

Impact of Lubricating Oil Condition on Exhaust Particulate Matter Emissions from Light Duty Vehicles

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ABSTRACT

Limited technical studies to speciate particulate matter (PM) emissions from gasoline fueled vehicles have indicated that the lubricating oil may play an important role. It is unclear, however, how this contribution changes with the condition of the lubricant over time. In this study, we hypothesize that the mileage accumulated on the lubricant will affect PM emissions, with a goal of identifying the point of lubricant mileage at which PM emissions are minimized or at least stabilized relative to fresh lubricant.

This program tested two low-mileage Tier 2 gasoline vehicles at multiple lubricant mileage intervals ranging from zero to 5000 miles. The LA92 cycle was used for emissions testing. Non-oxygenated certification fuel and splash blended 10% and 20% ethanol blends were used as test fuels. Results collected indicate that both the magnitude and variability of PM mass emissions decrease in the first 2000 miles of lubricant break-in, with potential increases as lubricant ages and decreases its performance activity. Fuel dilution of the lubricant with ethanol does not appear to deteriorate lubricant quality beyond expectations based on mileage alone.

INTRODUCTION

Comprehensive assessments examining the impact of lubricating oil on exhaust emissions, especially particulate matter (PM), from light duty in-fleet vehicles are sparse [1]. Most of the published technical studies concentrate their efforts on defining the impact of engine operating conditions, such as load, speed, ambient air temperature, and fuel composition on emissions [2,3,4,5,6,7,8,9].

The chemical composition of gasoline-fueled vehicle exhaust PM consists mainly of carbonaceous components including elemental carbon and high molecular weight organic constituents. PM is formed during the ignition process via incomplete fuel and oil combustion. Particulates are sometimes observed as visible smoke, when their relative size reaches larger diameter, although visible smoke is not necessarily a prerequisite for high PM emissions. Unlike in diesel engines, elemental carbon is not a very prevalent component of PM in gasoline engines, but it can form in relatively large quantities when engines operate under rich air-to-fuel ratio regimes e.g., during a cold start.

The amount of oil consumed and its contribution to PM can vary greatly from vehicle to vehicle depending on operating conditions or state of repair. It is well known that lubricating oil can access the combustion chamber via several pathways, such as intake and exhaust valve stem seals, piston-ring-liner systems, turbochargers, positive crankcase ventilation (PCV) systems, etc [10]. As engine components deteriorate, overall oil consumption can increase.

Lubricating oil properties can also impact engine oil consumption. Two key properties are the lubricant's volatility and viscosity. Differences in oil volatility can significantly impact oil consumption, especially when the vehicle is operating for an extended time at high speed/high load conditions. This may lead to evaporation of the low boiling components of a base stock [11, 12]. Oil volatility is commonly measured using the NOACK method (ASTM D5800). In this one hour long test, the oil sample is heated to 250°C and is exposed to a constant flow rate of air. NOACK evaporation loss is represented as % of original lubricant

mass lost. The temperature of the test represents typical range of lubricant temperatures within upper piston and ring areas.

It is generally believed that application of higher viscosity oils can lead to lower oil consumption, but higher fuel consumption.

Another aspect of lubricating oil that can have a significant impact on exhaust emissions is oil conditioning and aging. As oil gets older, more volatile fractions of the base stock can evaporate, polymers used as viscosity modifiers can shear leading to a decrease in kinematic viscosity, and lubricant oxidation products can lead to an increase in kinematic viscosity. All these changes can have significant impacts on regulated gaseous emissions and PM levels.

The question is on what timescale do these oil conditioning changes take place, and at what point are these effects on emissions minimized or at least stabilized? Anecdotal answers to this question ranged anywhere from driving a few aggressive cycles to driving several thousand miles in order to stabilize the overall system. Given the uncertainty and ambiguity of this answer, we decided to investigate this question via a pilot study using two high-volume sales Tier 2 light duty vehicles.

A second objective of this work was to investigate how the properties of the lubricant are affected by operating the vehicle on low-level ethanol blends (10% and 20% ethanol by volume).

One factor that sets this study apart from many other lube oil emission effects studies was that the oil was aged “in-situ” in each vehicle as opposed to simply testing a vehicle with fresh oil followed by an oil change to “used” oil, which is often a mixture of oils collected from other vehicles and composited together. Since lube oil conditioning is a process of shearing and surface chemistry, we hypothesize that our conditioning method more closely mimics that of an in-use vehicle.

EXPERIMENTAL

The central design theme of this test program is to accumulate mileage, conduct several repeat emissions tests, and sample the engine oil at set intervals in order to assess how tailpipe pollutant mass and lubricant quality change over time. Emissions tests were performed at intervals of 0, 500, 1000, 2000, and 5000 miles, with zero miles corresponding to freshly changed oil. Miles were accumulated in-between emissions tests using a mileage accumulation cycle on the chassis dynamometer in order to provide a repeatable method for oil conditioning.

The program was separated into two phases: (1) Initial oil conditioning and testing with non-oxygenated certification gasoline and (2) Ethanol blend testing. The original test plan

called for only 2000 miles of oil conditioning in phase one, at which point phase two ethanol testing would begin. At the end of phase two, we decided to add an additional on-road mileage accumulation period to the full useful life of the oil (5000 miles) with additional testing with the phase one test fuel. These additional mileage accumulation test results will be presented together with those of phase one.

In each phase, the vehicles were tested at 75°F over a cold start LA92 drive cycle on a 48” single roll chassis dynamometer in EPA's National Vehicle and Fuel Emissions Laboratory. An average of six repeat cold-start LA92 cycles are conducted at each test interval in order to provide a sufficient number of repeats for test-to-test variability to be assessed. Oil samples were collected from the vehicles' oil sump at the end of each testing interval for subsequent analysis.

DRIVE CYCLES USED

Several drive cycles were used in this study and will be referenced in subsequent sections of this paper. The 4-phase LA92 cycle was used for all sampled emission tests and preconditioning cycles in this study [13]. Two un-sampled cycles were utilized to condition the vehicle at specific intervals of the test program. The first is a mileage accumulation cycle called the Standard Road Cycle (SRC), commonly used in industry to age vehicle components for durability testing in the field [14, 15]. This cycle was used here as a repeatable method for accumulating miles over a wide range of speeds and loads on the dynamometer in-between emissions tests. A second cycle used is the EPEFE cycle, which is a catalyst desulfurization cycle defined in the European Programme on Emissions, Fuels, and Engine Technology (EPEFE) Report and referenced in the CRC E-60 project [16]. This is a very aggressive cycle that causes the vehicle to transiently run rich at high catalyst temperature, thereby removing any accumulated sulfur from the catalyst via hydrogen sulfide formation. It is important to remove any accumulated sulfur prior to each emission test interval to avoid confounding the effects of the variables we're investigating (oil condition and fuel ethanol content) with the effects of catalyst deactivation due to sulfur poisoning.

TEST VEHICLES

Two vehicles were selected from EPA's in-house fleet of test vehicles for use in this study: A 2006 Ford F-150 (Tier 2 Bin 8) with a starting odometer reading of 8000 miles, and a 2007 Toyota Camry (Tier 2 Bin 5) with 17,000 miles on its odometer at the start of testing. These two vehicles are high volume sellers in the US and provide us with two contrasting engine designs to study: a 4.6 Liter V8 engine vs. a 2.4 Liter in-line 4-cylinder engine. The manufacturer recommended oil change interval is 5000 miles for both vehicles. These low mileage normal-emitting vehicles were certified to the Tier 2 emissions standards listed in Table 1.



Table 1. Federal Tier 2 Emission Standards

FTP 75, FUL 100K Mi Std					
Bin	NMOG	CO	NOx	PM	HCHO
8	0.125	4.2	0.2	0.02	0.018
5	0.09	4.2	0.07	0.01	0.018

The test cycle for federal emission certification is the Federal Test Procedure (FTP) which differs from the LA92 cycle used in this program. Therefore, the emission standards shown in Table 1 are listed simply for reference and as a point of comparison between the two vehicles.

TEST FUELS

Three test fuels were used in this program: U.S. Tier 2 non-oxygenated unleaded certification fuel (E0), 10% ethanol splash-blended with E0 (E10), and 20% ethanol splash-blended with E0 (E20). Neat ethanol was used for blending to avoid any ambiguity in the use of an ethanol denaturant. A single batch of E0 certification fuel was used for blending. Each final fuel blend was stored between 50 and 55°F in 200 gallon dispensing containers. Properties for each fuel are listed in Table 2.

Table 2. Test Fuels Properties

PROPERTY	UNIT	ASTM METHOD	FUEL		
			E0	E10	E20
Ethanol Content	vol. %	D5599	0	9.7	19.5
T50	°F	D86	224	215	165
T90	°F	D86	312	309	300
RVP	psi	D5191	8.9	9.7	9.6
Aromatics	vol. %	D1319	30.7	27.8	25
Olefins	vol. %	D1319	0.9	0.9	0.7
Benzene	vol. %	D3606	0.5	0.5*	0.4*
S	PPM	D2622	30	26	25
(R + M)/2	-	Calc.	92	94*	97*

*Derived mathematically for ethanol blends

It is important to note that the two ethanol blends were splash-blended and not match-blended. This means that ethanol was added to a finished base gasoline as opposed to a sub-grade gasoline blendstock. The addition of ethanol to gasoline results in a shift in other key fuel properties besides ethanol (primarily RVP and T50, but also aromatics and sulfur by dilution) as shown above in Table 2. These fuel properties have been shown to have independent effects on exhaust emissions [17]. Therefore, any emissions effects observed when using these ethanol splash blends may be due to changes in fuel properties other than ethanol content alone. For this study, however, where the primary purpose for using ethanol was to determine its impact on lubricant quality, splash blending was determined to be sufficient.

LUBRICANT SPECIFICATIONS

Both test vehicles were lubricated with the same API SM/ILSAC GF-4 5W20 lubricant, which was provided by The Lubrizol Corporation along with all oil sampling supplies, used oil analysis, and analytical support. At the beginning of the program, each vehicle had its oil and oil filter changed three times in order to fully flush the old lubricant from the system. The properties of the fresh lubricant are listed in Table 3, below.

Table 3. Analytical Profile of the Fresh Oil Used

Viscosity Grade	5W-20
KV @ 100°C	8.432
Calcium (ppm)	1612
Sodium (ppm)	447
Phosphorous (ppm)	746
Sulfur (ppm)	2258
Zinc (ppm)	856

A two oz. oil sample was collected from the fully warmed-up engine at the conclusion of the last test in each interval between 0 and 5000 miles for subsequent analysis. On tests with ethanol blended fuels, oil samples were collected following the first, second, third, fifth, and final test - an additional sulfur purge (EPEFE) cycle after test 8 - in order to determine the rate of change of fuel dilution in the crankcase (if present). This high frequency of oil sampling resulted in approximately one quart of oil being withdrawn without replacement from each vehicle over the course of testing. In order to accommodate this, each vehicle was slightly overfilled by 0.5 quarts on the third initial oil change, meaning each vehicle finished the program roughly 0.5 quarts low - still within the filling tolerance of each vehicle.

Table 4. Analytical Techniques used in Evaluation of Fresh and Used Oil Samples

Method	Analysis
ASTM D5185	ICP Analysis: metallic elements: lubricant borne & engine wear derived
ASTM D445	Kinematic Viscosity at 40°C & 100°C
FTIR	Oxidation/Nitration
ASTM D4739	Total Base Number (TBN)
ASTM D664A	Total Acid Number (TAN)
ASTM D3525	Fuel Dilution; E10 and E20 fuel dilution evaluated using a test proprietary to Lubrizol based on ASTM D3525

Oil temperature was recorded for all soak and testing periods via a custom fabricated thermocouple port in the oil sump drain plug. Data was logged at 30 second intervals in order to



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characterize the lube oil temperature profile during both emissions testing and mileage accumulation intervals (see [Figures 15](#) and [16](#) for examples).

EXHAUST SAMPLING

The facilities used for testing meet or exceed the requirements of 40 CFR Part 86 Subpart B and Subpart C as they apply to vehicle testing. Exhaust Sampling consisted of phase-level THC, CH₄, NO_x, CO, and CO₂ using a Horiba MEXA gaseous emissions bench in accordance with 40 CFR Part 86.140 and 86.144. Particulate matter (PM) was composited across all 4 phases of the LA92, collected in parallel on four (4) Teflon membrane filters. This approach to PM sampling was selected to increase the mass per filter in order to improve the signal-to-noise ratio in the PM filter weighing process (with the tradeoff being loss of phase-level resolution). Four samples were collected in parallel in order to assess measurement variance to better understand the uncertainty in the measurement method. Particulate samples were otherwise collected, handled, and weighed in accordance with 40 CFR Part 1065 guidelines.

An attempt was made to analyze the organic and elemental carbon profiles of the PM using a Sunset Laboratories Semi-continuous OC/EC analyzer. However, due to unforeseen issues involving a leak in the system, the results of the analysis were not quantitative and had to be removed from the dataset. Use of such equipment is recommended for future studies as it provides insight into the contribution of Semi-Volatile Organic Carbon to total PM mass, some of which is likely to be from the lubricant.

VEHICLE PREPARATION

Prior to each test interval, the vehicles were prepared for testing by draining and filling the fuel tank twice (via the fuel rail) to completely purge any residual fuel from the system. The EPEFE catalyst desulfurization cycle was driven to remove any accumulated sulfur from the catalyst that could adversely affect catalyst efficiency, followed by an unsampled LA92 preparation. The vehicle was then removed from the dyno, without starting, to a 75°F soak area for 12 to 36 hours of temperature stabilization prior to testing. Eight (8) repeat, cold start LA92 tests were then driven to complete the test interval.

METHODS USED TO REDUCE VARIABILITY

The primary goal of this study is to identify small changes in emissions - from very clean vehicles - that happen slowly over time due to changes in the condition of the oil. Therefore, great care was taken to eliminate, or at least

minimize, other variables that may affect emissions and confound the emission effects of the variables tested. The following paragraphs list several examples.

The same driver and dynamometer were used for all emissions tests throughout the program in order to eliminate any driver-to-driver variability or test site bias. Vehicles were moved from the dynamometer without starting following each test to ensure the same key-off condition at the end of each emission test. Only Tier 2 emission-level vehicles were tested on this test site for the duration of this study to avoid contamination of the dilution tunnel, and periodic tunnel blanks were collected to assess any change in background PM levels.

The same fresh lubricant was used in each vehicle, and only after three complete oil and filter changes to fully flush the crankcase. The lubricant was aged “in-situ” in each vehicle to more closely mimic the oil conditioning process that can occur during normal use. Likewise, the test fuels were blended from a single batch of base fuel, and prior to each fuel change in Phase 2 the fuel system was flushed twice with test fuel to minimize fuel carryover. Each finished blend was stored and dispensed at low temperature to minimize drift in fuel properties.

Mileage accumulation for phase 1 was performed on the chassis dynamometer over a defined cycle in order to provide a repeatable method for accumulating miles. A catalyst sulfur removal cycle was driven after each block of mileage accumulation (before each emission test interval) to ensure the removal of any sulfur that could affect emissions. Separate tires were used for emissions test in this study to minimize tire wear from mileage accumulation and the aggressive catalyst desulfurization cycles.

Multiple repeat tests were conducted at each test interval to provide sufficient information for statistical tests to be conducted. PM measurements were collected on quadruplicate parallel filters to provide an uncertainty assessment for each measurement.

RESULTS AND DISCUSSION

PHASE 1: MILEAGE ACCUMULATION WITH E0

Phase one initially consisted of only 2000 miles of oil conditioning, but the decision was made after phase two to continue mileage accumulation to 5000 miles - the full useful life of the oil. Before presenting these results it is important to note that while the first 2000 miles were accumulated on a dynamometer, the last 3000 miles were done on-road following a prescribed mileage accumulation route. Commercially available fuel (containing up to 10% ethanol) was used during this on-road mileage accumulation rather