

Oxidation of Axle Lubricants - Laboratory Studies and a Model to Predict Service Life

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ABSTRACT

The continuing push for improved fuel economy, reduced carbon emissions, and lower operating costs has resulted in higher operating temperatures for axle lubricants in passenger cars and commercial vehicles. These higher operating temperatures, in turn, have placed more severe demands on the thermal & oxidative performance of axle lubricants. A number of industry-standard, laboratory methods exist to evaluate this key performance parameter. This paper discusses the use of laboratory methods to evaluate oil service life. We examine the behavior of five commercially available axle lubricants in the CEC L-48 oxidation test (Apparatus A). The oils were chosen so that different additives and base oils could be compared. We evaluated both the effect of time and temperature on the oxidation behavior. In agreement with previous studies, we found that infrared (IR) spectroscopy provides a convenient and meaningful way to track the extent of oxidative degradation. We define the "breaking point" of an oil as the value of IR Peak Area Increase (PAI) at which deposits first appear. We propose a simple model for estimating the total endurance life of an axle lubricant by dividing the breaking point by the rate of oxidation as measured by PAI.

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INTRODUCTION

Design improvements by car, truck, and axle builders have posed increasing challenges for the axle lubricant. The drive for better fuel economy and lower emissions has resulted in aerodynamic styling that reduces the cooling air flow over the differential. This has caused a significant increase in average axle operating temperature. Demands for reduced vehicle weight have led to reduced oil volumes and smaller overall differential sizes - despite increasing torque throughput. Again, these changes have resulted in higher oil temperatures. Finally, customer and OEM demands for lower cost of ownership, longer drain, reduced maintenance, and longer equipment life have led to exceptionally long drain intervals and improved lubricant performance in all areas.

There has been a lot of research activity devoted to understanding the factors that affect axle oil service life. Before 1980, the standard axle oil drain intervals for Class 8, on-highway trucks in North America was about 80,000 km. In the 1980s, this interval took a dramatic jump to 400,000 km. From the 1990s to the present, the extended service intervals are now 800,000 km, with a number of vehicles exceeding 1,000,000 km without an oil drain.

From the earliest days of lubrication it was known that oxygen and high temperature have a detrimental effect on oil life. In particular, the oxidation of hydrocarbons, which increases

exponentially with temperature, results in the progressive formation of oxygenated hydrocarbons, leading ultimately to polymer formation. This results in increased oil viscosity, increased oil acid number, and increased sludge and deposit tendencies. It is rather ironic that oxygen, the very molecule that sustains our life on this planet, is also responsible for decreasing the life of our lubricants.

Graham, Schwind, & Jordan [1] published an early effort to understand the effects of high temperature on oil performance in the field. They compared 7 different lubricants in 3 of the most common oxidation bench tests: the GFC, L-60, and ISOT (see next section for more details of the methods). They tested the same lubricants in actual transmissions on a test track for 100 hours at 160°C. The authors found that the ISOT method, which used the lowest temperature compared to either GFC or L-60, was the best predictor of viscosity increase and Total Acid Number (TAN) increase for field transmissions. They noted that the actual transmission operating conditions of 100 hours at 160°C appeared milder than the ISOT conditions of 96 hours at 135°C. Also, the field transmissions showed no correlation between viscosity increase and deposits. In the authors' view, the biggest source of field issues came from varnish and deposits, and the traditional bench-measured viscosity increase and TAN increase parameters were not helpful in determining real service life. Interestingly, the transmission tests showed that lubricants with the worst

deposit problems actually displayed decreases in TAN after the test. The authors proposed that the acidic components precipitated from the oil and were therefore not measured during oil sampling.

Wetzel, Bein, et al. [2] compared the properties of oil field tested for 632,000 km with the properties of the same oil after bench GFC oxidation testing. They found that bench oxidation testing at 160°C was much more severe than the conditions encountered in the field trial. In particular, the extent of oxidation as measured by IR did not correlate between the lab and the field; the lab sample showed much higher carbonyl peak absorbance than the field sample. The authors ran the bench test using nitrogen instead of air, and found that the nitrogen method also did not correlate with the field results. The best simulation of field service resulted from oxidation testing for 192 hours at 130°C in the presence of metal catalyst.

Obiols [3] gives a thorough explanation of the use of FTIR to monitor lubricant oxidation and compares bench and field data. The main oxidation tests used were the GFC and the Iron Catalyzed Oxidation Test (ICOT). Obiols found that the Peak Area Increase (PAI), which is the area between 1650 cm⁻¹ and 1820 cm⁻¹ of the differential IR spectrum, correlated well with TAN for a series of bench-oxidized engine lubricants. However, in engine tests the PAI did not correlate well with TAN possibly because the combustion environment creates more acidic species, notably sulfuric and nitric acids. Obiols concluded that you cannot differentiate long drain engine oils with fixed duration bench tests. So, he used the shape of the degradation curves over time to show enhanced differentiation between oils. Both PAI and viscosity increase show an induction period. Obiols proposed that the best way to shorten test time is to fix the oxidation duration at 72 hours and to vary the catalyst content.

In an attempt to establish a lab method that correlates with the field, Matsumoto et. al. [4] used the FZG gear tester under severe conditions to degrade oil. The FZG was run for 500 hours at 120°C with a contact pressure of 1080 N/mm². The change in TAN with time varied little for any of the tests used - FZG, ISOT, and field. However, their study was done on a manual transmission oil formulated with zinc dialkyl dithiophosphate (ZDDP). In addition to its antiwear properties, ZDDP is a well-known antioxidant and this may have resulted in a long induction period for oxidation during which few acidic species were generated. The authors found, from ³¹P-NMR measurements on the oil, that the ZDDP deterioration process is similar in the FZG and field tests, but different from that observed in the ISOT.

Morgan and Linden [5] presented data from DKA and L-60-1 oxidation tests run at 6 different temperatures, from 100 to 170°C, on a gear oil containing varying amounts of limited slip additive. They found that the change in TAN had shortcomings

for evaluating the extent of oxidation. Their main conclusion was that increasing the concentration of limited-slip additive resulted in poorer oxidation stability and cleanliness.

Gao [6] used a modified Universal Oxidation Test (ASTM D4871) for testing an 80W-90 axle oil at varying times and temperatures. The oxidation tester used 30 grams of oil in a glass tube with no catalyst. The standard test was run for 192 hours with 200 mL/min of air flow. Instead of measuring PAI, Gao focused on the FTIR absorbance at 1715 cm⁻¹, and found that value to correlate well with extent of oxidation. His data showed a smooth increase in all 3 parameters - Δ TAN, Δ IR, and Δ vis - with increasing time at any given temperature. The Δ IR value was linear with time; however it could not represent severity well at higher temperature because the oil sample underwent an exponential increase in viscosity at those conditions. Also, the Δ IR value had an inconsistent correlation with Δ TAN. Gao found that the Arrhenius rate equation worked well for Δ vis, Δ TAN, and Δ IR over most of the temperature range, except that you had to exclude data at the highest temperatures because of rapid polymerization.

Bouffet [7] attempted to develop an improved bench test for predicting the long-term field performance of axle and transmission lubricants. He noted that used oil from very long no-drain field tests does not show very high viscosity increase, unlike what is typically seen in bench oxidation tests. The same trend has been found in our own extended-drain field tests [8, 9], done with hundreds of trucks for intervals of 800,000 km. The used oil samples collected at various field test times showed small increases in both TAN and viscosity compared to fresh oil.

Bouffet wanted to separate the effects of oxidation and thermal aging processes, so he used a thermal aging method with oil heated at 120°C in an open 2-L beaker with no forced air bubbling. He monitored the depletion of P additive with time and found a good correlation to field data. One interesting finding was that the thermal degradation impacted the additive chemistry more strongly than the base oil. Synthetic base was not necessarily better than mineral oil base under the thermal aging conditions. Also, the change in TAN did not correlate with additive degradation. One drawback to the thermal aging method is that lower temperature was used to better simulate field operating conditions. This meant that long aging times, up to 6 months, were needed to get meaningful data. Even though a 6-month lab test is better than a multi-year field test, the time involved for the lab test is longer than desirable for product development. Bouffet concluded that "although oxidation should not be ignored, thermal degradation appears to be the prime factor of axle oil fluid aging".

Bouffet and Abellaneda [10] followed up their 2008 work by expanding the study to include manual transmission fluids. They used a DKA apparatus with N₂ bubbling instead of air. In an effort to accelerate the test time, they ran for 192 hr at 160°C with 2 L/hr nitrogen flow rate. Their data showed a similar degradation process between the open test at 120°C

and the nitrogen accelerated test at 160°C. However, both of the bench methods did not completely predict the known field performance of the test oils. Nevertheless, the authors concluded that thermal aging is significantly better than oxidation testing as a means to reproduce long-term field behavior. Deposit formation was the one area where oxidation testing had a good correlation to field experience.

Bastian and Vautier [11] reinforced the conclusions of Bouffet and Abellaneda in a recent paper at the Uniti Mineral Oil Technology Congress. They reported that MTF durability is determined by thermal stability and not oxidation. They announced a new test method, GFC Tr-41-A-12, that was developed for thermal aging of transmission lubricants under nitrogen blanketing.

Clearly, there is still a lot of technical debate and room for more complete understanding of the degradation mechanism(s) of both axle oils and MTFs in field service. Because oxidation has historically been the preferred bench test approach and because oxidation tests appear in numerous OEM specifications, our work focused on oxidation testing.

EXPERIMENTAL

Table 1 shows some key properties of the lubricants evaluated in this study. The oils are all commercially available and commonly used in axles in both Europe & North America. The designation “clean additive” means that the oil has passed the cleanliness requirements outlined in SAE Standard J 2360 for the ASTM D5704 (L-60-1) test.

Table 1. Properties of Test Lubricants.

Oil Code	A	B	C	D	E
SAE Grade	75W-90	75W-90	80W-90	75W-90	85W-90
Clean additive?	Yes	Yes	Yes	No	No
API Base Group	III	IV	I, II	IV	I
Vis, cSt, 40 C	110.8	105.4	136.6	96.1	182.2
Vis, cSt, 100 C	15.2	15.39	14.27	14.85	16.83
Viscosity Index	144	154	102	162	97
Brookfield, cP (Temperature, C)	135,000 (-40)	56,000 (-40)	74,800 (-26)	100,000 (-40)	43,000 (-12)
Acid Number, mg/kg	1.9	2.1	0.7	1.6	1.3
Elements, wt%					
Boron	0.0222	0.0476	0.1892	---	---
Calcium	---	0.0012	0.0057	0.0009	0.0004
Magnesium	---	0.1170	---	---	---
Phosphorus	0.138	0.163	0.046	0.111	0.111
Sulfur	2.35	2.13	1.10	2.12	2.41

Table 2 compares the most popular oxidation test methods used by axle OEMs in the same format presented by Graham et. al. [1]. The * in Table 2 signifies that the test temperature is not standardized. The value shown is one traditionally used for

driveline lubricants. Note that there are 2 variations of the CEC L-48 test. This is because the method is a fusion of two tests developed independently by GFC (France) and DKA (Germany). French OEMs tend to favor the GFC version whereas German OEMs favor the DKA version. The DKA apparatus has a water-cooled condenser at the top of the test tube, so volatiles can be condensed and returned to the oil. The GFC method is open to atmosphere and is less suitable for oils with high volatile content or at high test temperatures. The L-60-1 (ASTM D5704) is favored by North American OEMs whereas the ISOT (JIS K2514-1) is heavily used by Japanese OEMs.

It is evident that these common oxidation methods have widely different conditions. For example, both the GFC and DKA have very high air/oil ratios. This may explain why these methods often fail to correlate with field results; the operating environment in either a transmission or axle does not involve forced air bubbling, especially at such high amounts. The ISOT does not use forced circulation; instead the oil oxidation occurs via the diffusion of oxygen from the atmosphere into the stirred oil. In this sense, it is similar to the thermal aging method used by Bouffet [7], except that his oven method did not stir the oil. As Graham et. al. [1] noted, the ISOT gives a more realistic comparison with certain properties of oils aged in the field. The L-60-1 has a lower air/oil ratio than either CEC L-48 test; however it runs at a temperature that is much higher than encountered in continuous field operation. This definitely accelerates the test (the test hours are the lowest of all methods in Table 2), but at the expense of possibly changing the degradation mechanism compared to real-world service.

Table 2. Comparison of Oxidation Bench Test Methods.

	CEC L-48, App.A (GFC)	CEC L-48, App.B (DKA)	ASTM D5704 (L-60-1)	JIS K2514-1 (ISOT)
Apparatus	Erlenmeyer flask (glass)	Flat bottom tube (glass)	Steel case w glass front	Glass beaker
Metals?	No	No	Fe, Cu	Fe, Cu
Agitation	Air blow	Air blow	Air blow, gear rotation	Glass stirrer
Time, hrs	192	192	50	96
Temperature, C	150*	150*	163	135*
Air Rate, L/h	10	5	1.1	None
Total air for test, L	1920	960	55	---
Oil volume, mL	300	100	120	250
Air/Oil vol. ratio	6400	9600	458	---

The oxidation results in this paper were obtained using the CEC L-48 method, Apparatus A (GFC). The choice was arbitrary and mostly based on the fact that the testing was carried out in our European laboratory.