2019-01-0732 Published 02 Apr 2019

Enhanced Fuel Economy Retention from an Ultra-Low Ash Heavy Duty Engine Oil

Shawn Whitacre and Wim Van Dam Chevron Lubricants

Citation: Whitacre, S. and Van Dam, W., "Enhanced Fuel Economy Retention from an Ultra-Low Ash Heavy Duty Engine Oil," SAE Technical Paper 2019-01-0732, 2019, doi:10.4271/2019-01-0732.

Abstract

Diesel particulate filters are remarkably efficient in reducing emissions of particulate matter from heavy-duty diesel engines. However, their efficiency and performance are negatively impacted by contaminants derived from consumed engine lubricant. This accumulation of incombustible ash imparts a fuel economy penalty due to increased system backpressure and demand for more frequent regeneration events. This study documents a systematic evaluation of lubricant impacts on DPF ash loading, system performance, and fuel economy. A novel, ultra-low ash heavy-duty engine oil demonstrates significant advantages in aged systems when compared to tests using conventional lubricants. The ultra-low ash oil yields a significantly lower ash loading that is also more dense therefore offering extended DPF maintenance interval and potential for 3% fuel economy retention benefit. These advantages offer potential for significant reduction in cost to operate and maintain a DPF equipped engine.

Introduction

Diesel engine exhaust gas after-treatment systems, including diesel particulate filters (DPF), have been pervasive since the mid 2000s to enable the reduction of particulate matter (PM), nitrogen oxide, and hydrocarbon emissions. Coincident with their introduction, a new generation of engine lubricants with lower sulfated ash, phosphorous and sulfur levels was introduced [1]. These constituents, sometimes referred to collectively as SAPS are derived largely from metallic additives that include calcium, magnesium, zinc, molybdenum and boron and that are used to enhance the functionality of the lubricant.

Since the introduction of DPFs, the industry has gained experience with the maintenance of these devices. By design, the DPF accumulates exhaust soot particles that are later burned off by elevating the temperature of the DPF. This "regeneration" is facilitated, in part, by an exotherm generated by supplemental fuel injection and therefore contributes to a "fuel economy penalty". Noguchi, et al. [2] documented fuel economy penalties in the range of 2.0-4.5%. It is also widely documented that DPFs are vulnerable to accumulation of incombustible particles that are derived largely from the additives and wear particles found in consumed engine oil [3, 4, 5, 6, 7, 8]. Although specifications limit the amount of ash in the engine oil, DPFs do still require periodic maintenance to remove this incombustible material which otherwise accumulates and interferes with PM reduction efficiency and imposes a backpressure on the system that impacts engine efficiency and fuel economy. Sappok and Wong [9] reported a doubling of regeneration frequency with ash loadings in a DPF at 40 g/L. Liu, et al. [10] as well as Zollner and Brueggemann [11] resolved the relative impacts of ash and soot on DPF backpressure and quantified the impact of ash on the exotherm associated with regeneration.

As the industry learned more about the in-use DPF maintenance requirements, engine builders raised a question about the possibility of further reducing the sulfated ash of engine lubricants. This was deemed difficult or even impossible because the additives that contribute to sulfated ash in the lubricant are essential to the lubricant's performance. Over time a new generation of engine lubricant was developed with significantly lower sulfated ash. This work builds upon previously published studies that documented the performance of the oil [12] and its impact on limiting ash accumulation in DPFs [13].

This publication extends that work and addresses the performance evaluation of these new Ultra-Low Ash (ULA) oils in limiting the performance degradation associated with ash accumulation. Among the benefits are the potential for significantly extended maintenance intervals, and fuel economy retention benefits associated with the lower frequency of DPF regeneration and control of system backpressure.

Experimental

This experiment compares the impact of two different heavy-duty engine oils on their propensity to deposit ash in a DPF and evaluates the resulting effect on the fuel consumption and other performance characteristics of the diesel engine. A DPF aging protocol was employed to rapidly expose the devices to ash and allowed for periodic evaluations at increasing levels of ash loading. The aged devices were visually imaged to characterize the ash deposition as a function of the ash loading and allowed for comparisons of the two devices at equivalent aging times. Periodic evaluations of the system back-pressure and the accompanying impact on transient and steady-state fuel economy performance were conducted. Further details of this protocol are summarized here.

Test Fluids

This study compares the DPF aging effects of engine oils with two different sulfated ash levels. The "baseline" oil is a conventional 1% sulfated ash oil meeting API CJ-4 standard which was first introduced in 2006. The ULA oil is a pre-commercial 0.4% sulfated ash lubricant that meets the performance requirements of the API CK-4 specification. To normalize any impact of oil viscosity on fuel economy performance, both oils tested are SAE 15W-40 viscosity grade. Key properties of the two test oils are summarized in Table 1.

DPFs

Five production catalyzed cordierite DPFs with a volume of 6.25L were acquired for this study. These units were slightly but deliberately undersized for the application in order to increase the rate of ash loading per unit volume of DPF. The standard DPF for this application is 10.42L.

All of the DPFs were first exposed to an on-engine 4 hour "degreening" procedure consisting of a high engine speed and load condition followed by an active regeneration. This sequence was run a total of five times for a total of twenty hours of operation prior to the initial evaluations. A total of five DPFs were obtained, and the three with the most similar baseline performance were used for the balance of the study (one for repeat baseline measurements on an unaged part, the other two for the aging studies on their respective test oil).

DPF Aging Protocol

DPF aging was conducted in a test cell that has been specifically designed to facilitate rapid ash-loading of emission control devices. A model year 2010 Cummins ISB6.7 engine rated at 210 kW was modified to accelerate oil consumption and ash exposure to the DPF. The lower compression rings in all six cylinders were inverted, resulting in a 3X oil consumption increase over the engine's baseline oil consumption. In addition, an external oil reservoir suspended from a load cell with a pump for supply and return oil was utilized to maintain a fixed oil level in the engine's sump and to allow for real-time monitoring of the oil consumption rate. To further accelerate oil consumption, an oil injection system was installed to deliver fresh oil into the fuel supply at a known and carefully metered rate of approximately 0.14% of total fuel consumption. A schematic of this test cell configuration is included in the Appendix.

In this configuration, the consumed lubricant from the engine and via the oil injected into the fuel were roughly equivalent and could be carefully tracked throughout the course of the aging experiments by gravimetric measurements.

Ash loading rates were predicted from the measured oil consumption rates, and then confirmed via weighing the DPF after a soot regeneration.

TABLE 1 Test Engine Oil Properties

	Baseline Oil	ULA Oil
% Sulfated Ash	1%	0.4%
% Phosphorus	0.12%	0%
Kinematic Viscosity @100°C (cSt)	15.7	14.7
SAE Viscosity Grade	15W-40	15W-40

DPF Performance Evaluations

At each aging interval, the DPF was comprehensively evaluated as follows:

- Computerized Tomography (CT) scan to monitor ash deposition profile
- Flow sweep to determine soot/ash impact on DPF restriction
- Steady-state fuel economy performance during World Harmonized Stationary Cycle (WHSC)
- Transient and regeneration fuel economy performance during World Harmonized Transient Cycle (WHTC)

Performance evaluations were conducted on a test engine/stand that is separate from the aging engine. The aged DPFs were transferred from the aging cell and installed behind the engine in the evaluation cell at specific intervals. The evaluations were conducted on a model year 2013 Cummins ISB6.7 engine rated at 180 kW. Using the Cummins engineering tools, the test lab was able to communicate with the engine's electronic control unit to fix actuator positions, as well as to command active regenerations. The engine test cell was equipped with an exhaust system fitted with heat exchangers and valves so that the engine exhaust temperature could be regulated without altering the engine operating conditions. Combustion air was sourced from a temperature and humidity conditioned intake system which targeted an intake temperature of 25°C and a dewpoint of 15°C.

This test stand was used for soot loading, flow sweep cycles, and transient and steady-state performance evaluations for fuel economy measurement. All active regenerations used to determine ash loading level were run on this stand using a DPF inlet temperature of 650°C.

Computerized Tomography Scan At each evaluation interval, the DPF was removed from the exhaust and sent for imaging by CT. These tests allow for visual comparison of the ash deposition inside the DPF. It helps to estimate ash density, distribution, and uniformity. It can also detect large cracks or voids that develop in the DPF substrate during the aging sequence.

Scans were conducted on a GE v|tome|x 240m Industrial CT System, which is a cone-beam system with a maximum power of 320W and a tube voltage that can be adjusted to a maximum of 240 kV. This system uses a high-precision rotational stage to collect a large number of X-ray images as a part is rotated during the scan. These images are combined using geometric reconstruction software to produce a three-dimensional (3D) representation of the object that can be manipulated to expose internal features. For this study, the system was configured based on a previously established procedure for DPF X-ray CT examination using a tube voltage of 210 kV. 2000 images were collected, and the resulting voxel size was approximately 140 microns. The DPF data was analyzed by virtually slicing through the three-dimensional volume to expose the ash within the DPFs. Images were generated from these slices to document the distribution of the ash within the part and ash depth measurements were made using the analysis software to quantify the results.

Flow Sweep A flow sweep cycle characterized the DPF by measuring the pressure drop across the filter at a series of exhaust flow rates. A linear curve fit is applied to the average values from the final 30 seconds of each test mode so that a pressure drop across the DPF can be calculated for each fixed flow rate. These backpressures could then be compared as a function of both increasing soot and increasing ash loads.

World Harmonized Stationary Cycle Steady state evaluations were conducted using a modified version of the World Harmonized Stationary Cycle. The WHSC is a steady-state engine dynamometer test procedure that has been developed to mimic typical modes of vehicle operation under the auspices of the United Nations [14]. The cycle began with a fifteen-minute stabilization condition before beginning the first steady-state mode. Each mode was run for five minutes so that a stable fuel consumption reading could be logged.

World Harmonized Transient Cycle Repeated tests over the World Harmonized Transient Cycle [15] were conducted to determine the fuel economy performance and regeneration frequency. Successive WHTC tests were conducted until the first full cycle after a DPF regeneration was commanded by the engine's electronic control unit. Total fuel consumption was measured at the start and end of each cycle, and cycle fuel consumption (in g/kWh) was computed for each run. As regenerations became more frequent, they accounted for a greater fraction of the engine's total fuel consumption. A maximum engine run-time before regeneration was set to 12 hours to avoid running indefinitely if the ECU's regeneration threshold was not met.

Testing Sequence The first series of aging evaluations was conducted with the "baseline" oil at 5 g/L intervals ash loading starting from degreened but unaged condition (0 g/L) up to 40 g/L of ash loading. The ULA oil evaluations were then conducted at intervals of equivalent fuel/oil consumption. This allowed for pairwise comparison of parts aged for similar time duration and oil exposure to approximate mileage or hour equivalence in real-world operation. Because the ULA oil contained significantly lower sulfated ash content, the ash loading at each interval was proportionally lower than the ash loading at the corresponding baseline evaluation. During testing of the ULA oil, the evaluations corresponding to 15.7, 25.5, and 35.2 g/L of baseline ash loading were omitted to save time and because the ash loading rate was much slower for this oil. Table 2 summarizes the testing matrix and the actual ash loading in the ULA testing that corresponds to the baseline oil at equivalent aging duration. The ULA testing was extended to achieve 30 and 40 g/L of actual ash loading to demonstrate the advantage to DPF maintenance interval.

TABLE 2 Experimental test sequence (each row represents pair of tests with equivalent aging time exposure)

Baseline Oil Ash Loading (g/L)	ULA Oil Ash Loading (g/L)
0.0	0
5.2	2.6
10.4	4.4
15.7	
19.9	8.4
25.5	
30.6	13.0
35.2	
40.2	17.8
	29.4
	39.9

Results

CT Scans

CT scans allow for a detailed visual depiction of the ash accumulated in the DPF at each evaluation interval. Figures 1 and 2 represent the CT images collected with the baseline 1% sulfated ash engine oil aged to 40 g/L ash loading and the corresponding image of the DPF aged with ULA oil for same exposure duration. At this equivalent aging time, the ULA aged part had an actual ash load of 17.8 g/L or 44% of the ash in the baseline part - almost exactly proportional to their respective sulfated ash contents.

The 0.4% ash ULA oil not only produced drastically less ash accumulation, it also generated a denser ash plug at the back of the channel. Through post analysis of the collected images, the baseline part had a 65.3 mm ash plug which was

FIGURE 1 CT image of DPF aged to 40 g/L ash loading with baseline 1% ash test oil.

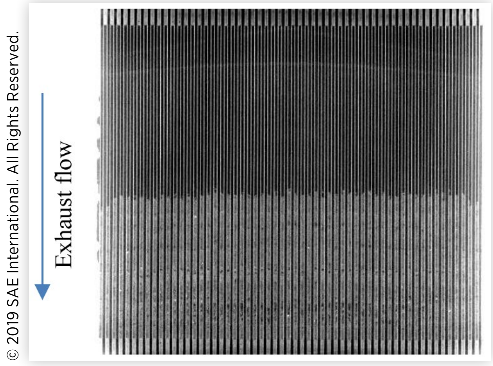
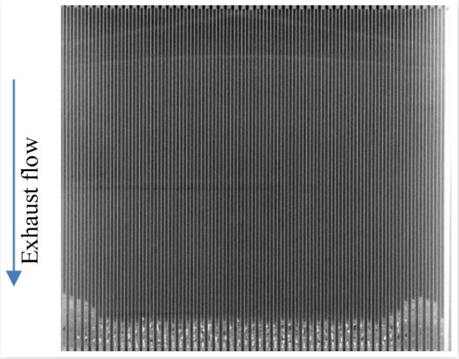


FIGURE 2 CT image of DPF aged with ULA 0.4% ash test oil to 40 g/L equivalent (17.8 g/L actual) ash loading



uniform across the width of the component. The analogous DPF aged with 0.4% ash ULA oil had an ash plug 18.9 mm at the outside diameter and 9.9 mm across much of the width.

Additional pairs of CT images for each interval in the aging sequence are included as part of the Appendix.

Flow Sweeps

Conducting periodic flow sweeps over the course of aging allowed for the characterization of the impact of accumulated ash on the backpressure exerted by the DPF.

Figure 3 summarizes the flow sweep upper bound backpressure results for the baseline oil as a function of ash accumulation at three different soot loading levels (1, 3, and 6 g/L). Although the ash impact on DPF backpressure is modest up to 10 g/L loading, it becomes more significant at 20 g/L and above, especially with increased soot loading. For comparison, Figure 4 summarizes the same flow sweep conditions with results plotted based on equivalent oil exposure. In this case, there is an indistinguishable impact of ash loading on the backpressure exerted by the DPF.

The testing demonstrates the advantages of using this ULA oil in maintaining a uniformly low backpressure from the DPF. When compared to DPF aged with the baseline oil, the system backpressure is as much as 60% lower with ULA.

FIGURE 3 DPF flow sweeps (upper bound) as a function of ash loading for the 1% ash baseline oil aging

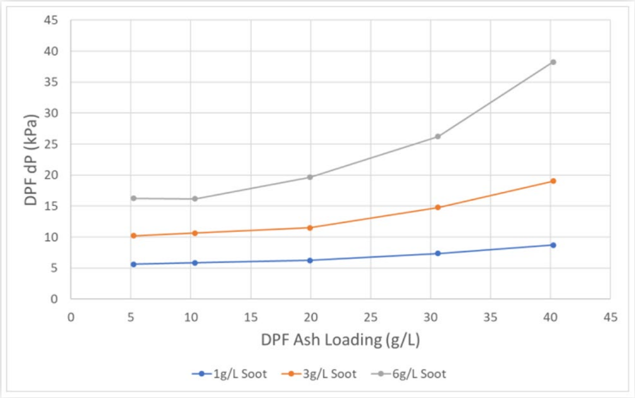
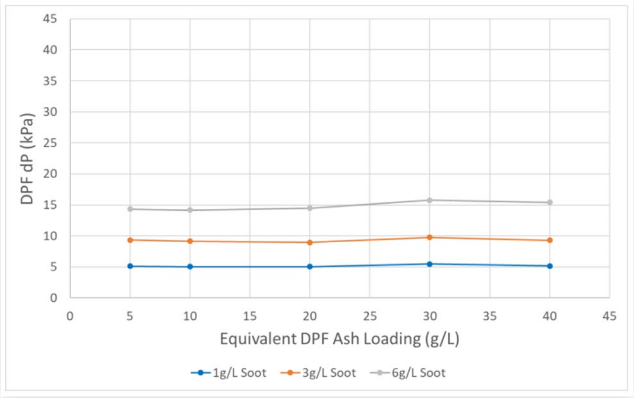


FIGURE 4 DPF flow sweeps (upper bound) as a function of ash loading for the 0.4% ash ULA oil aging (ash loading is expressed as time equivalent to baseline ash loading state)



Steady-State Fuel Economy Performance

The flow sweep data illustrated how significantly the ash accumulation can impact the backpressure exerted by the DPF, especially when the DPF is loaded with soot. The objective of the steady-state performance evaluations was to quantify the extent to which this backpressure impacted fuel economy performance.

During the initial performance evaluations, the WHSC was run without any existing soot load on the DPF. However, given the strong dependence of the combination of ash and soot loading on DPF backpressure, the final (40 g/L ash) WHSC runs were also conducted with 0, 1, 3, and 6 g/L soot. This allowed for a more representative characterization of engine performance impact in actual service where soot loads fluctuate.

A summary of the WHSC cycle average fuel consumption measurements over the course of the ash loading experiments with both oils are summarized in Figure 5 (baseline) and Figure 6 (ULA). In these tests, without any soot in DPF, the impact of progressive ash loading is relatively modest and very little difference is observed between aging characteristics of the two test oils. This observation is aligned with the flow sweep data which showed no discernable ash impact on the DPF backpressure when soot loadings were low. There are slight differences in the baseline (0 g/L) results that are attributable to part-to-part differences and measurement uncertainty.

To more fully characterize how the backpressure differences from the combination of soot and ash affected WHSC fuel economy, the DPF aged with baseline oil to 40 g/L ash loading and the DPF aged with ULA oil to 17.8 g/L (40 g/L equivalent) were tested with increasing soot loading. The summarized results are plotted in Figure 7 (baseline oil) and Figure 8 (ULA oil). With this experiment, the fuel economy advantage of the lower ash loading from the ULA oil is more evident. As soot accumulates on the ash loaded DPF the backpressure impact drives a more significant increase in steady-state engine fuel consumption.

To put these results in proper context, an analogous evaluation was conducted on a degreened but otherwise unaged part with no ash accumulation. This allowed for a characterization of the relative

FIGURE 5 Cycle average brake specific fuel consumption over WHSC as a function of ash loading for the 1% ash baseline oil aging

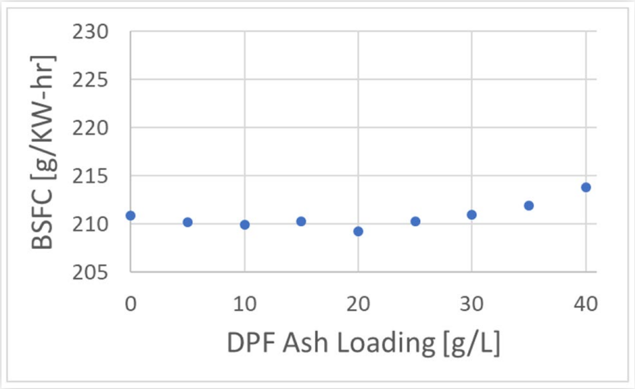


FIGURE 6 Cycle average brake specific fuel consumption over WHSC as a function of ash loading for the 0.4% ash ULA oil aging (ash loading is expressed as time equivalent to baseline ash loading state)

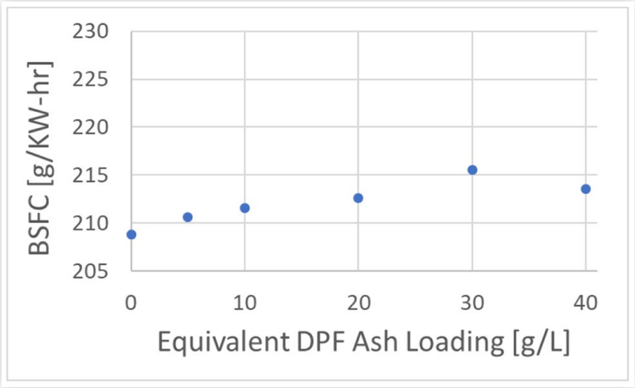


FIGURE 7 Cycle average brake specific fuel consumption over WHSC as a function of soot loading for the 1% ash baseline oil aged to 40 g/L ash loading

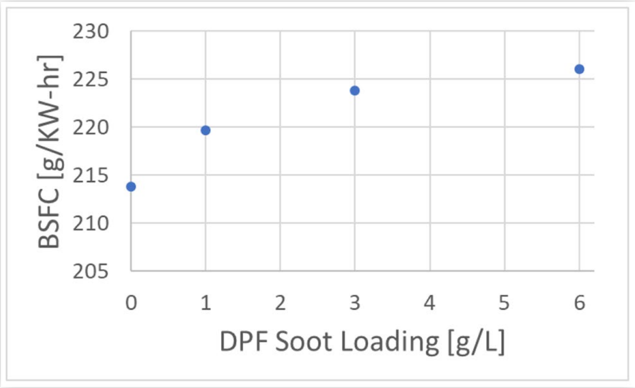


FIGURE 8 Cycle average brake specific fuel consumption over WHSC as a function of soot loading for the 0.4% ash ULA oil aged to 40 g/L baseline equivalent ash loading (17.8 g/L actual)

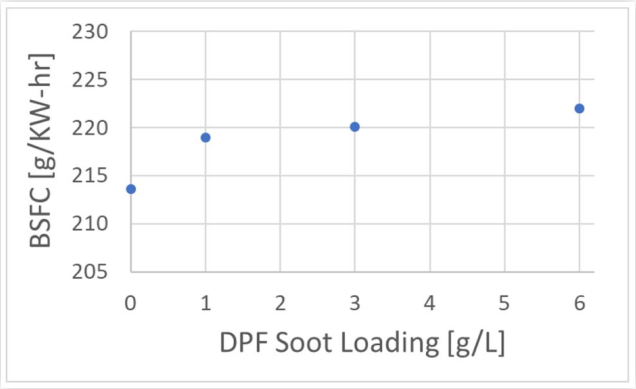


FIGURE 9 Cycle average brake specific fuel consumption over WHSC as a function of soot loading for a DPF with 0 g/L ash loading

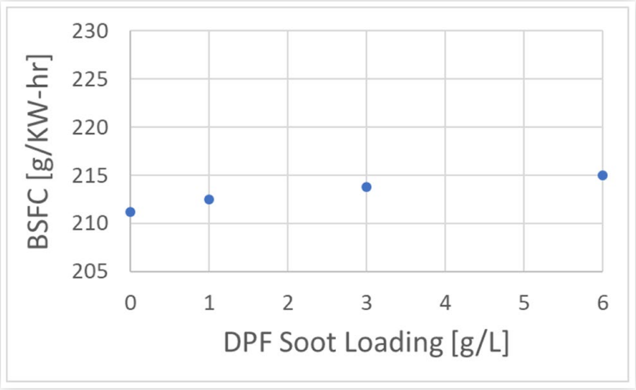
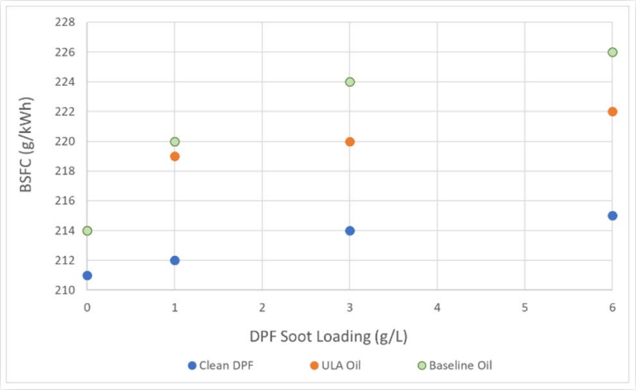


FIGURE 10 Cycle average brake specific fuel consumption over WHSC as a function of soot loading for a DPF without ash accumulation, and the two aged DPFs (to 40 g/L baseline and equivalent aging time for ULA)



performance degradation attributable to the ash accumulation and as a gauge of the extent to which ash control promotes fuel economy retention. The engine fuel consumption using the DPF with no ash accumulation is shown in Figure 9. For this DPF, the steady-state average fuel consumption is lower than that measured with either of the aged parts. Clearly, both the soot and the ash accumulation are affecting fuel economy performance.

To better illustrate the relative difference in the aging characteristics and the associated fuel economy retention differences, the fuel consumption results are plotted together in Figure 10. The data show that fuel economy retention is enhanced through control of ash accumulation. The difference in fuel consumption between the baseline oil aged DPF and the ULA oil aged DPF is more significant with the higher (3 and 6 g/L) levels of soot loading. In service, a DPF's soot load will fluctuate depending on operating conditions and regeneration frequency. At equivalent operating time and consumed oil exposure when compared to the clean DPF, the fuel economy retention advantage of the ULA oil is 0.5% at 1 g/L DPF soot load, and 1.9% at the two higher soot loadings.

Transient Fuel Economy Performance

The steady-state fuel economy testing showed benefit derived from maintaining a low DPF backpressure by controlling ash accumulation. Another potential cause of increased fuel consumption is the increase in DPF regeneration frequency. To evaluate this impact, successive WHTC runs were conducted up to the point that a regeneration was commanded by the ECU. The sequence was repeated three times at the final evaluation interval to gauge the repeatability of the measurement.

Figure 11 plots the average fuel consumption over the course of the aging experiments for both test oils. With increasing ash load, the system aged with the baseline oil exhibits an increase in fuel consumption due largely to the more frequent regeneration event. This increase is most significant at the 40 g/L point. In contrast, the fuel consumption profile for the ULA aged DPF is more tempered and exhibits a slight fuel economy benefit with modest ash loading, and on average does not exceed the fuel consumption rate measured without ash.

FIGURE 11 Cycle average fuel consumption over repeated WHTCs as a function of ash loading in the DPF (expressed based on baseline oil ash exposure)

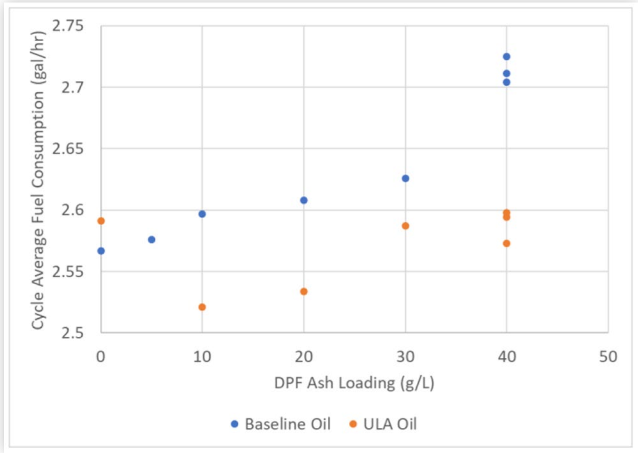
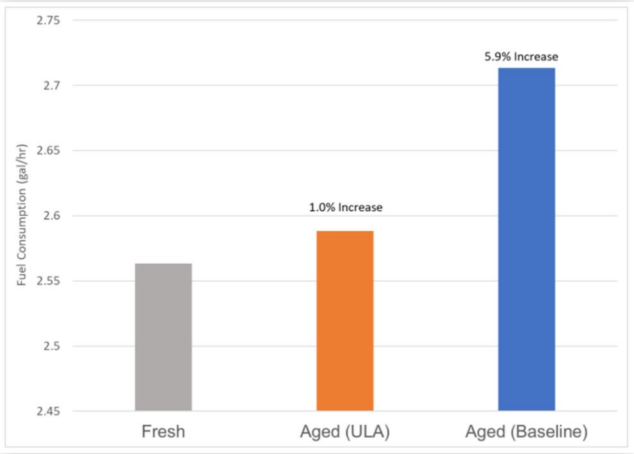


FIGURE 12 Cycle average fuel consumption over repeated WHTCs - clean DPF compared to parts aged with ULA oil (17.8 g/L ash) and baseline oil (40 g/L ash)



In alignment to the treatment of the steady-state data, it is prudent to compare WHTC fuel consumption (including regeneration fuel) of the two aged parts to that of the degreened but clean DPF. When compared to the fuel consumption measured with no ash on the DPF, there is a 1.0% fuel consumption increase with the ULA oil, but a 5.9% increase due to the higher ash loading yielded by the baseline oil.

Conclusions

This study provides a systematic comparison of DPF aging effects with a conventional heavy-duty engine oil containing 1% sulfated ash and an ultra-low ash engine oil containing 0.4% sulfated ash.

As was confirmed in previous testing with this ULA technology, reducing the sulfated ash in the engine oil provides a proportional reduction in ash accumulation in the DPF. When aged to equivalent time exposure and total oil consumption, the baseline oil yielded 40.2 g/L of DPF ash compared to 17.8 g/L with the ULA oil. In service, this translates into an increase in service interval between ash cleaning events of 2.3x. This could increase standard service intervals for DPFs well beyond 1,000,000 miles of operation. CT imagery confirmed this lower level of DPF ash from ULA oil as well as a denser ash packing which resulted in other performance benefits.

This testing confirmed that aging with the ULA oil provides a significant benefit in terms of DPF backpressure control, which is attributable to both the lower level and higher density of ash, and which translated into a more tempered impact on fuel economy degradation.

In steady-state testing, a fuel economy retention benefit attributable to the lower backpressure was as high as 1.9% in the fully aged systems. Over the course of the DPF maintenance interval, this translates to an average improvement in fuel economy retention of approximately 0.7% for ULA oil compared to the baseline oil.

In transient testing to account for fuel burned during regeneration, total fuel consumption is nearly 5% higher when the DPF is fully aged with the baseline oil as compared to the ULA aged DPF at the same exposure time. On average over the course of the aging ULA yielded a fuel consumption benefit of 2.3%.

In this testing, the backpressure effects and regeneration effects combine for a total 3% lifecycle fuel economy retention advantage for the ultra-low ash engine oil technology.

References

1. McGeehan, J., Moritz, J., Shank, G., Kennedy, S. et al., "API CJ-4: Diesel Oil Category for Pre-2007 Engines and New Low Emission Engines Using Cooled Exhaust Gas Recirculation and Diesel Particulate Filters," SAE Technical Paper 2007-01-1966, 2007, doi:10.4271/2007-01-1966.
2. Noguchi, S., Sogawa, Y., Kawaguchi, H., and Kono, N., "A Quantitative Study of Fuel Efficiency of Diesel Vehicles with Diesel Particulate Filter in Repeated Test Cycles," SAE Technical Paper 2012-01-1704, 2012, doi:10.4271/2012-01-1704.
3. McGeehan, J., Yeh, S., Rutherford, J., Couch, M. et al., "Analysis of DPF Incombustibles Materials from Volvo Trucks Using DPF-SCR-Urea With API CJ-4 and API CI-4 PLUS Oils," *SAE Int. J. Fuels Lubr.* 2(1):762-780, 2009, doi:10.4271/2009-01-1781.
4. McGeehan, J., Yeh, S., Couch, M., Hinz, A. et al., "On The Road to 2010 Emissions Field Tests Results and Analysis With DPF-SCR System and Ultra-Low Sulfur Diesel Fuel," SAE Technical Paper 2005-01-3716, 2005, doi:10.4271/2005-01-3716.
5. Sappok, A., Santiago, M., Vianna, T., and Wong, V., "Characteristics and Effects of Ash Accumulation on Diesel Particulate Filter Performance: Rapidly-Aged and Field-Aged Results," SAE Technical Paper 2009-01-1086, 2009, doi:10.4271/2009-01-1086.
6. Sappok, A. and Wong, V., "Detailed Chemical and Physical Characterization of Ash Species in Diesel Exhaust Entering Aftertreatment Systems," SAE Technical Paper 2007-01-0318, 2007, doi:10.4271/2007-01-0318.
7. Sappok, A., Wong, V., Morrow, R., Zisholtz, E. et al., "Investigation of Ash Formation, Accumulation, and Distribution in Diesel Particulate Filters Using Lubricant Additive Tracers," in *Proceedings ASME 2011 Internal Combustion Division Fall Technical Conference ICEF 2011*, Oct. 2-5, 2011.
8. Bardasz, E., Mackney, D., Britton, N., Kleinschek, G. et al., "Investigations of the Interactions Between Lubricant-Derived Species and Aftertreatment Systems on State-of-the-Art Heavy-Duty Diesel Engine," SAE Technical Paper 2003-01-1963, 2003, doi:10.4271/2003-01-1963.
9. Sappok, A. and Wong, V., "Ash Effects on Diesel Particulate Filter Pressure Drop Sensitivity to Soot and Implications for Regeneration Frequency and DPF Control," *SAE Int. J. Fuels Lubr.* 3(1):380-396, 2010, doi:10.4271/2010-01-0811.
10. Liu, Y., Su, C., Clerc, J., Harinath, A. et al., "Experimental and Modeling Study of Ash Impact on DPF Backpressure and Regeneration Behaviors," *SAE Int. J. Engines* 8(3), 2015, doi:10.4271/2015-01-1063.
11. Zöllner, C. and Brueggemann, D., "Studies on the Influence of Engine Conditions and Different Ash Levels on the Regeneration Behavior of Particulate Filters," SAE Technical Paper 2018-01-1704, 2018, doi:10.4271/2018-01-1704.
12. Mc Geehan, J., Van Dam, W., Narasaki, K., Boffa, A. et al., "Extending the Boundaries of Diesel Particulate Filter Maintenance With Ultra-Low Ash - Zero-Phosphorus Oil," *SAE Int. J. Fuels Lubr.* 5(3), 2012, doi:10.4271/2012-01-1709.
13. McGeehan, J., Van Dam, W., Nelson, K., Boffa, A. et al., "Minimizing Diesel Particulate Filter Incombustibles by Using Ultra Low Ash - Zero Phosphorus Oil," *SAE Int. J. Fuels Lubr.* 7(3):890-900, 2014, doi:10.4271/2014-01-2798.
14. World Harmonized Stationary Cycle: https://www.dieselnet.com/standards/cycles/whsc.php.
15. World Harmonized Transient Cycle: https://www.dieselnet.com/standards/cycles/whtc.php.

Contact Information

Shawn D. Whitacre, Chevron Lubricants
shawnwhitacre@chevron.com

Acknowledgments

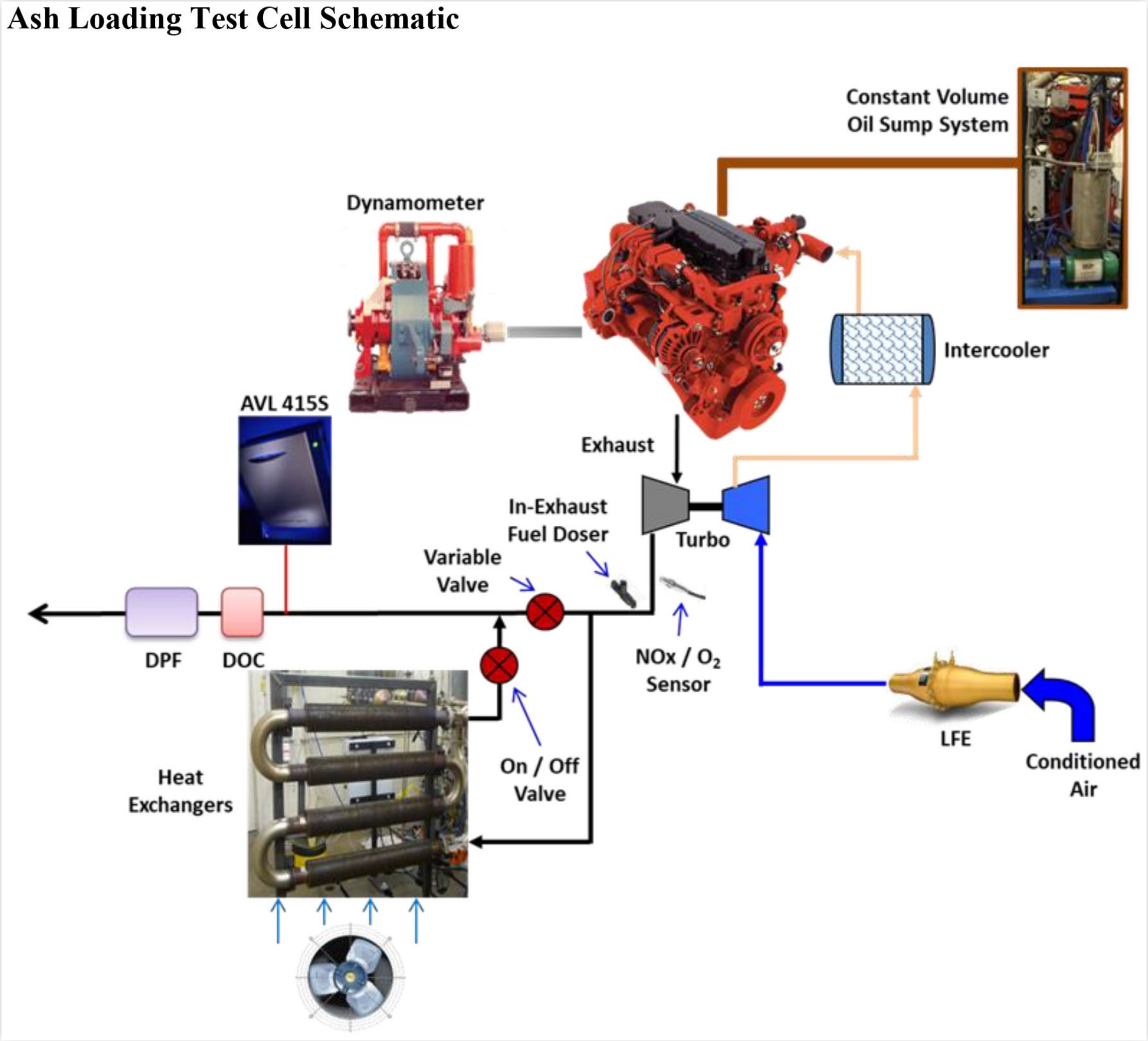
The authors would like to thank the staff of Southwest Research Institute's Engine and Aftertreatment Evaluation team for their expert guidance and for conducting this test program. The support of Michael Chadwell throughout this program is particularly notable.

Abbreviations

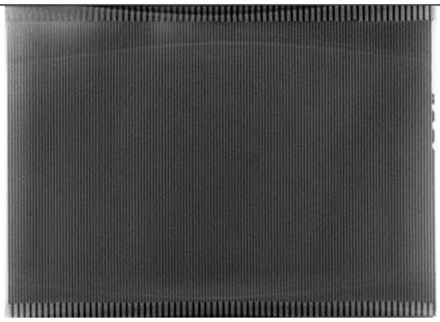
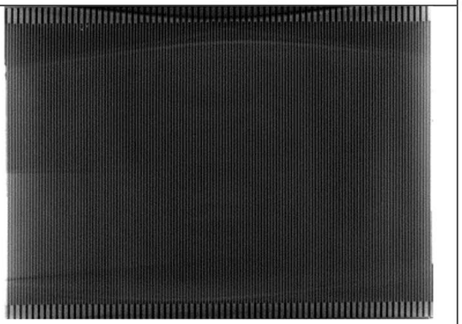
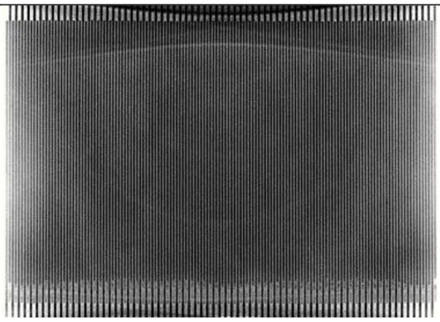
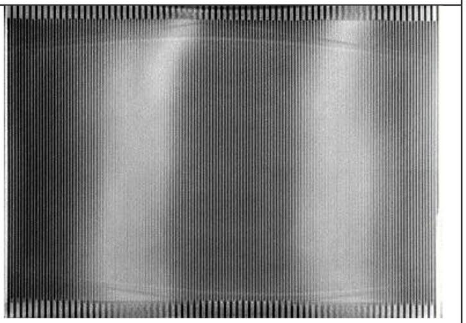
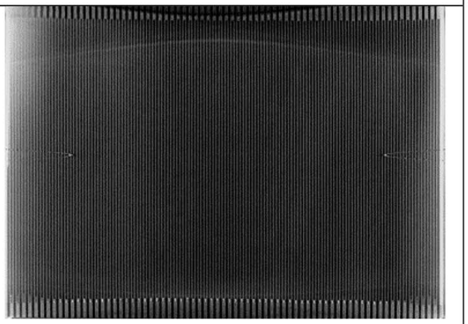
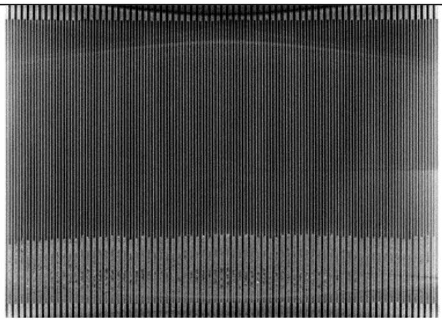
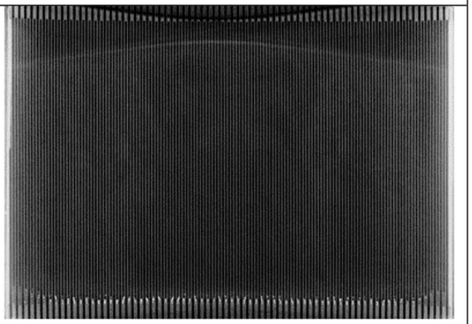
CT - Computerized tomography
DPF - Diesel particulate filter
ECU - Electronic control unit
PM - Particulate matter
SAPS - Sulfated ash, phosphorus, sulfur
ULA - Ultra-low ash
WHSC - World Harmonized Stationary Cycle
WHTC - World Harmonized Transient Cycle

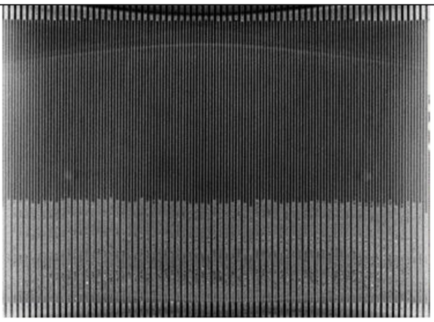
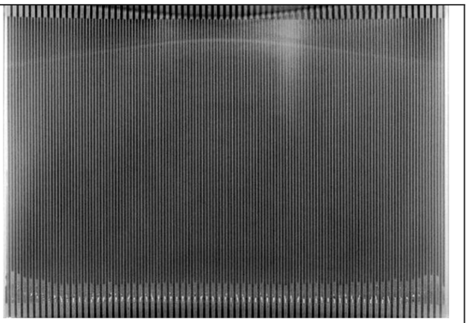
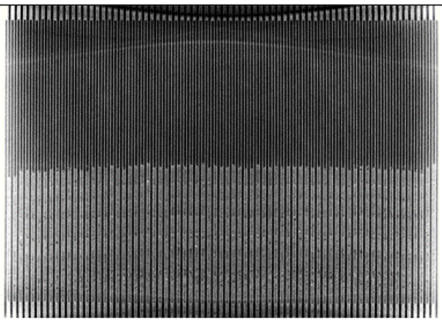
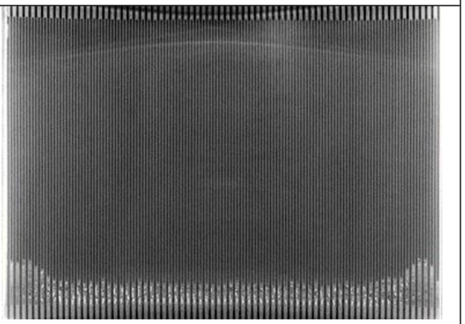
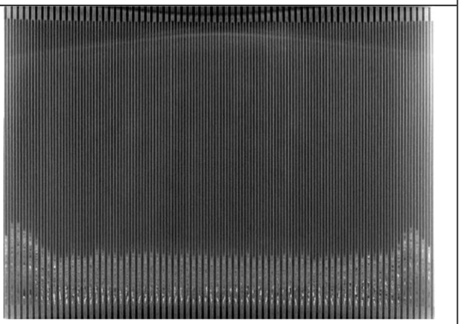
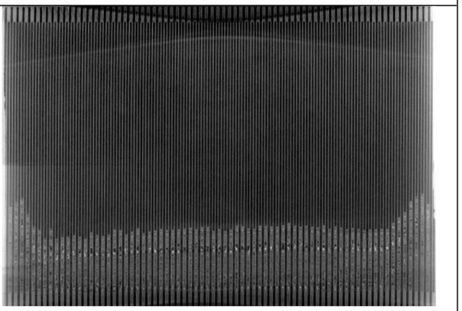
A. Appendix

A.1. Ash Loading Test Cell Schematic



A.2. CT Images

Baseline Ash Loading (ULA actual)	**Baseline 1% Ash Aging**	**ULA 0.4% Ash Aging**
0 g/L (0 g/L)		
5.2 g/L (2.6 g/L)		
10.4 g/L (4.4 g/L)	*Due to laboratory oversight, CT image was not collected at this interval*	
19.9 g/L (8.4 g/L)		

30.6 g/L (13.0 g/L)		
40.2 g/L (17.8 g/L)		
30 g/L (actual for ULA)	Not applicable	
40 g/L (actual for ULA)	Not applicable	

ISSN 0148-7191