00	0.010	0.81
Test segment 2	10.06	50.11	1.32	2.38	0.010	0.79
Test segment 3	12.14	53.85	0.53	0.95	0.012	0.94
Test overall	10.67	51.21	1.86	3.35	0.030	2.61

TABLE 9 Weather conditions during fuel consumption testing – wind speed variation

	Wind speed					
	Mean		Mean variation		Maximum gust	
Test	km/h	mph	km/h	mph	km/h	mph
Baseline segment	6.13	3.81	1.11	0.69	16.57	10.30
Test segment 1	3.45	2.14	1.07	0.66	10.12	6.29
Test segment 2	4.86	3.02	2.84	1.76	19.33	12.01
Test segment 3	6.26	3.89	1.13	0.70	23.01	14.30
Test overall	5.18	3.22	1.77	1.10	23.01	14.30

The temperature of the fuel in the tank was randomly checked several times during the tests and never exceeded 44 °C (108 °F); the maximum temperature suggested by the test procedure is 71.1 °C (160 °F) [12]. Fuel temperature was controlled, given that the portable tanks used for fuel consumption measurements had a large capacity (144 L, 38 U.S. gal.) and the return of the fuel into the tank was made by splashing.

In order to eliminate the influences of traffic and variations in driver response, testing was conducted on a closed-loop test track at a fixed speed of 105 km/h (65 mph), using a standard acceleration and braking protocol for all drivers. In addition, travel speeds were monitored throughout the tests using radar, and drivers were instructed by radio if it became necessary to adjust their travel speed. Moreover, the vehicles were equipped with GPS, and GPS data were used to confirm vehicle speed. The drivers' influence on the results was thus minimized as much as possible by strictly controlling the driving cycle.

Minimum vehicle spacing was 0.8 km (0.5 mi.), which is within the limits stipulated by the test procedure: 0.4–1.2 km (1/4–3/4 mi.) [12].

To minimize measurement uncertainties, the only measured parameter used to calculate the test results was the weight of the portable tanks. Other parameters, such as vehicle speed, distance, and time, were recorded for information purposes only. In order to avoid potential problems related to the instruments, two recently calibrated scales were available on-site. For each run, the portable tanks were weighed using the same portable scale. Furthermore, the scale was checked against a known weight of 120 kg (264 lb.) before each series of weighing. The portable scale was not moved between the initial and final weighing for a given test run.

Distance measurement was not a factor because for each run, all vehicles departed and arrived at the same point after travelling the same number of laps and following the same path along the track.

Conclusion

Tests were conducted to evaluate the efficacy of three diesel particulate filter (DPF) cleaning methods: 1) thermal and pneumatic cleaning, 2) ultrasonic cleaning, and 3) aqueous cleaning methods. A novel non-destructive method to quantify soot and ash deposits in filters was developed, validated and used to determine the effectiveness of the identified cleaning methods. Filters were cleaned with an aqueous system, two pneumatic and thermal systems, and an ultrasonic system. In terms of amount of ash deposits removed, the best performing cleaning systems were the pneumatic-thermal system 2 and the ultrasonic system. In terms of the cleaning process, the aqueous system demonstrated the best experience. It should be noted that the ultrasonic system showed the highest relative percentage of deposit removed for a DPF (96%).

Fuel consumption tests based on SAE J1321 and TMC Fuel Consumption Test Procedure – Type II were also performed to determine the effect of diesel particulate filter cleaning methods on fuel consumption. The tests were conducted on a high-speed test track at a constant speed of 105 km/h (65 mph). Test results showed that excluding the fuel consumed during passive regeneration, the level of obstruction of the diesel particulate filter showed little impact on fuel consumption. Results comparing the fuel consumption of a cleaned DPF versus that of a used DPF ranged from 0.65% to 1.43%.

References

1. Guan, B., Zhan, R., Lin, H., and Huang, Z., "Review of State-of-the-Art Exhaust Particulate Filter Technology in Internal Combustion Engines," *Journal of Environmental Management.* (2015).

2. EPA, U.S., (2016), "Verified Technologies for SmartWay and Clean Diesel. Retrieved from Https://www.epa.gov/verified-diesel-tech/verified-technologies-list-clean-diesel (Dec. 9, 2016b)".
3. Hua, X., Herrin, D.W., Wu, T.W., and Elnady, T., "Simulation of Diesel Particulate Filters in Large Exhaust Systems," *Applied Acoustics* 74, no. 12 (2013): 1326-1332.
4. Berg, T., (2008), Emissions Report: Servicing the New Diesel Particulate Filters. Retrieved from http://www.truckinginfo.com/article/story/2008/02/emissions-report-servicing-the-new-diesel- particulate-filters.aspx
5. Bennink, C., (2013), "Don't Let Reliability Go out the Pipe," Retrieved from http://www.forconstructionpros.com/article/10975495/medium-and-heavy-duty-trucks-dont-let-reliability-go-out-the-pipe
6. American Radiator, (2016), "Understanding your Diesel Particulate Filter," Retrieved from http://radiatorpros.com/index.php/how-a-dpf-works/?store=default
7. Insight, *Gasoline Particulate Filters* (Infineum International Limited, 2018)
8. Dadam, S.R., Van Nieuwstadt, M., Lehmen, A., Ravi, V.K. et al., "A Unique Application of Gasoline Particulate Filter Pressure Sensing Diagnostics," *SAE International Journal of Passenger Cars-Mechanical Systems* 14, no. 06–14-02-0007 (2021): 105-116.
9. Sturgess, S., (2009), "Diesel Particulate Filters," Retrieved from http://www.truckinginfo.com/article/story/2009/05/diesel-particulate-filters.aspx
10. Heavy-duty Parts Report, (2022), "Understanding the Different Types of DPF Cleaning Processes," Retrieved from https://heavydutypartsreport.com/understanding-the-different-types-of-dpf-cleaning-processes/
11. FPInnovations, (2019), "Industrial CT Scanner," Retrieved from https://fpinnovations.ca/solutions-and-technologies/Pages/industrial-ct-scanner.aspx
12. Technology & Maintenance Council (TMC), *TMC Fuel Consumption Test Procedure Type II, RP 1102A* (Arlington, VA: American Trucking Associations, 2014)
13. Surcel, M.-D., Michaelsen, J., and Provencher, Y., "Track-Test Evaluation of Aerodynamic Drag Reducing Measures for Class 8 Tractor-Trailers," SAE Technical Paper 2008-01-2600 (2008, 2008). https://doi.org/10.4271/2008-01-2600.
14. SAE International, *Fuel Consumption Test Procedure – Type II, SAE Surface Vehicle Recommended Practice J1321* (PA: Warrendale, 2012)

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