Engine Friction and Wear Performances with Polyalkylene Glycol Engine Oils

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Abstract

The application of polyalkylene glycol (PAG) as a base stock for engine oil formulation has been explored for substantial fuel economy gain over traditional formulations with mineral oils. Various PAG chemistries were explored depending on feed stock material used for manufacturing. All formulations except one have the same additive package. The friction performance of these oils was evaluated in a motored single cylinder engine with current production engine hardware in the temperature range 40°C-120°C and in the speed range of 500 RPM-2500 RPM. PAG formulations showed up to 50% friction reduction over GF-5 SAE 5W-20 oil depending on temperature, speed, and oil chemistry. Friction evaluation in a motored I-4 engine showed up to 11% friction reduction in the temperature range 40°C-100°C over GF-5 oil. The paper will share results on ASTM Sequence VID fuel economy, Sequence IVA wear, and Sequence VG sludge and varnish tests. Chassis roll fuel economy data will also be shared.

Introduction

Engine oils play a critical role in engine friction reduction. It is important to understand the impact of lubrication regimes of an engine on fuel economy. The cam and follower system in an engine valvetrain operates under boundary and/or mixed lubrication regimes. The bearings (main and connecting rod) operate mostly in the hydrodynamic regime, except during start/stop situations. The piston ring/cylinder bore contact operates in boundary, mixed and hydrodynamic lubrication regimes. The proportions of each of these lubrication regimes vary depending on the engine design but in an automotive engine the hydrodynamic lubrication regime dominates, followed by the mixed lubrication regime. The frictional losses in hydrodynamic regime can be reduced by controlling viscometric characteristics of engine oils. In motored engine tests, SAE 0W-20 engine oils showed lower friction than SAE 5W-30 at different oil temperatures and engine speeds (1). Damen et al. based on a fleet study estimated 0.2 % fuel economy improvement for SAE 0W-20 oil over SAE 5W-20 oil, both meeting GF-4 specification (2). Koyamaishi et al. explored engine friction reduction potential with decreasing high temperature high shear viscosity (HTHS) of engine oils. Reducing HTHS from 2.9 MPa.s (typical values for SAE 5W-30 oils) to 1.7 MPa.s improved fuel economy by about 2.5% in NEDC (New European Drive Cycles) (3). However, other investigations identified that fuel economy improvement may plateau around 2.6 MPa.s beyond which fuel consumption may increase because of increased boundary friction contribution (4, 5). Cockbill and Bennet (6) demonstrated lower engine friction with lower viscosity engine oils at low engine oil temperatures (-20°C to -35°C). Another option of reducing friction in engines is by using oils with high viscosity index (VI) as high viscosity index engine oils provide lower dependence on oil viscosity on temperature, thereby offering reduced viscosity at low temperatures. This translates into lower friction during engine warm up. Nagashima et al. (7) showed about 15% friction reduction in motored valvetrain tests and also lower engine friction using high VI (137) engine oil compared to lower VI (123) oil. Advanced VI improver based on comb polymer architecture demonstrated about 1.5% fuel economy improvement in NEDC cycles (8). The addition of friction modifiers plays a significant role in reducing friction. Glycerol monooleate is one of the organic friction modifiers most widely used in engine oils today, although there are others. Molybdenum dithiocarbamate (9) is another friction modifier which is very effective in reducing friction under boundary lubrication condition. SAE 5W-20 engine oil with molybdenum dithiocarbamate friction modifier can improve fuel economy by 1-2% over SAE 5W-30 engine oils with no friction modifier, depending on drive cycles and engine design (10). However, its use in the North American oil market is restricted due to (a) cost, (b) inability to retain friction advantage with oil aging (11, 12) (6400-10000 km), and (c) concern over turbocharger deposits (13). The proper selection of friction modifier and viscosity modifier combination can provide fuel economy benefit over extend drain period (14).

A small but significant fuel economy benefit was realized in each successive engine oil specifications, GF-1 through GF-5. The improvement was possible through changes in base oil and additive chemistry. Additional fuel economy improvement through engine oil is expected to be small and therefore, may need to focus on non-traditional base oils. In recent years, polyalkylene glycol oils have been explored as a basestock for engine oil formulations and initial data showed encouraging results (15-16). Polyalkylene glycols are classified as API group V synthetic basestocks (23) and are currently used as fire resistant hydraulic fluids, refrigeration lubricants, etc. They have also been used for lubricating two-cycle engines as early as the1970s. Polyalkylene glycols offer several advantages in engine oil application, including lower boundary friction coefficient because of their polar nature, low volatility (5%) for potential lower oil consumption, clean burning leading to less engine deposit and higher oxidative stability (17) leading to increased oil drain intervals. The friction reduction potential and wear performance of engine oils formulated from polyalkylene glycol base stock has been reported recently. The objectives of the paper are to evaluate the friction reduction potential of polyalkylene glycol base engine oil formulations in motored and fired engine tests along with wear protection capability and sludge and varnish formation tendency.

Lubricant Formulation

The lubricants considered for this investigation are described in Table 1 (pg 9) along with some of the physical property data. Various types of PAGs were evaluated to determine the impact of structure on tribological properties. The general structures of the PAGs studied are depicted in Figure 1.

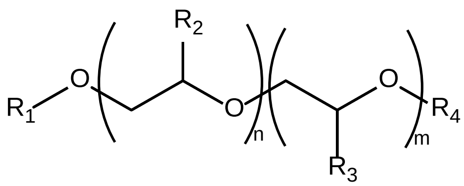

Figure 1: General Chemical Structure of PAG

The five different chemistries were created by varying the starting alcohol, R_1; the oxide monomers, R_2 and R_3 being either –H if ethylene oxide, $-CH_3$ propylene oxide, or $-C_2H_5$ if butylene oxide and R_2 the same as R_3 if a homopolymer or R_2 different from R_3 if a random copolymer and changing the end group R_4. If R_4 is an alkyl group, the PAG is "capped" or alternatively called a diether. If R_4 is hydrogen the PAG is a monol or simply referred to as a "PAG". The five different polymers being investigated are capped random copolymer of ethylene oxide and propylene oxide with alcohol 1; capped homopolymer of propylene oxide with alcohol 1; capped homopolymer of propylene oxide with alcohol 2; monol homopolymer of propylene oxide with alcohol 1; and monol copolymer of propylene oxide and butylene oxide with alcohol 2. The viscosity of the polymer is determined by the molecular weight, which in turn is determined by the number of moles of oxide added to the starting alcohol (m and n in Figure 1). It is therefore possible to create series of chemically similar polymers with different HTHS viscosities by varying m and n. Blending chemically similar polymers with different viscosities will make fluids with viscosities between the two starting polymers. All fluids except 17-1 were formulated with a proprietary additive package (18, 19) that was designed to be low SAPS, low ash and to have an inherently high viscosity index (VI). None of the fluids studied contained a viscosity index improver or an overbased detergent. In addition to the proprietary additive package, 17-1 included ZDDP for improved anti-wear properties and a molybdenum-based friction modifier. The high inherent VI of PAG-based lubricants and the lack of a VII did not permit meeting both the 150°C HTHS and the 100°C low shear viscosities for an XW-20 lubricant as required by SAE J-300 Engine Oil Viscosity Classification. The lubricants used for various types of evaluations are shown in Table 1 (pg 9). And their viscosity-temperature relationship is shown in Figure 2.

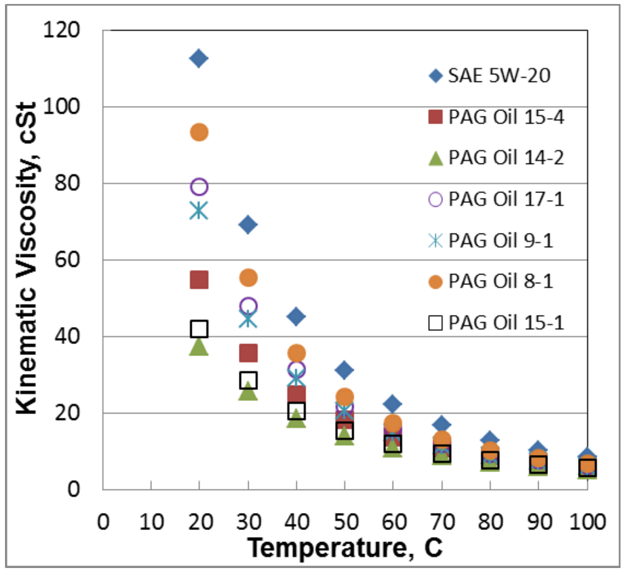

Figure 2. Viscosity-temperature relationship for various oils tested.

Experimental Details

The friction reduction potential of the oils were evaluated using a (a) motored non-pressurized single cylinder engine, (b) motored engine, and (c) ASTM Sequence VID fuel economy tests. In an engine frictional loss at cylinder liner and piston skirt and rings contacts contribute about 45% of the total frictional losses (20). These contacts operate in boundary lubrication regime near top and bottom dead centers, in hydrodynamic lubrication regime near mid-stroke, and in mixed lubrication regime on the remaining portion of the cylinder surface. The regions of boundary, mixed, and hydrodynamic lubrication regimes vary depending on engine speed, load, and oil temperature. There are opportunities to reduce frictional losses at these contacts through low friction and lower viscosity engine oils. However, measurements of friction at these contacts are challenging to say the least. A motored single cylinder engine employing a "floating liner" method was used for friction measurements. The single cylinder engine was constructed using current production hardware (piston, piston rings, piston pin, and connecting rod) from a V-6 engine. The friction force at the piston and liner interface was measured using three pre-loaded force sensors 120 degrees apart pressed against the floating liner through a deck spacer. Any deviation of the recorded friction force from the pre-set value is representative of the friction force acting at the piston and liner interface. The crankshaft is driven by a 56 kW motor through a set of couplings and bearings. The friction torque was measured using an in-line torque meter. The friction measurements were conducted at oil temperatures 40°C-120°C and in crankshaft speed range 62 RPM-1750 RPM. Prior to friction measurements, the piston, piston ring and liner surfaces are broken-in by motoring the engine at 100°C for several hours at various speeds until a stable friction force was observed at each speed.

Motored engine friction tests were conducted using an I-4 engine. Prior to friction measurements the engine was broken-in using a standard corporate procedure. Friction data was collected from 700 RPM to 5000 RPM engine speed and oil was supplied to the engine from an external sump. At each oil temperature three tests were run and the average of the three tests reported. Tests were conducted at three engine oil temperatures: 40°C, 80°C, and 100°C.

ASTM Sequence VID tests were run to get an assessment of fuel economy improvement under fired engine conditions. The test is run in two steps; step 1 consists of measuring fuel economy after the oil has aged for 16 h and is known as FEI 1 and step 2 consists of measuring fuel economy after an additional 84 hours of aging for a total of 100 h of aging and is known as FEI 2. The sum of FEI and FEI 2 is reported as FEI SUM. The fuel economy is measured under specific engine load, speed, and oil temperature as shown in Table 2 (pg 9) using a GM 3.6L engine. Indicated in the table is the lubrication regime associated with each stage which helps understanding the stages beneficial for fuel economy improvement (21). The test is heavily weighted on boundary (34.6%) and mixed (61%) lubrication regimes.

An ASTM Sequence IVA test was conducted for an assessment of the wear protection capability of PAG oils. This test is designed to represent extended idling conditions and low temperature wear protection capability. Oil temperatures are maintained at 50°C and 60°C and are reflective of typical taxi cab driving conditions (22). The test duration is 100 hours and is a combination of two drive cycles that are repeated 100 times: the first consists of running the engine at 800 RPM at 50°C for 50 min followed by the second at 1500 RPM at 60°C for 10 minutes. The cam nose wear is reported at the end of test.

An ASTM Sequence VG was run to evaluate the capability of PAG oils in controlling deposit formation. This is a 216 hour test designed to simulate moderate temperature taxi and delivery services. The test is run in three stages; with Stage 1 running at 1200 RPM for 120 minutes at 68°C oil temperature, Stage 2 running at 2900 RPM at 100°C oil temperature for 75 minutes and Stage 3 running at 700 RPM at 45°C oil temperature for 45 minutes. At the end of test, sludge deposits on rocker arm covers, cam baffles, timing chain cover, oil pan baffle, oil pan, and valve decks are rated. Varnish deposits are also rated on piston skirts (thrust) and cam baffles.

Chassis roll dynamometer fuel economy tests were conducted to evaluate fuel economy improvement capability using the Federal Test Procedure cycle (FTP-75) and the Federal Highway Fuel Economy Test cycle (HWFET). The tests were run on a vehicle equipped with an I-4 engine, the same engine used for motored engine tests. The vehicle had 40,000 km to ensure the engine was broken-in. The existing engine oil was drained, flushed with the candidate oil and then a charge of fresh oil was added. Two oils were run, GF-5 SAE 5W-20 and PAG oil 15-1. Three to five repeat fuel economy tests were run following 800, 8000, and 16,100 km accumulation to get an understanding of fuel economy improvement with oil aging. Mileage accumulation was done using EPA SRC 2.5.2 drive cycles used for catalyst aging To avoid influence of tire wear and emission system aging on fuel economy a separate set of tires and emission systems were used. An oil sample was collected after each mileage accumulation for analysis.

Results and Discussion

Motored Single Cylinder Piston Ring Friction Tests

Figure 3 shows excellent repeatability of friction force measurements at 100°C oil temperature with GF-5 SAE 5W-30 oil as a function of engine speed. Friction force is expected to decrease with engine speed due to increased oil film thickness at the piston ring/liner interface, which reduces the severity of asperity interactions. Figure 4 shows a comparison of friction force measured at 120°C oil temperature as a function of engine speed between GF-5 SAE 5W-20 and various PAG oil formulations. PAG oils show significant friction benefit over GF-5 SAE 5W-20 (nearly half the friction force) at all speeds. PAG oil 15-4 and PAG oil 14-2 have the same formulation with the exception that high temperature high shear viscosity of the former is 2.66 mPa·s while the latter is 2.4 mPa·s. PAG oil 14-2 showed lower friction force than PAG oil 15-4 particularly at higher speed as expected. The friction benefits could be due to lower viscosity of PAG oils compared to SAE 5W-20 oil and/or difference in chemistry of base oils. At 80°C temperature, the benefits are observed only at lower speeds.

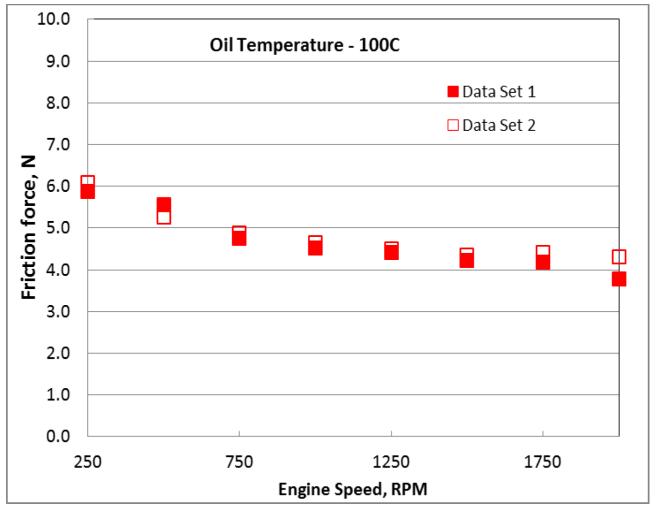

Figure 3. Variation of friction force as a function of engine speed at 100°C temperature with GF5 SAE 5W-30 oil. Also, shows data repeatability.

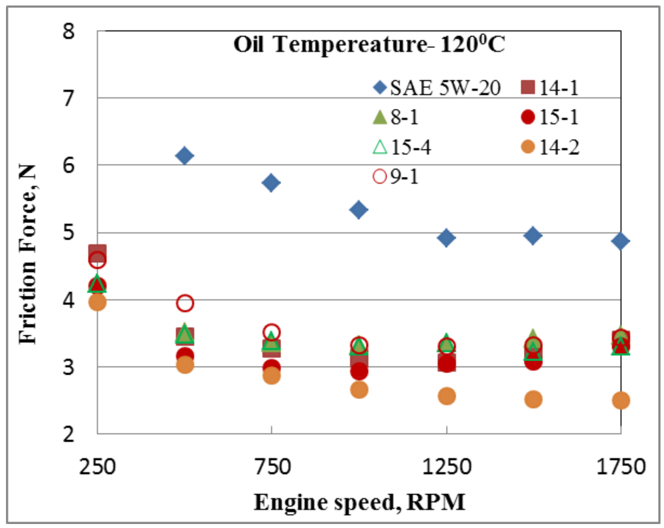

Figure 4. A comparison of friction force per cycle as a function of engine speed of different PAG engine oils with SAE 5W-20 oil at 120°C temperature.

To better understand the importance of chemistry and viscosity, the above results are plotted in a different way in Figure 5 which shows iso-viscosity plots. This is achieved by comparing friction torque data for GF-5 SAE 5W-20 oil data at 120°C for which the kinematic viscosity was 7.1 mm^2/s with those of PAG oil 14-2 at 80°C (kinematic viscosity of 6.8 mm^2/s), and PAG oil 8-1 at 100°C (kinematic viscosity of 6.6 mm^2/s). Although the viscosity numbers are not exactly the same, they are within 0.5 mm^2/s, close enough to understand the role of base oil chemistry on friction. As the results show, the friction response of the two PAG oils is close to one another and they are significantly lower than that of the GF-5 SAE 5W-20 oil. Similar analysis done at other viscosity levels showed the same trend indicating that the chemistry of PAG oil is primarily responsible for lower friction.

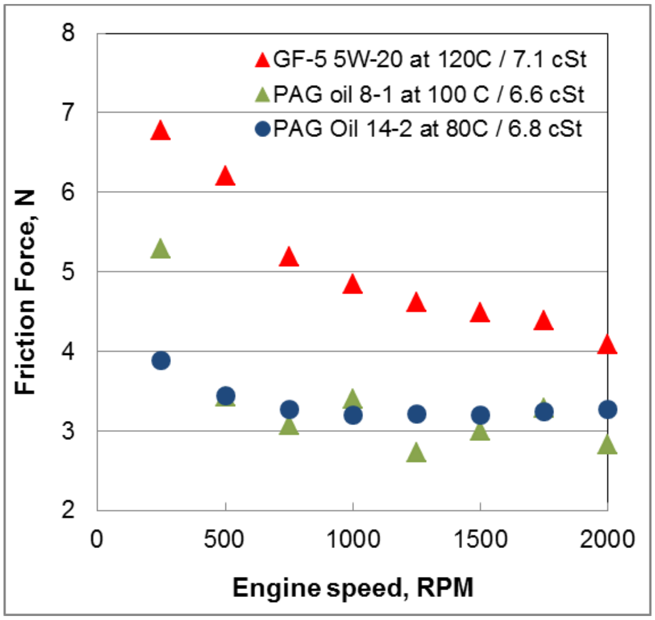

Figure 5. A comparison of friction force at about the same viscosity level for different engine oils.

Motored Engine Friction Tests

Five repeat tests were run prior to friction data collection to establish repeatability. Figure 6 shows excellent repeatability at 93°C with SAE 5W-20 oil. Figure 7 shows engine friction data as a function of engine speed. Although friction data was collected up to 5000 RPM, only friction data up to 2500 RPM engine speed is shown because no significant difference could be observed between the oils beyond this speed. At 100°C oil temperature, and at lower engine speed where mixed lubrication regime prevail, PAG oils showed significant friction reduction compared to GF-5 SAE 5W-20 oil. At 700 RPM, XZ97019.01showed 10.9% friction reduction compared to GF-5 SAE 5W-20 oil. No significant friction difference could be observed between PAG oils until the oil temperature dropped to 40°C. Table 3 (pg 10) shows percent friction reduction of PAG oils over GF-5 SAE 5W-20.

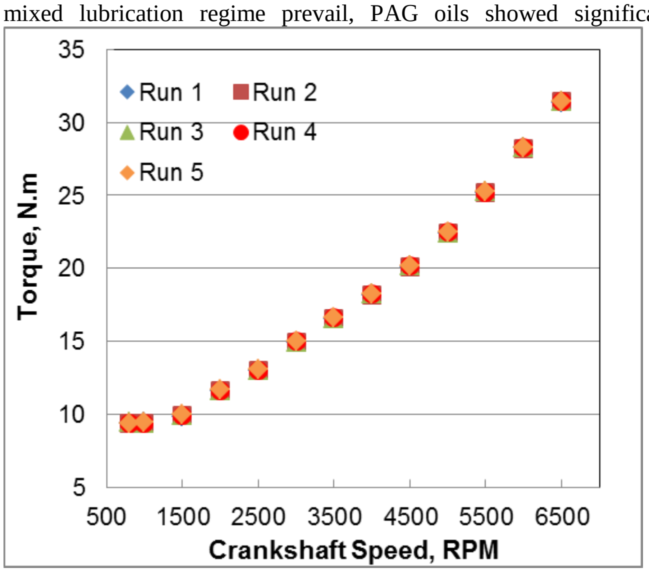

Figure 6. Repeatability of motored engine friction data at 93°C with GF-5 SAE 5W-20 oil.

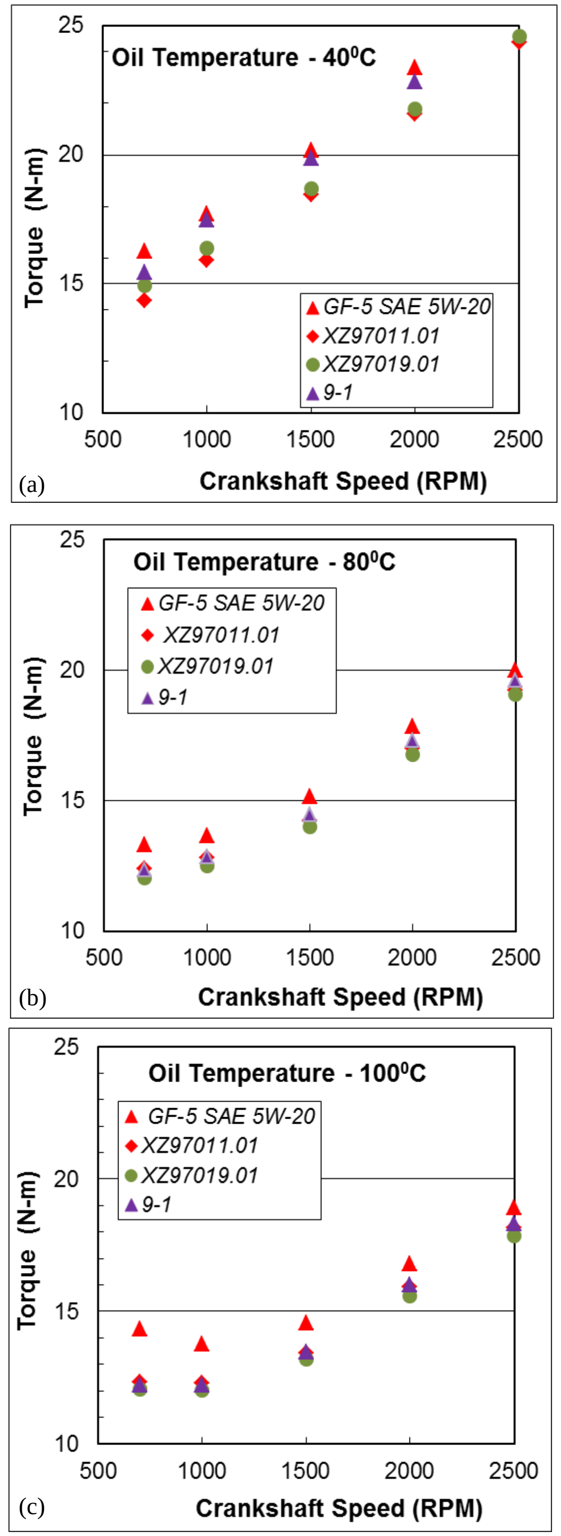

Figure 7. Motored engine friction as a function of speed at (a) 40°C, (b) 80°C, and (c) 100°C

at 100°C. PAG oil 15-1 showed the most friction reduction over the speed range investigated. PAG oil 14-2 with high temperature high shear viscosity of 2.4 mPa·s at 150°C, showed a significant jump in friction at 800 RPM indicating a transition from hydrodynamic to mixed lubrication regime

Sequence VID Tests

Table 4 (pg 10) shows Sequence VID fuel economy data for PAG oil XZ97011.01 and PAG oil XZ97019.01 and Reference Oil 1010 compared to SAE 5W-30 minimum requirements. Both PAG oils showed encouraging results and no drop in fuel efficiency with aging. PAG oil XZ97019.01 showed better fuel economy benefits than PAG oil XZ97011.01 probably because of its lower HTHS. According to SAE J300 viscosity classification, both PAG oils can be considered SAE 12 oils for which no fuel efficiency requirement has yet been established. A further analysis of breakdown of data revealed improvements in FEI 1 and FEI 2 for PAG oil XZ97019.01 and PAG oil XZ97011.01 were on Stage 2 and Stage 5 (both hydrodynamic lubrication regime). The tests were run in order of PAG oil XZ97019.01, followed by Reference Oil 1010, followed by PAG oil XZ97011.01. At the end of test with PAG oil XZ97011.01, the Oberge filters were found clogged. This was thought to be due to the interaction of detergents left over from prior test with Reference Oil 1010 and PAG oil XZ97011.01 resulting in formation of gel-like substance.

Sequence IVA Test

A Sequence IVA test was run with PAG oil 17-1 as this oil showed wear performance similar to GF-5 SAE 5W-20 oil in motored valvetrain tests (not reported here). The average camshaft wear was reported as 1037.36 µm, which was well in excess of the 90 µm maximum allowed in the GF-5 specification. Additional camshaft measurements, Table 5, show that wear was equally severe on both intake and exhaust camshaft lobes.

Table 5. Additional Camshaft Lobe Wear Measurements

Intake Lobe	Maximum, µm	1259
	Average, µm	1047
Exhaust Lobe	Maximum, µm	1155
	Average, µm	1016
Nose	Maximum, µm	214
	Average, µm	179

Lubricant samples were taken every 25 hours over the course of the test and analyzed for metal content. Iron analysis by Inductively Coupled Plasma (ICP) of the samples showed that the iron content of 17-1 was relatively low for the first ~ 50 h of the test, but increased rapidly after the initial 50 h. After 100 h there was approximately twice as much iron found in the fluid as compared to typical passing lubricant, Figure 8. The high levels of iron found in the fluid after 50 h clearly correlate with the wear measured on the camshaft.

ICP analysis for zinc, sulfur, phosphorus and molybdenum gives some indication of the anti-wear and friction modifier additive concentration over the test, Figure 9. The elemental concentrations are normalized by their starting concentrations, converting the measurements to mass fractions (Zn(t)/Zn(t=0)). It is clear that the zinc and molybdenum concentration decreased uniformly and at approximately the same rates over the 100 h test, whereas the phosphorus and sulfur decreased at a much lower rate. Given that the only sources of phosphorus and sulfur in the 17-1 were the anti-wear and friction modifier additives, it is not immediately obvious how the different depletion rates can occur. After 50 h the zinc and molybdenum concentrations were <50% of their initial values, which corresponds with increasing levels of iron found in the fluid. This indicates that the anti-wear additives were depleted or reduced below an effective concentration at ~50 h, leading to increased wear of the camshaft.

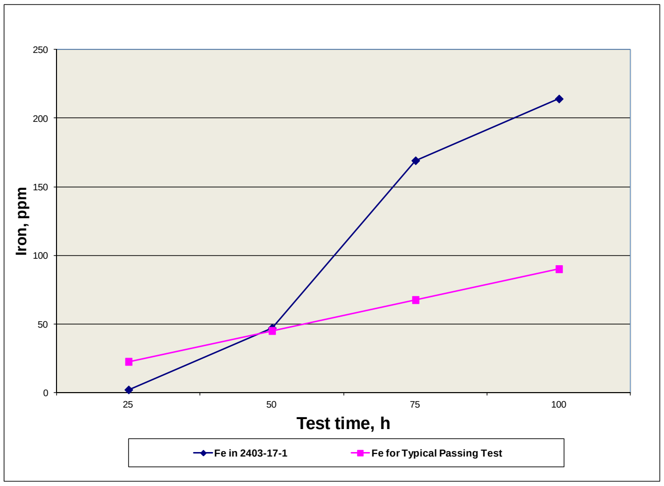

Figure 8: Iron increase over time for 17-1

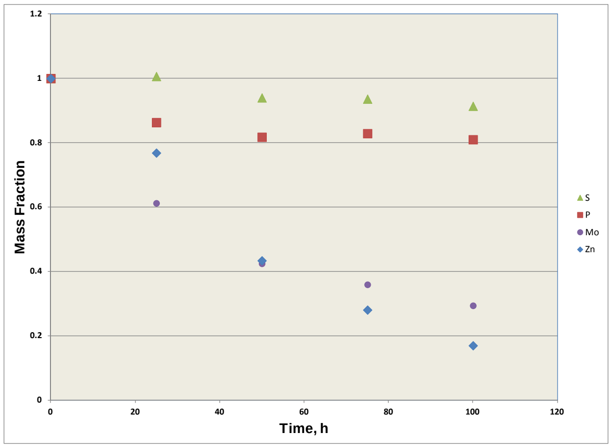

Figure 9: Additive depletion over time for 17-1

Photos taken of a rocker arm with an optical microscope, Figure 10, show areas of high wear. Photo on left shows areas of possible pitting, photo on right highlights an oblong area of increased wear.

Sequence IVA wear results were somewhat surprising because of low wear observed in the vehicle after 16,000 km with PAG oil 15-1, as well as low wear observed in the valve train wear test with vehicle aged PAG oil 15-1. PAG oil 17-1 was the only PAG oil evaluated that contained ZDDP and a molybdenum based friction modifier. ZDDP was added to 17-1 to improve its anti-wear performance in the various bench tests used to screen the PAG oils prior to engine testing (24). 17-1 had wear properties similar to 15-1 and the SAE GF-5 5W-20 base line in the valve train wear tests. It was observed that the 40°C EOT viscosity of 17-1 was 28.4 (mm^2/s), which was approximately 9% lower than the starting viscosity. The EOT fluid contained ~ 7% fuel contributing to the reduction in viscosity. To determine if fuel dilution had an impact on anti-wear properties of the fluid by reducing the lubricating film thickness, 4-ball wear scars were measured on fresh 17-1, EOT 17-1 and fresh 17-1 + 7% fuel. While the 4-ball wear test has not been correlated to Sequence IVA, it was felt that the 4-ball wear scars might give some indication as to whether the excessive wear was due to reduced film thickness caused by fuel dilution or depletion of the anti-wear additives. The wear scars of fresh 17-1 and 17-1 Fresh + 7% fuel dilution (Table 6) were essentially the same while the wear scars for EOT 17-1 were significantly larger, which is further evidence supporting the depletion of the anti-wear additives as a key factor in the excessive camshaft wear observed in this test.

The compositional analysis of the fluids coupled with the results from the 4-ball wear tests indicates aging of oil in this test depletes anti-wear additive suggesting more robust anti-wear additive is required.

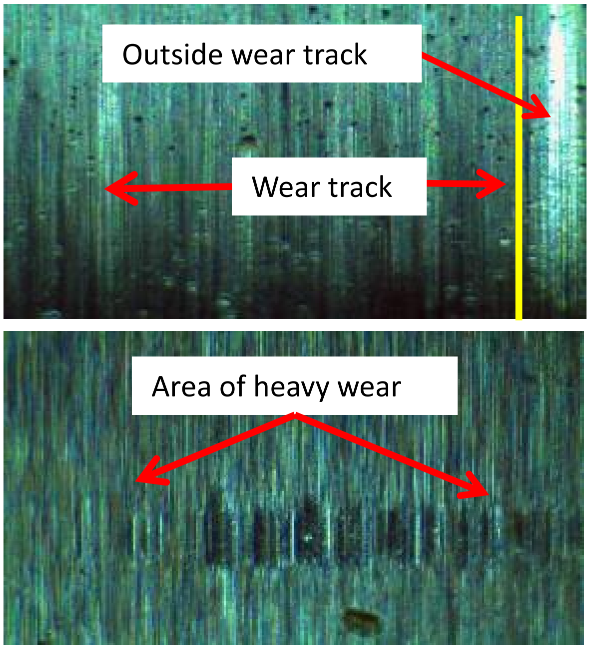

Figure 10: Wear areas from rocker arm

Table 6: 4-ball wear scars of 17-1 40kg load for 1 hour at 1200 RPM and 75°C (ASTM D4172)

Fluid	4-ball wear scar, mm
17-1 Fresh	0.457
17-1 EOT	0.824
17-1 Fresh + 7% fuel dilution	0.340

Sequence VG Test

A Sequence VG test was run with PAG oil 17-1. The results are shown in Table 7. PAG oil 17-1 performed well on sludge but not varnish formation. None of the PAG oils studied contained a conventional overbased detergent. High TBN overbased detergents were insoluble in PAG fluids. A proprietary acid scavenger was used to neutralize acidic materials that formed in the fluid during use (18,19). Bench tests and some engine test data suggested that the non-varnishing properties of PAG oils would be sufficient to ensure engine cleanliness (15,16).

Table 7: Results of Sequence VG Test

Parameters	17-1	GF-5 limits
Average Engine Sludge, Merits	8.76	8.0 min
Rocker Cover Sludge, Merits	9.32	8.3 min
Average Engine Varnish, Merits	8.19	8.9 min
Average Piston Skirt Varnish, Merits	5.17	7.5 min
Oil Screen Sludge, % Area	4.96	15 max
Number of Hot Stuck Rings	0	None

Chassis Roll Dynamometer Test

Chassis roll dynamometer tests were done using PAG oil 15-1 which showed the most friction reduction in motored engine test. The tests were run with GF-5 SAE 5W-20 oil first followed by PAG oil 15-1. Some of the physical properties of aged oils are reported in Table 8. Figure 11a shows fuel economy data for the two oils after 800 km in FTP-75 city cycles. The bars represent 95% confidence interval. There

Table 8: Physical Properties of oils from Chassis roll dynamometer tests

Properties	0 km	800 km	8,000 km	16,100 km
GF-5 SAE 5W-20 Oil				
Viscosity at 40C, mm²/s	50.2	41.3	42.45	40.7
Viscosity at 100C, mm²/s	8.5	7.6	7.6	7.4
Total Acid Number, mg KOH/g	2.31	1.78	2.85	2.95
Total Base Number, mg KOH/g	7.05	7.29	1.85	4.77
Fuel dilution, wt%	0	2.1	1.7	2.5
Water content, wt%	0.05	0.07	0.11	0.29
Fe, ppm	<1	6	11	17
15-1				
Viscosity at 40C, mm²/s	20.3		21.91	22.93
Viscosity at 100C, mm2/s	5.5		5.51	5.73
Total Acid Number, mg KOH/g	0.1		1.04	2.28
Fe, ppm	Non-Detectable			

was some significant test-to-test variability observed. Data was chosen for each oil and drive cycle combination from 3 to 5 consecutive runs with a coefficient of variation (COV) < 0.5% and FTP-Weighted EER values ≤ 1.5% . The average and confidence intervals of runs meeting these criteria were reported.

PAG oil 15-1 showed 1% fuel economy improvement. Since city cycles consist of three phases, fuel economy contribution from each phase was explored to understand which phase played a dominant role. Phase 1 of the city cycles, when the vehicle started from ambient temperature, PAG oil 15-1 showed 2.1% fuel economy benefit over GF-5 SAE 5W-20 oil as shown Figure 11b. This is possibly related to lower viscosity of PAG oil 15-1 compared to GF-5 SAE 5W-20 oil. Other phases in city cycles showed no statistical difference between the two oils. PAG oil 15-1 offered no benefit in highway cycles and the combined (city and highway) cycles over GF-5 SAE 5W-20 oil. No fuel economy benefits could be observed after 8,000 km and 16,100 km. The analysis of PAG oil 15-1 samples at 8,000 and 16,100 km miles indicated that the anti-oxidant package was substantially consumed by 8000 km as evidenced by the TAN exceeding 1 mg KOH/g, Table 10. Depletion of the anti-oxidant package would result in the observed increased oil consumption. Analysis of the used oil specifically for the antioxidants revealed that ~90% were consumed by 8000 km and effectively all were consumed by 16,100 km.

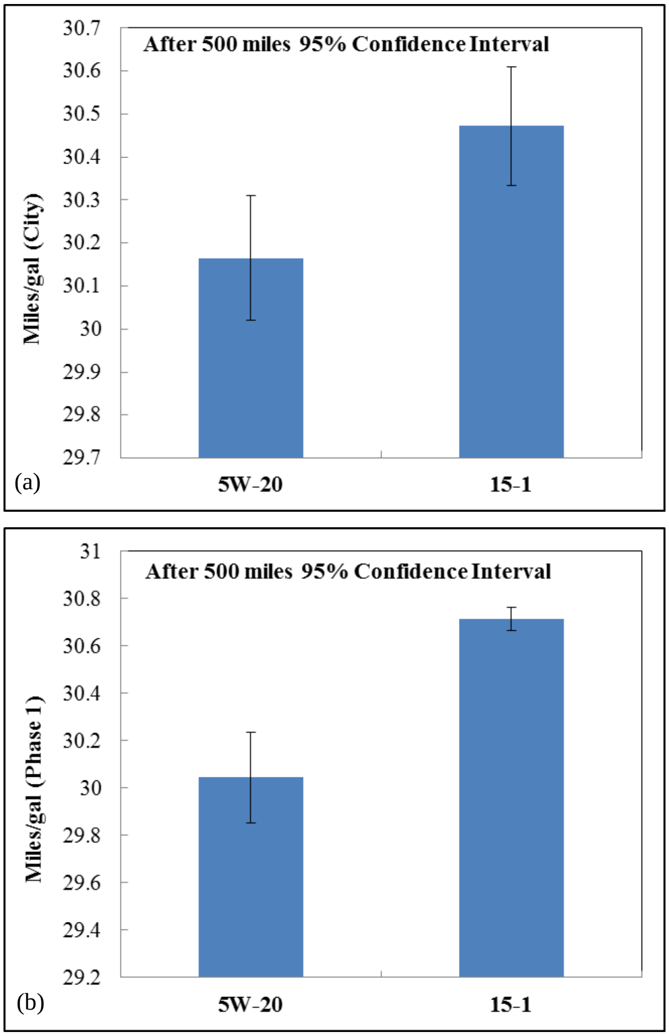

Figure 11: Fuel economy improvement of PAG oil 15-1 over GF-5 SAE 5W-20 oil in (a) FTP-75 city cycles, and (b) Phase 1

Conclusions

In motored single cylinder piston ring friction tests, PAG oils showed nearly fifty percent friction reduction compared to GF-5 SAE 5W-20 oil depending on speed and oil temperatures. The friction reduction appears to be related to PAG base oil chemistry and not due to their lower viscosity.

In motored engine friction tests, PAG oil XZ97019.01 showed about 11% friction reduction over GF-5 SAE 5W-20 oil at 100°C oil temperature.

When PAG oil (15-1) was slightly aged (800 km miles), chassis roll dynamometer tests showed 1% fuel economy benefit over GF-5 SAE 5W-20 oil in EPA city cycles and not in highway cycles. The benefit disappeared with oil aging which is believed to be due to severe deterioration of the oil resulting from rapid consumption of the additive package.

Engine dyno tests showed issues with varnish formation (in ASTM Sequence VG test) and wear (in ASTM Sequence IVA test). The wear issue is related to depletion of anti-wear additive.

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Definitions and Abbreviations

ASTM	American Society for Testing and Materials
EPA	Environmental protection Agency
FTP	Federal test Procedure
HWFET	Highway Fuel Economy test
NEDC	New European Drive Cycles
PAG	Polyalkylene glycol
SAE	Society of Automotive Engineers
SRC	Standard Road Cycle

Table 1. Lubricants considered for investigation

Base Oil Description	Fluid ID	Base fluid or Formulated	HTHS @150 C mPa s[1]	KV 100 C mm^2/s	KV 40 C mm^2/s	VI	Noack[2] wt%
Alcohol 1 initiated copolymer of ethylene oxide and propylene oxide – Capped	XZ97011.00	Base fluid	2.66	5.55	20.26	239	
	XZ97011.01	Formulated	2.83	5.6	22.49	233	10.1
	15-1	Formulated	2.68	5.5	20.34	232	
	14-2	Formulated	2.4	5.06	18.36	229	
	27-2	Formulated	2.8	5.71	21.49		
Alcohol 1 initiated homopolymer of propylene oxide - Capped	XZ97019.00	Base fluid	2.3	5.21	19.4	223	
	XZ97019.01	Formulated	2.37	5.1	20.01	202	7.4
	24-1	Base fluid	2.63	5.99	23.3	223	
	15-4	Formulated	2.66	6.06	25.08	204	
Alcohol 2 initiated homopolymer of propylene oxide - Capped	XZ97038.01	Formulated	2.28	5.19	19.8	214	
	24-2	Base fluid	2.61	6.02	23.4	224	
	5-2	Formulated	2.6	6.06	24.87	207	
Alcohol 1 initiated homopolymer of propylene oxide - monol	22-2	Base fluid	3.57	8.54	42.15	186	
	14-1	Formulated	3.58	8.79	46.57	171	3.9
	9-1	Formulated	2.56	5.95	29.14	155	
	22-1	Formulated	3.58	8.79	46.57	171	
	17-1	Formulated	2.6	6.27	31.29	156	
Alcohol 2 initiated copolymer of propylene oxide and butylene oxide - monol	8-1	Formulated	2.6	6.62	35.55	144	
Group II mineral oil	Commercial GF-5 5W-20	Formulated	2.6	8.6	48	164	
	Commercial GF-5 5W-20 base oil	Base oil					

[1] ASTM D4683 Standard Test Method for Measuring Viscosity of New and Used Engine Oils at High Shear Rate and High Temperature by Tapered Bearing Simulator Viscometer at 150 °C

[2]ASTM D5800 Standard Test Method for Evaporation Loss of Lubricating Oils by the Noack Method

Table 2. ASTM Sequence VID test conditions

Stage	Speed (RPM)	Torque, N.m	Oil Temp, C	Coolant Temp, C	Lubrication Regime	Stage Weighting, %
1	2000	105	115	109	Mixed	30
2	2000	105	65	65	Hydrodynamic	3.2
3	1500	105	115	109	Mixed	31
4	695	20	115	109	Boundary	17.4
5	695	20	35	35	Hydrodynamic	1.1
6	695	40	115	109	Boundary	17.2

Table 3. Percent friction reduction of PAG oils over GF-5 SAE 5W-20 oil

Speed, RPM	17-1	15-4	15-1	8-1	14-2	XZ97011.01	XZ97019.01	8-1
700						8.9	10.9	9.7
800	5.7	7.1	8.3	0.5	-15.9			
1000	4.5	6.4	7.6	0.6	5.4	7.5	9.6	8.2
1500	2.7	5.1	6.9	0.7	5.3	5.0	6.8	4.7
2000	1.8	4.5	5.7	0.7	4.6	3.4	5.3	2.9
2500	1.3	3.8	5.5	0.9	4.5	2.7	4.4	1.7
3000	0.9	3.3	4.4	0	3.6	1.2	3.0	0.3
3500	0.8	2.7	3.6	0.1	2.9	1	3.0	0.6
4000	0.7	2.3	3	0.3	2.6	0.1	2.2	-0.1
4500	0.6	1.8	2.5	-0.2	1.9	-1	1.8	-0.9
5000	0.4	1.3	2	-0.5	1.3	-2	1.9	-1.1

Table 4. Sequence VID fuel economy results

Oils	Vis. at 100C, mm^2/s	HTHS at 150C, mPa.s	FEI SUM	FEI 2
XZ97019.01	5.3	2.4	3.2 %	1.8%
XZ97011.01	5.9	2.85	2.5%	1.4%
Ref Oil 1010		2.6	2.7%	1.2%
			GF-5 Limits	
xW-20	6.9 - <9.3	2.6	2.6%	1.2%
xW-30	9.3 - <12.5	2.9	1.9%	0.9%