

Extending the Boundaries of Diesel Particulate Filter Maintenance With Ultra-Low Ash - Zero-Phosphorus Oil

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ABSTRACT

By 2014, all new on- and off-highway diesel engines in North America, Europe and Japan will employ diesel particulate filters (DPF) in the exhaust in order to meet particulate emission standards. If the pressure across the DPF increases due to incombustibles remaining after filter regeneration, the exhaust backpressure will increase, and this in turn reduces fuel economy and engine power, and increases emissions.

Due to engine oil consumption, over 90% of the incombustibles in the DPF are derived from inorganic lubricant additives. These components are derived from calcium and magnesium detergents, zinc dithiophosphates (ZnDTP) and metal-containing oxidation inhibitors. They do not regenerate as they are non-volatile metals and salts. Consequently, the DPF has to be removed from the vehicle for cleaning.

Ashless oil could eliminate the need for cleaning. This study initially focused on development of an ashless oil, but eventually concluded that this oil could not meet the valve-train wear requirements of the API CJ-4, SN/ACEA E9 oil categories. However, a zero-phosphorus oil with no ZnDTP and an extremely low sulfated ash of 0.4% demonstrated that it could meet critical engine tests in API CJ-4/ACEA/SN. Passing results for piston deposit and oil consumption were also achieved in the Daimler 501LA and VW TDi engine tests, which are part of several ACEA oil categories.

The above oil, which has been optimized at 0.3% sulfated ash, has proven field performance in Cummins ISX engines and should extend the cleaning interval of the DPFs. The engine wear and viscosity control at oil drains of 97,000 km (60,000 miles) equals that of API CI-4 PLUS/ACEA E7 at 1.4% sulfated ash oil. This study demonstrated that the oil's total base number (TBN) is not a critical factor in controlling wear with engines using Ultra-Low Sulfur Diesel (ULSD) fuel.

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INTRODUCTION

The U.S. 2010, Euro VI 2013 and Japan 2010 emission standards have necessitated the use of DPFs with selective catalytic reduction (SCR) for the majority of on-highway engines. In the U.S., off-highway vehicles will also need to use a DPF in order to meet Tier 4 Stage 3B emission standards for 2011. And finally, by 2014, all new on- and off-highway diesel engines in the U.S., Europe and Japan will be

employing a combination of DPFs, cooled exhaust gas recirculation (CEGR) and SCR with urea to meet both the particulate and NO_x exhaust emissions. In the U.S., inland marine and railroad diesels will also use DPFs by 2014. (See [Figure 1](#) and [Figures A-1, A-2, A-3.](#))

The California Air Resources Board (CARB) has required that all on-highway diesel vehicles registered in the state must employ DPFs by 2014. In addition, the Ports of Oakland, Los Angeles and Long Beach have adopted CARB's



Port Truck Rule which requires that trucks with 1994 to 2003 engines install a CARB-verified retrofit device, which is a DPF. Trucks built before 1993 are banned from the ports. Due to all the above emission standards and regulations, clean diesels have arrived. This achievement has been enabled by limiting diesel fuel sulfur to 10-15 ppm and using DPFs [1,2,3].

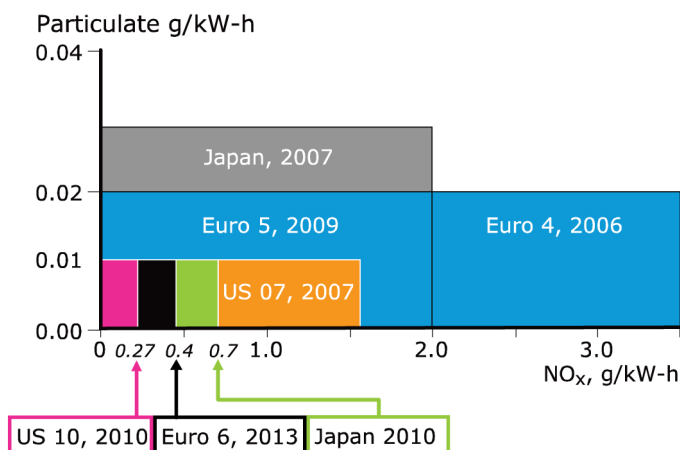


Figure 1. On-highway emission standards for E.U., U.S. and Japan.

DPF requires cleaning due to the accumulation of incombustibles from the engine oil. Therefore, fundamental research was initiated by the authors to develop an ashless oil which could eliminate the need to clean the DPF and possibly reduce its size. This study reports the results of this exploration, using API CJ-4 and ACEA engine and bench tests, followed by the results obtained in a field demonstration of performance in Cummins ISX engines.

The findings of this study are presented in the following six sections:

- Reduction of Particulate and NO_x Through Use of the DPF-SCR-EGR
- Characterization of Incombustibles and the Effect of the Fresh Oil's Sulfated Ash on Incombustible Levels in DPF
- Previous Development of Zero-Phosphorus Oils and the API/ACEA Tests Used in This Study
- Ashless Oil Development Program Defined in Six Distinct Phases
- Cummins ISX Field Tests
- Conclusions

REDUCTION OF PARTICULATE AND NO_x THROUGH USE OF THE DPF-SCR-EGR

Despite recent improvements in regard to in-cylinder combustion, diesel engines cannot meet the U.S.

Environmental Protection Agency (EPA) 2007 on-highway or the 2011 off-highway emission standards without DPFs. In order to meet the U.S. 2010, Japan 2010 and Europe 2013 emission standards for on-highway vehicles, the majority of truck manufacturers have selected a DPFs-SCR-urea system combined with a relatively low level of cooled EGR.

The DPF is comprised of an oxidation catalyst followed by a wall-flow particulate filter. The DPF traps the particulate matter and the oxidation catalyst oxidizes a portion of the engine's NO exhaust to generate NO₂. This NO₂ results in thermal combustion of particulate matter at temperatures in the range of 250-350°C. This process is enhanced by the use of a "wash-coat" on the ceramic filter. The "wash-coat" is expensive, but it enables a chemical reaction with continuous particulate removal.

Passive regeneration occurs in the DPF provided that the exhaust temperatures are sufficiently high for combustion of the particulate. If the temperature is not sufficiently high for regeneration, fuel is injected into the exhaust system at the outlet of the turbocharger when the delta pressure across the DPF is too high. This situation occurs generally in engines over 10 liters in which thermal combustion occurs in DPF at temperatures of 600°C (this is analogous to cleaning your oven). In passenger car diesels, there is post-injection of fuel into the cylinder during the exhaust event. This increases the exhaust temperature to produce "thermal combustion" in DPF. In all cases, DPFs are employed to reduce particulate (Figure 2).

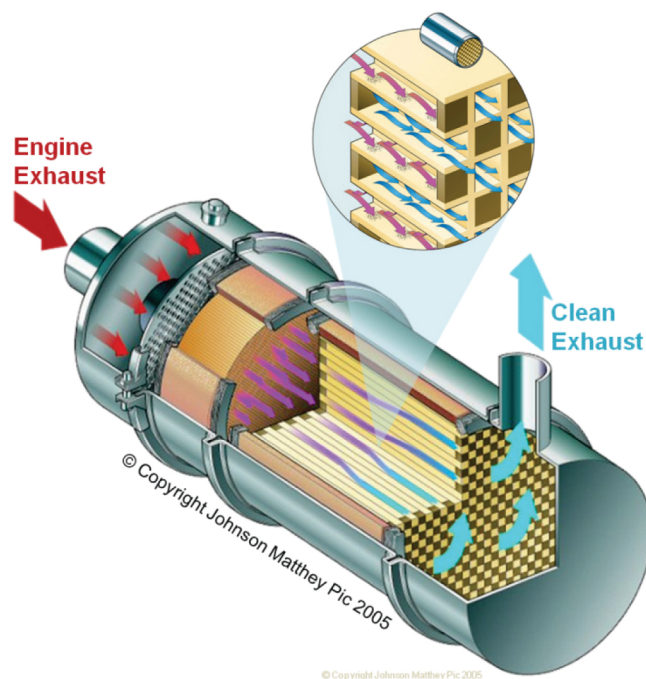


Figure 2. Passive DPF shown with wall-flow filter substrate.

The DPF is a complex system. Pressure drop is measured across the wall-flow filter to ensure correct timing of fuel

injection into the exhaust stream, and this initiates regeneration of the particulate filter. The temperature across the platinum oxidation catalyst is monitored for safe operation. In addition, the size of DPF increases with engine brake horsepower (BHP) due to the larger quantities of exhaust flow. The complexity is particularly significant in off-highway and railroad engines where packaging of the system on the vehicle is challenging.

The exhaust gas first passes through the DPF system which prevents the particulate matter from fouling the SCR catalysts. Urea is injected into the particulate-free exhaust as it leaves the DPF. To ensure adequate mixing of the urea into the exhaust high in NO_x , mixing devices are employed to adequately distribute the urea in the exhaust stream. Alternatively, the exhaust gas flow direction is reversed by 180 degrees, which allows for effective mixing with the urea before flowing through the SCR catalysts. The most common design has the DPF and SCR systems in series to reduce manufacturing cost. In the U.S., urea is called "diesel exhaust fluid" and in Europe urea is called AdBlue™. (See [Figure 3](#).)

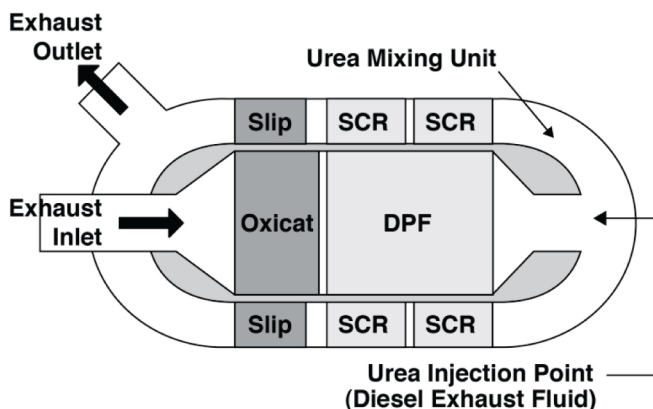
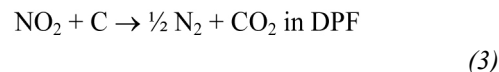
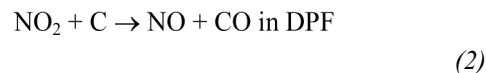
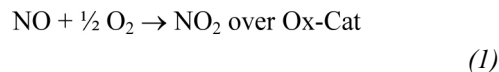


Figure 3. Schematic representation of compact DPF-SCR system. The DPF material was cordierite in this field test.

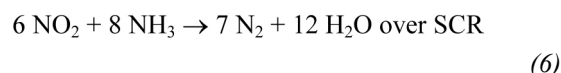
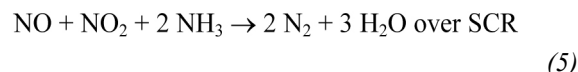
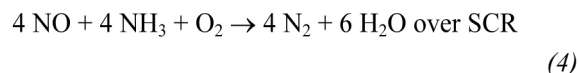
The SCR system reduces the NO_x via reaction with ammonia, which is generated on board the vehicle through the rapid hydrolysis of urea. In regard to the possibility of excess urea in the exhaust, it is necessary to match the amount of urea injection to the amount of NO_x to be reduced. Furthermore, as an additional safeguard, a cleanup catalyst is installed downstream of the urea-SCR catalysts to prevent possible ammonia slip. The ratio of urea to diesel fuel is nominally 3.5% in engines using EGR, which also reduces NO_x . In Iveco's engines for Euro VI, they do not use EGR and rely only on SCR to control the NO_x , which increase the urea use to 7-8% [4]. The Iveco system reduces the size of the radiator and enables lower injection pressures in the absence of EGR, without an EGR cooler.

The oxidation reactions in DPF-SCR are shown in [equations 1,2,3](#) and the reduction reactions of SCR-urea are shown in [equations 4,5,6](#).

DPF System:



Urea-SCR System:



The after-treatment system of DPF-SCR is both complex and expensive, posing vehicle installation challenges, including required continuous monitoring of DPF pressures, temperatures and exiting NO_x levels. The SCR system must be constructed of stainless steel in order to prevent corrosion due to the urea. The size of the system is particularly an issue for high horsepower off-highway vehicles.

In order to meet the 2010 EPA on-highway emission standard, one U.S. engine manufacturer has selected DPF with high levels of cooled EGR. In order to control the NO_x in the cylinder, the peak flame temperature must be controlled. A percentage of cooled exhaust gas is returned to the cooled intake air. When combustion takes place, some energy is being used to heat this inert gas which reduces the peak flame temperature and reduces NO_x . This system is generally used in combination with retarded fuel injection-timing. Retarded fuel injection timing lowers peak flame temperature, which reduces the NO_x formation by displacing the combustion event until later in the expansion stroke when the volume is increasing in the cylinder [5]. Nevertheless, this system still uses a DPF to meet the particulate emissions.

CHARACTERIZATION OF INCOMBUSTIBLES AND THE EFFECTS OF THE FRESH OIL'S SULFATED ASH ON INCOMBUSTIBLE LEVELS IN DPF

In regard to incombustible materials in the DPFs, previous research studies indicate that the material is primarily derived from calcium or magnesium detergents and ZnDTP in the oil. This is well documented [6,7,8,9,10,11,12,13,14,15,16]. Calcium detergents were first patented by Chevron in 1940 for piston deposit and corrosion control [17]. ZnDTP was first patented in 1941 by Lubrizol to provide oil oxidation control, and its structure was later modified to also provide

valve-train wear control [18]. These two additives are the fundamental building blocks of engine oils, and, in combination with other new additives, they enable the excellent engine durability of today's diesel and passenger car engine oils worldwide. The maximum level of the above metal components in the oil is generally defined by ASTM D874, Sulfated Ash Test.

Due to oil consumption, these metal components from detergents, ZnDTP and other oxidation metal inhibitors cannot be incinerated in the DPF. In our studies, the gray powder of incombustible materials is dominated by inorganic lubricant additive elements-Ca, P, S, Zn, Mg and Mo. These elements, together with the oxygen with which they are associated, account for more than 90 wt % of the recovered material. In addition there are low levels of engine wear metals-Cr, Pb, Fe, Cu and Al. (See Figure A-4.) The aluminum is in part associated with the "wash-coat" used on passive DPFs. As the final constituents of the recovered material, we have identified low levels of carbon and adsorbed moisture. Crystalline materials of CaSO_4 (calcium sulfate) as anhydrite, ZnP_2O_7 (zinc pyrophosphate) and $\text{Zn}_2\text{Mg}(\text{PO}_4)_2$ (zinc magnesium phosphates) were identified in the incombustibles. The incombustible particle size is bimodal, with large numbers of particles at 0.4 micron and the remaining at 10 microns [6,7]. (See Figure 4.)



Figure 4. Typical bags of incombustibles received from the Volvo Truck test after each DPF cleaning [6].

Due to these incombustibles, the U.S. EPA set design targets for DPF cleaning. When DPFs were first used on U.S. engines in 2007, the EPA mandated that the DPF must be capable of working without cleaning for at least 241,000 km (150,000 miles) or 4,500 hours of operation in vocational or delivery vehicles. It has been reported in retrofit applications that the cleaning interval has been as low as 80,000 km (50,000 miles) in vocational vehicle service and as high as 644,000 km (400,000 miles) in line-haul trucks [1,2]. In our current field tests, 2010 EPA-compliant Volvo engines using DPF-SCR-EGR in line-haul delivery service averaged 402,000 km (250,000 miles) before cleaning.

The DPF filter must be removed from the truck and placed in a cleaning machine. With the filter inside the completely enclosed cleaning machine, compressed air is forced through the DPF and incombustibles are collected. Because the particle size of the incombustibles (0.4 to 10 microns) presents inhalation and irritation health risks, exposure to incombustible trap ash should be minimized [6,7]. Simple precautions to minimize exposure would include breathing masks, safety goggles and incombustible containment within a hood.

To remove the incombustibles, maximize the interval between DPF cleanings, it was recommended that the fresh oil sulfated ash be limited to 1.0% in the API CJ-4, ACEA E6/E9 and JASO DH-2 oil categories. In addition, there are limits on fresh oil phosphorus, sulfur and volatility, although these limits vary according to the oil category. The phosphorus is limited to minimize potential DPF catalyst deterioration. Sulfur is limited to prevent acid formation in the DPF, and volatility is limited for oil consumption control [19]. To meet the sulfur requirements of API CJ-4, ACEA E6/E9, and Noack volatility, low sulfur API Group II or Group III base stocks must be used. (See Table 1.)

Table 1. Comparison of API CJ-4 to ACEA E6 and JASO DH-2 chemical limits.

Oil Category	ACEA E6	API CJ-4	JASO DH-2
% Sulfated Ash	1.0	1.0	1.0
% Phosphorus	0.08	0.12	0.12
% Sulfur	0.3	0.4	0.5
% Volatility	13	13	18

In field tests with Volvo on-highway trucks using DPF-SCR and ULSD fuel, the rate of accumulation of the incombustibles in the DPF was measured. The average rate of incombustibles accumulation for the API CJ-4/ACEA E9/VDS-4 oil at 1.0% sulfated ash was 1.23 mg/km based on three trucks. For the eleven trucks using the API CI-4 PLUS/ACEA E7/VDS-3 oil at 1.4% sulfated ash it was 2.90 mg/km. The difference between the two groups was highly significant at the 99% confidence level [6]. Lower ash in the fresh oil results in lower incombustibles in the DPF. This indicates that an API CJ-4 oil at 1.0% sulfated ash should extend DPF cleaning intervals further than an API CI-4 PLUS oil at 1.4% sulfated ash. It also indicates that further reductions in sulfated ash from 1.0% would extend cleaning intervals even longer, as long as oil consumption remains constant.

In addition, incombustible material weights removed from the DPF decreased consistently and substantially within a truck at later measurements after subsequent cleanings. It is possible that total removal of incombustibles from the DPF is more difficult with repeated cleanings. It is speculated that the mechanism is associated with the ash sintering and

adhering to the walls of the filter channels, making it more difficult to remove (Figures 5 and 6).

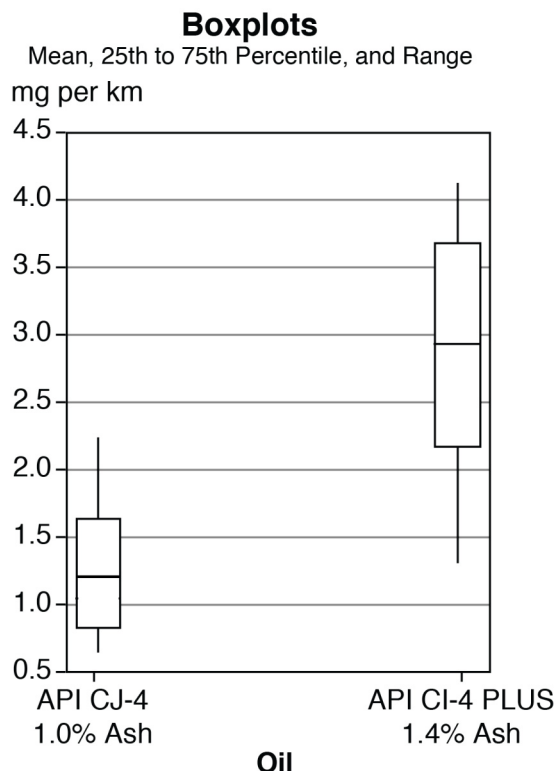


Figure 5. Incombustibles in DPF per km were significantly ($p < 0.01$) lower for API CJ-4 (1.0% ash) than for API CI-4 (1.4% ash) units [6].

PREVIOUS DEVELOPMENT OF ZERO-PHOSPHORUS OILS AND THE API/ACEA TESTS USED IN THIS STUDY

Based on all the above findings, an ashless oil could eliminate incombustibles in DPF and therefore, the servicing of the DPF. Fundamental research on eliminating phosphorus from engine oils and the elimination of both phosphorus and sulfated ash has become a focus in lubricant development. This is because the oil's phosphorus has been shown to deteriorate gasoline engine catalysts and may affect the performance of oxidation catalysts in DPF and NO_x sensors [20,21,22,23,24,25,26].

In 1991, Colcough et al. [27] reported a study in which they eliminated ZnDTP by replacing it with soluble copper carboxylate. This formulation passed the gasoline Sequence IIID and L-38 bearing corrosion tests. This was supported by field tests in Peugeot 1.6-liter passenger car engines. Unfortunately, the soluble copper carboxylate was a metal, which would contribute to sulfated ash.

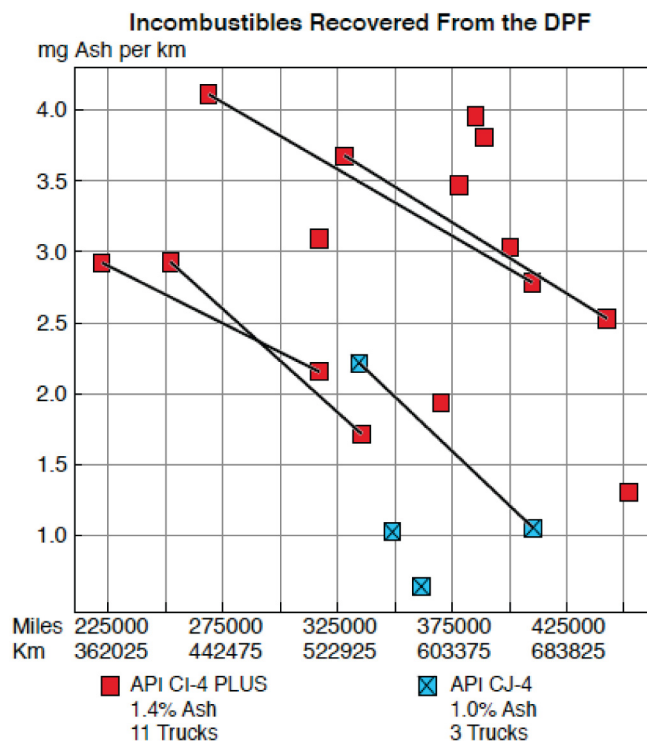


Figure 6. Within a truck, incombustible materials per km decreases with increasing mileage at DPF cleaning. The lines connect multiple observations from the same truck [6].

Gangopadhyay et al. studied a zero-phosphorus engine oil which demonstrated some promise in bench tests but failed the Sequence IIIG gasoline test due to wear [28]. In 2011, Shimizu et al. [29] reported on a zero-phosphorus - non-ash containing oil which gave acceptable results in JASO M354 diesel and M328 gasoline engine cam wear tests. Unfortunately, there was no explanation of these tests or test conditions, although used oil analysis from field performance in V6-3.5-liter gasoline engines was reported. H. A. Spikes has completed research on ZnDTP wear films and conducted an extensive literature review on antiwear films, but as he points out, "different studies have employed very different tests conditions, so it is difficult to assess the relative antiwear effectiveness of the various additive types investigated" [30,31].

In the study reported here, the evaluation of the oils was conducted in industry-recognized engine tests used in the oil categories API CJ-4, CI-4, SN and ACEA E6, E9. In the API CJ-4 category, the diesel tests used were the Mack T-12, Cummins ISM and Cummins ISB. In the API SN category, the gasoline tests used were Sequence IIIG, Sequence IVA and Sequence VIII. These tests were all conducted at Southwest Research Institute (SwRI) in registered stands. In addition, the ACEA categories included the Daimler OM 501LA and VW TDi diesel engine tests. These were registered tests which are well established in the lubricant industry and have specific reference oils to define their

performance. In API categories the tests are monitored by the ASTM Test Monitoring Center (TMC). The above tests and their operating conditions are described in detail in the [Appendix](#).

The Cummins ISM and Mack T-12 tests have five different parameters to be controlled, and a merit system is used in each of these tests. This allows a specific number of parameters to be higher or lower than the “anchor” point, which is multiplied by a weighting factor. If a test achieves results all at the “anchor” point, the merit would be 1,000, which was selected as the passing limit for Cummins ISM and Mack T-12. A merit of 2,000 could be achieved if the results were at the minimum or better for all the criteria. In contrast, any result worse than the maximum for any criteria would result in a failure. The Cummins ISB test has only two control parameters, and therefore, a merit system is not used in this test [19].

With the above as background, the following section focuses on the step development of an oil which would provide both engine durability and an extended cleaning interval for DPFs by reducing its sulfated ash.

ASHLESS OIL DEVELOPMENT PROGRAM DEFINED IN SIX DISTINCT PHASES

Various additives that are included in conventional heavy-duty diesel engine oils contribute to sulfated ash. The most obvious contributors are a class of components called metallic detergents such as calcium- or magnesium-based sulfonates, phenates or salicylates. And the most commonly used antiwear additive is ZnDTP. In addition, there is a host of minor contributors that mostly fall in the category of inhibitors.

In the effort of formulating for low ash lubricant, a first obvious step was to reduce the treat rate or completely eliminate the greatest contributors-detergents and ZnDTP. This was done initially by designing a matrix of candidate oils to be tested in Cummins ISB. The ISB was selected because ashless oils have been developed for two-cycle natural gas engines to prevent pre-ignition and detonation caused by ash in the combustion chamber, but they cannot meet the valve-train wear requirements of diesel engines generating relatively high soot level as in the Cummins ISB.

Consequently, with this background, we started this program to develop an ashless oil capable of passing the API CJ-4 valve-train wear requirements in engines with relatively high soot levels in the oil, and then progressed to other critical tests in the API CJ-4 and ACEA categories. The following section describes the evolution of the research process which eventually resulted in the development of a zero-phosphorus - low ash oil with proven engine dynamometer and field test performance. There were six distinct phases in the process.

1. Passing Results in Cummins ISB Test at Low Ash

At the start of this program, the Cummins ISB was selected to study cam and tappet wear. A fully formulated API CJ-4/ACEA E9/VDS-4 SAE 15W-40 oil was altered by removing a specific component in three separate tests. In the first test, only the detergent was removed from the fully formulated oil, reducing the ash to 0.6% at 0.12% phosphorus. In the second test, only the ZnDTP was removed from the fully formulated oil, reducing the ash to 0.7% with 0% phosphorus. In the third test, both the detergent and ZnDTP were removed from the formulation, reducing the ash to 0.2% at 0% phosphorus.

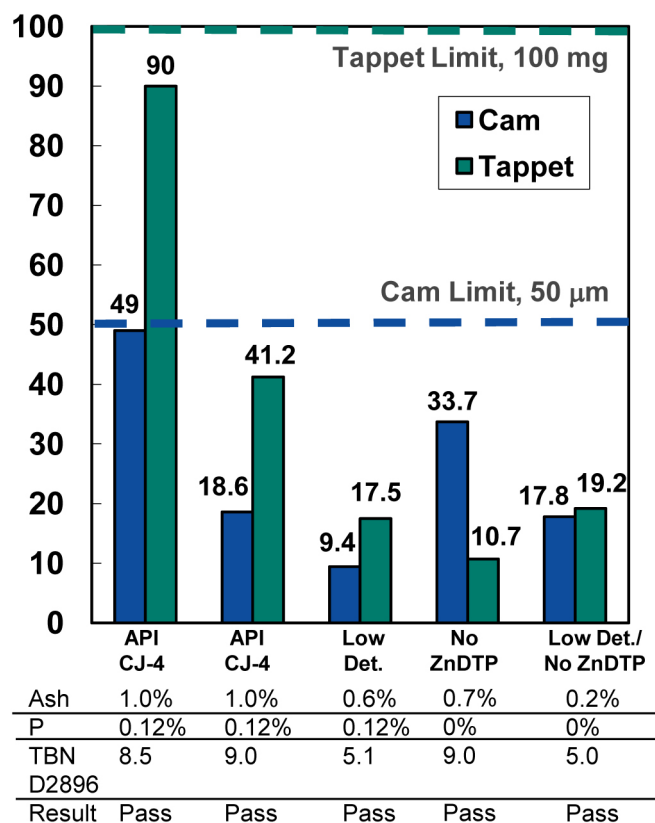


Figure 7. Matrix of three oils in Cummins ISB (tested at SwRI registered standards).

All three modified formulations passed the Cummins ISB at API CJ-4 levels, with the lowest wear in our experience compared to commercial CJ-4 oils. (See [Figures 7](#) and [8](#).) This excellent performance in Cummins ISB for wear control was not anticipated and shows the value of strategic research for stepping outside the normal formulating box in understanding wear mechanisms. This engine uses a rotating tappet on a cam-tapered face profile to assure tappet rotation. The engine generates 3-3.5% soot at 1,600 RPM due to retarded timing in the first 100 hours of the test. The remaining 250 hours of the test comprise cycles every 27 seconds from low speed idle, to rated load and speed to

peak-torque. In this second stage, the engine completes 32,000 cycles.



Figure 8. Cummins ISB cam and tappet, low detergent - no ZnDTP, 0.2% ash, 0% phosphorus.

2. Failing Results in Mack T-12, Cummins ISM and Sequence IIIG Tests with 0% Phosphorus - 0.2% Ash Oil

After the extremely successful testing in Cummins ISB, the formulation at 0.2% ash and 0% phosphorus was evaluated in the Mack T-12, Cummins ISM and Sequence IIIG tests, which are in the API CJ-4 oil category. The 0% phosphorus - 0.2% ash oil failed all three of the above tests. In the Sequence IIIG gasoline test, this oil produced catastrophic cam and lifter wear, extreme oxidation and severe piston deposit formation. In the Cummins ISM, there was severe injector screw and crosshead wear. Nevertheless, the ring wear was low, with passing results in filter delta P and sludge values. The failure of this oil in the Mack T-12 proved to be very instructive. The test failed due to poor oxidation control, which resulted in lead levels from the copper-lead bearings which exceeded the test limits. However, this oil recorded extremely low liner wear and oil consumption, well within the limit of the Mack T-12 test. (See Table 2.)

The absence of ZnDTP provided the extremely low liner wear and resulting low oil consumption in the Mack T-12 test. Using the Surface Layer Activation technique for cylinder liner wear in Mack T-10, Wim Van Dam et al. [32] found that a two-thirds reduction in ZnDTP reduced the 1,800 RPM liner wear by 30% and the 1,200 RPM wear by 50%. It is postulated that at top-ring reversal the extreme surface temperature decomposes the ZnDTP to the point that free sulfur is present. The sulfur can react with the liner to form iron sulfide, and resulted in liner wear in this test. Previous testing in ZnDTP-free railroad oils in DDC 8V71TA produced the same result of extremely low liner wear [33].

Table 2. 0.2% Ash - 0% phosphorus - failing wear in Mack T-12, Cummins ISM and Sequence IIIG, but passing in Cummins ISB.

Oil Description	Low Detergent No ZnDTP 0.2% Ash – 0% Phosphorus SAE 15W-40 TBN ASTM D2896 – 5.0	
Test	Result	Limit
Mack T-12	Fail	(Max.-Anchor-Min.)
Liner Wear (μm)	7.3	24 – 20 – 12
Top Ring Wear (mg)	79	105 – 70 – 35
0-300 Hrs Pb (ppm) Increase	44	35 – 25 – 10
250-300 Hrs Pb (ppm) Increase	16	15 – 10 – 0
Oil Consumption (g/Hr)	47.6	85 – 65 – 50
Merits	728.6	1,000
Cummins ISM	Fail	
Crosshead Wear (mg)	7.9	7.1 – 5.7 – 4.3
Filter ΔP (kPa)	3	19 – 13 – 7
Injector Screw Wear (mg)	165.4	49 – 27 – 16
Sludge	9.1	8.7 – 9.0 – 9.3
Top Ring Wear (mg)	38.6	100 Max.
Merits		1,000
Cummins ISB	Pass	
Cam Wear (μm)	17.8	50
Tappet Wear (μm)	19.2	100
Sequence IIIG	Fail	(Test Stopped)
% Viscosity Increase	972	<150
Piston Skirt Varnish	–	Report
WPD	5.8	3.5 Min.
Wear ACLW (μm)	796	60 Max.
Hot Stock Rings	2	None
Oil Consumption (g/Hr)	3.55	Report
Hours	75	100

3. Passing Results in GM Sequence IIIG Test with Zero-Phosphorus Oil at 0.4% Ash

The above tests provided two significant findings with passing results in the Cummins ISB, and the demonstration of extremely low liner wear with 0% phosphorus in the Mack T-12. However, the failing results in oxidation, piston deposit and valve-train wear needed to be addressed. Consequently, a matrix was designed to evaluate the addition of new components to remedy the loss in performance in oxidation, piston deposits and wear control in Sequence IIIG and wear control of the injector screws in Cummins ISM.

First, the above formulation at 0.2% ash - 0% phosphorus which failed the tests, was boosted with antioxidant to compensate for the loss of antioxidancy from the ZnDTP. This boosted formulation was then used to build a matrix design where four variables were antiwear additives. These

new formulations were evaluated in Sequence IIIG gasoline tests.

Sequence IIIG Piston Deposit Rating

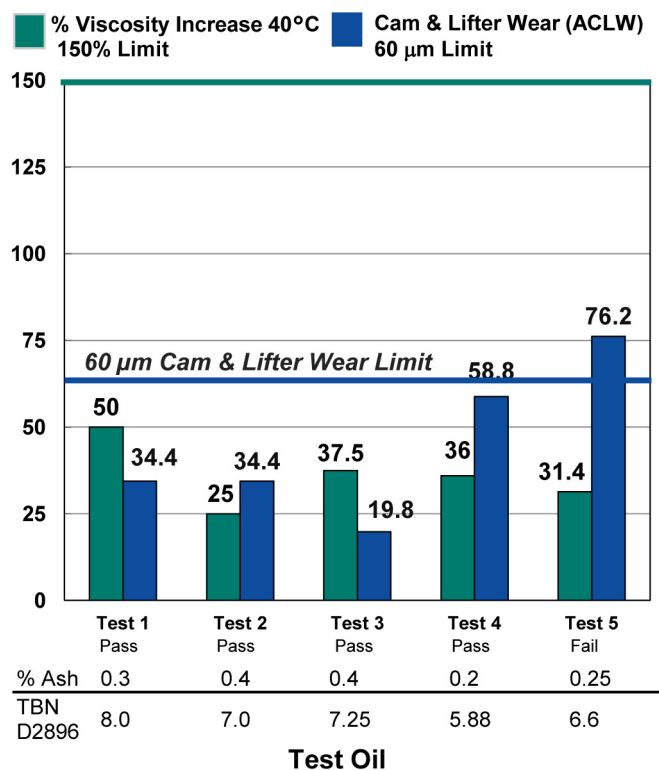
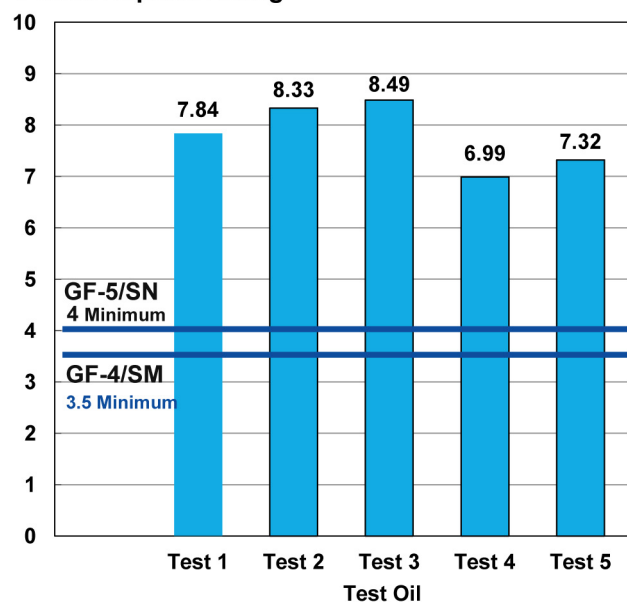


Figure 9. Sequence IIIG matrix of oils.

Four of the five tests conducted in the Sequence IIIG produced outstanding passing results. They range in ash from 0.2-0.4% with 0% phosphorus. The average viscosity increase was controlled to 36%, with the limit being 150% increase. The average cam and lifter wear (ACLW) was 37

µm, with a limit of 60 µm. Only one test failed due to wear control at 76 µm. The piston deposit control was outstanding, with ratings ranging from 6.99 to 8.49, when the limits for the current API SM (GF-4) are 3.5 minimum and the limits for API SN (GF-5) are 4.0 minimum. (See Figure 9.) Based on our experience these were the best results ever achieved in Sequence IIIG.

4. Passing Results in Cummins ISM; VW TDi; Sequence IIIG, IV and VIII Tests with 0% Phosphorus - 0.4% Ash Oil

Table 3. 0.4% Ash - 0% phosphorus - summary of engine tests (field test oil).

Oil Description		0.4% Ash – 0% Phosphorus SAE 15W-40 TBN ASTM D2896 – 7.0 TBN ASTM D4739 – 4.0	
Test	Result	Limit	
Cummins ISM	Pass	(Max.-Anchor-Min.)	
Crosshead Wear (mg)	4.9	7.1 – 5.7 – 4.3	
Injector Screw Wear (mg)	20.8	49 – 27 – 16	
Filter ΔP (kPa)	9.0	19 – 13 – 7	
Sludge	9.3	8.7 – 9.0 – 9.3	
Top Ring Wear (mg)	11.5	100 Max.	
Merits	1,647	1,000	
Sequence IIIG	Pass		
% Viscosity Increase	25	<150	
Wear ACLW (µm)	34	60 Max.	
WPD (Piston Deposits)	8.33	3.5 Min.	
Piston Skirt Varnish	9.88	Report	
Oil Consumption	2.13	Report	
Sequence IVA (SN)	Pass		
Cam Wear (µm)	65	90	
VW TDi	Pass		
Piston Deposits	63	Ref. Oils	
Sequence VIII	Pass		
Bearing Wt Loss (mg)	18.3	26	
Ball Rust Test	Pass		
Grey Value	120	100	
HTCBT	Fail		
Lead (ppm)	1	120	
Copper (ppm)	194	20	
ACEA Seals	Fail		
AK6-Tensile Strength (% Change)	-56	-50	
Cummins Field Test	Pass	Pass	

We conducted cam lobe film analysis on the four passing oils above, using X-ray Photoelectron Spectroscopy (XPS) and Ar-ion etching to determine the thickness, composition and chemical make-up of the antiwear films. The oil with the