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Optimizing Engine Oils for Fuel Economy with Advanced Test Methods

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ABSTRACT

Increasingly stringent fuel economy and emissions regulations around the world have forced the further optimization of nearly all vehicle systems. Many technologies exist to improve fuel economy; however, only a smaller sub-set are commercially feasible due to the cost of implementation. One system that can provide a small but significant improvement in fuel economy is the lubrication system of an internal combustion engine. Benefits in fuel economy may be realized by the reduction of engine oil viscosity and the addition of friction modifying additives. In both cases, advanced engine oils allow for a reduction of engine friction. Because of differences in engine design and architecture, some engines respond more to changes in oil viscosity or friction modification than others. For example, an engine that is designed for an SAE 0W-16 oil may experience an increase in fuel economy if an SAE 0W-8 is used. However, if this same SAE 0W-8 oil is evaluated in an engine designed for SAE 5W-30, friction may increase and fuel economy could actually worsen. This hypothetical example illustrates the need for optimization of engine oils to specific hardware. In this paper, a motor-driven engine test is developed to investigate the effects of specific engine component friction on total engine friction. This data is then combined with the work from two previous papers to select an engine oil that optimizes fuel economy in a specific engine. Fired engine and vehicle test results are then presented that demonstrate the fuel economy improvement from the optimized engine oil.

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INTRODUCTION

Many technologies have been developed and demonstrated that increase a vehicle's fuel economy. These technologies run the spectrum from relatively minor improvements in combustion efficiency (1, 2, 3) to more invasive designs to achieve variable compression ratios (4, 5, 6), and waste heat recovery (7, 8, 9), all the way to partial or complete electrification (10). While these technologies result in measurable fuel economy improvements, generally speaking, those that offer the largest benefit are often the most costly to implement (11). One technology that offers a small but significant benefit, and can usually be implemented easily and inexpensively, is the use of advanced engine oils. Additionally, since these advanced engine oils improve fuel economy via friction reduction, all the savings are directly applied as increased crankshaft power. This stands in contrast to other improvements, which may improve fuel economy performance, but may have a debit in another area.

The improvements in fuel economy that result from the use of low friction engine oils are well known within the industry, and can be obtained both by reduction in oil viscosity (12, 13, 14, 15, 16) and through the addition of specialty chemicals like friction modifiers (FMs) (17, 18, 19, 20, 21). It is important to note, however, that an internal combustion engine is a complex system of components, many of which experience different conditions and respond to different lubricant optimizations. For example, some high-pressure contacts found in an engine's valvetrain may operate in or near the boundary lubrication regime. In this lubrication regime, FMs typically offer a reduction in friction while a reduction in lubricant viscosity does not. Conversely, journal bearing friction is observed to be insensitive to FMs, but can be reduced via reduction of engine oil viscosity.

The purpose of this work is to develop a test using an electric motor driven engine that will be used to investigate the impact in friction of specific engine components, and friction of the complete engine. This tool is then used to evaluate engine oils that vary both in viscosity and additive chemistry. The data from this new test is combined with findings from previous works and an engine oil is produced that maximizes fuel economy. This optimized oil is then evaluated in a chassis dynamometer test and an engine dynamometer test that confirm and quantify the fuel economy benefits.

LITERATURE REVIEW

In (22), the authors developed improvements to vehicle chassis dynamometer testing and demonstrated a high level of precision and statistical significance between fuel economy based on engine oil viscosity and additive chemistry. This work was done using a 2012 model year, Chevrolet Malibu® vehicle and the Federal Test Procedure - 75 (FTP-75) and Highway Fuel Economy Test (HwFET) driving schedules. The paper concluded that over the selected driving schedules and with this specific vehicle, the presence of a proprietary friction modifier was just as effective at fuel economy improvement as viscosity reduction. Interestingly, while both oils improved fuel economy above a baseline to the same level (within statistical repeatability), the benefits in fuel economy resulted from improvements in different test stages. The lowest viscosity oil (SAE 0W-16), which contained no FM, was observed to improve fuel economy most during the first stage of the FTP-75 test. This is consistent with lubrication theory that suggests the lowest viscosity oil will create the least friction under cold-start conditions. The higher viscosity (SAE 5W-30) oil, which also contained an FM, was observed to offer the best improvement in fuel economy during the last testing stage, the HwFET. By this stage, engine oil was approximately 105 °C. The high oil temperature, together with the higher engine loads experienced during the HwFET stage, created an environment where the SAE 5W-30 with FM provided greater friction reduction than the SAE 0W-16 and resulted in the highest fuel economy. The paper concludes that test conditions are critical when determining overall fuel economy.

In a second paper (23), the same set of oils are evaluated in the proposed ASTM Sequence VIE test, which uses the same engine as was used in the earlier paper (22). The results from the chassis dynamometer test are then compared to those from the engine dynamometer (ASTM Sequence VIE). While some differences in results exist between methods, trends between the datasets are common. Again in this test method, test stages that are in or near the boundary lubrication regime favor oils that contain FM. Conversely, oils that represent a reduction in viscosity provide the biggest benefit in the test stages, which are macroscopically closer to the hydrodynamic lubrication regime. In both cases, a detailed study of exactly which oil is most or least beneficial in specific engine components/tribocouples is impossible because only macroscopic engine/vehicle conditions were controlled and monitored.

The current work details the development of a non-fired, motor-driven engine test rig that is used to evaluate the exact same set of five test oils. Further, this new test tool uses the same make and model engine as was used in the previous two papers (22, 23). Using this new test, the impact from specific hardware components/tribocouples can be quantified. This data is then used to select an optimized engine oil for fuel economy. This new oil is then evaluated in both chassis dynamometer and engine dynamometer tests to demonstrate the maximum fuel economy performance.

TEST OILS

Test oils were carefully designed to represent relevant formulations and decouple the two variables being studied, oil viscosity and additive chemistry. Indeed, each oil uses the same Group III oil base stocks, viscosity modifier (VM) type, and base additive package. To achieve desired viscometrics, different viscosity base stocks and VM treat rates were used. To minimize variability, all base stock cuts came from the same oil slate. Additionally, while the VM treat rate was altered for each viscosity grade, the VM type was fixed. Similarly, the exact same additive package was used for each oil, with the exception of the friction modification (FM) chemistry used to evaluate FM as a variable.

This careful approach to test oil formulation was done to minimize any potential confounding. The additive package used for all oils was based on an ILSAC GF-5 licensed product. More information about the test oils can be seen in Table 1.

Table 1. Test oils

Test Oil	Description	SAE Grade	ASTM D4683 HTHS Viscosity (cP)	FM
1	ILSAC GF-5 Baseline	5W-30	3.1	Standard
2	High Viscosity	10W-40	3.7	None
3	Mid Viscosity	5W-30	3.1	None
4	Low Viscosity	0W-16	2.3	None
5	Mid Viscosity + High FM	5W-30	3.1	High

The two variables studied are oil viscosity and additive chemistry, specifically the FM. In this manner, differences in fuel economy can be isolated as a function of viscosity or friction modification, or considered together. A graphic representing each test oil can be seen in Figure 1.

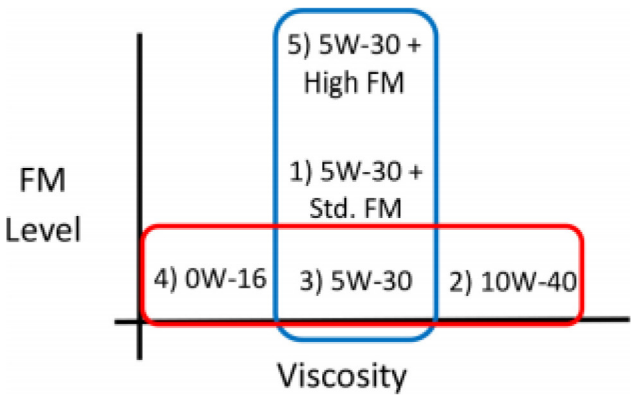

Figure 1. Test Oil Graphic

MOTORING FRICTION TEST METHOD

The oils were evaluated on a motoring friction test stand developed to isolate the individual component contributions to total engine friction. The test engine was the same 2012 Chevrolet Malibu® engine used in parts I and II of this study (22 and 23). As the difference in friction between test oils was expected to be small, great care was taken to maintain consistent test conditions between oils. The boundary conditions of the engine were carefully controlled with the addition of heating and cooling elements in the oil and coolant circuits. Both fluid loops were controlled to 90 °C ±1°C in order to balance the cold and hot portions of the HWFET. In addition, the ambient air temperature was maintained at a consistent temperature via dedicated test cell HVAC system. The inlet air to the engine was controlled to SAE standard conditions.

The friction of the engine was measured at the various speeds seen in Table 2. Test points were taken ramping up through the speed range and then again with decreasing engine speed. In order to calculate actual engine friction, the in-cylinder work was subtracted from the motoring torque as shown in Figure 2. Motoring torque was measured using an inline torque transducer with a calibrated full range of 100 Nm. In-cylinder work was measured using Kistler 6125 piezoelectric pressure transducers with a sensitivity of ~-36 pC/bar. Transducers were calibrated to a full range of 50 bar. Data points were averaged over a 120 second period at a frequency of 10 Hz for the slow speed data. The in-cylinder work was averaged over 500 continuous engine cycles. For each configuration, the resolution of the FMEP measurement was +/- 1 kPa.

Table 2. Tested engine speeds.

Stage	Speed (rpm)	Stage	Speed (rpm)
1	750	7	2250
2	1000	8	2500
3	1250	9	2750
4	1500	10	3000
5	1750	11	4000
6	2000	12	5000

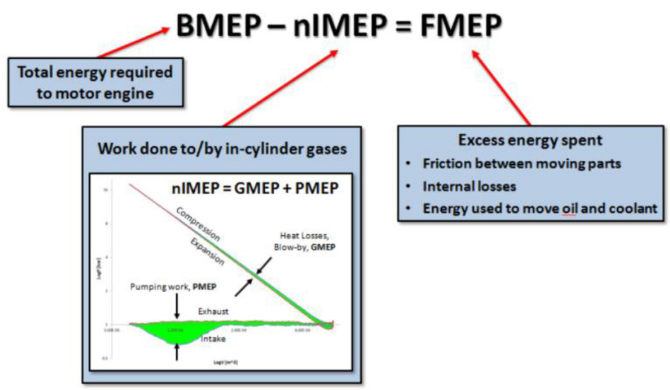

Figure 2. Friction measurement method

To determine component friction, the engine friction was measured with the specific component removed or deactivated and then subtracted from the engine friction with the component active, Figure 3 and Figure 4. This process was repeated for each component of interest. Differences in component friction were significant at +/- 2 kPa. The full teardown process is shown in Figure 5. For configurations 1-3, the complete engine is used, but with different manifold conditions to observe the impact on ring friction. The complete engine configuration is a useful data point, but is not included in any component friction calculations. This engine experienced significant vibration issues in configuration 6 due to the pistons being removed and therefore the rest of the test sequence was not completed. The piston friction data is supplemented by Ring-On-Bore Tribometer testing

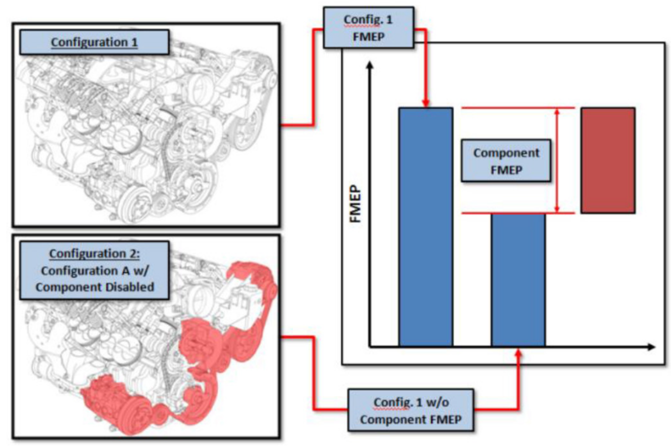

Figure 3. Determining component level friction

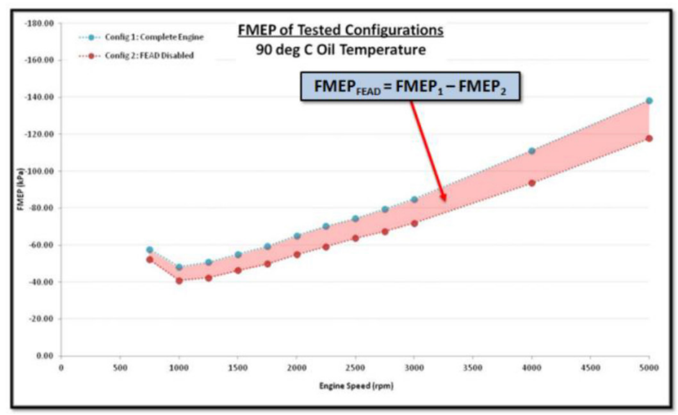

Figure 4. Component friction determination across engine speed

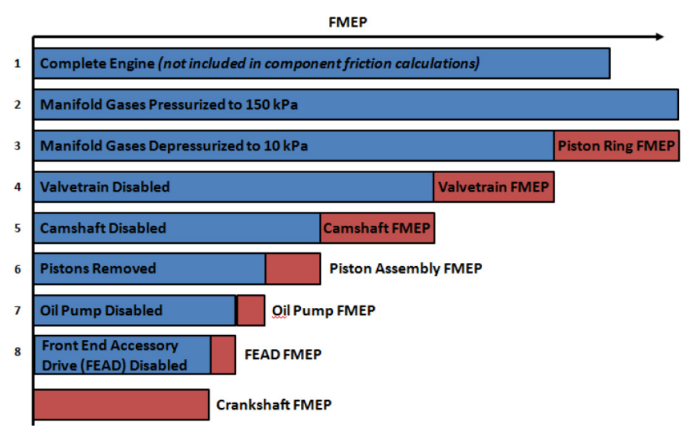

Figure 5. Friction teardown method (*Not to scale)

Typical friction modifiers are designed to reduce tribocouple friction that occurs primarily in the boundary lubrication regime. This is the lubrication regime that exists between the top piston ring and cylinder bore at and near Top Dead Center (TDC), and is illustrated in Figure 6. In order to simulate the higher in-cylinder pressure near TDC, the intake manifold is pressurized to 150 kPa. The exhaust system is also pressurized to the same level using a back pressure valve to minimize the air flow rate during the valve overlap period. The resulting in-cylinder pressure is similar to a fired engine at medium loads, Figure 7, although the phasing is closer to TDC than the actual location of peak pressure of a fired engine. The total piston assembly friction is normally calculated by removing the pistons in step 6. Unfortuntately, the V configuration of this engine resulted in significant imbalance issues. Because this tribocouple represents an important contribution to total engine friction, a second bench test was used to evaluate friction under these conditions. Data from this bench test was used to supplement the data generated in the motored friction rig.

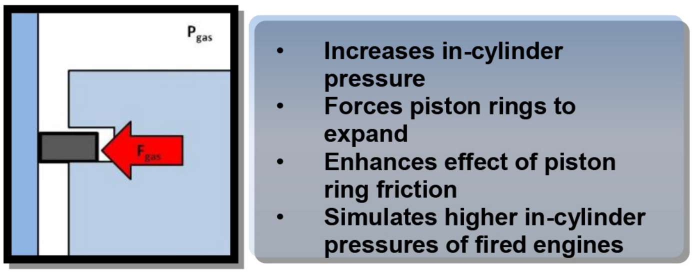

Figure 6. Effect of increased in-cylinder pressure on ring friction

RING-ON-BORE TRIBOMETER TEST METHOD

To supplement the motored friction testing data and provide an estimate of power cylinder friction at TDC, a specialty tribometer was used. The tribometer was a Phoenix Tribology TE-77 reciprocating rig that was modified to accept sections of the top piston ring and cylinder bore from the 3.6 L engine, the same engine used in the motored friction test and previous testing (22 and 23). To further replicate the actual power-cylinder tribocouple, loading was applied to mimic the pressure that would be experienced in this contact near TDC during the power stroke of the fired engine. The overall test conditions were designed to operate the tribocouple in the boundary lubrication regime, but at much lower contact stresses than typical ball-on-flat testing might induce. A load of 100N was applied to a 12-mm piston ring segment and reciprocated at 10 Hz over a stroke of 10.8 mm. Temperature was maintained at 115 °C, and the lubrication condition was fully flooded.

The test was structured similarly to the proposed Sequence VIE engine test, where a reference oil is run both before and after each candidate oil. To initially reference the tribocouple coefficient of friction, the ring and bore was run with a high friction reference oil formulation for 30 minutes and the oil was then drained. The candidate oil was then injected and run for 30 minutes. A flushing oil was injected after draining the candidate and a further 30 minutes reciprocating occurred. Finally the reference oil was run again. Using this referencing structure ensures all candidates are compared equally. Candidate oil performance is presented as percent coefficient of friction (CoF) reduction.

This novel bench test structure deviates from convention by utilizing the same specimens throughout the entire lubricant test matrix. A conventional approach would present new specimens to each candidate oil. Similar to engine testing, this benchtop experiment relies on the fact that negligible tribocouple wear occurs during the experiments due to the careful replication of engine test conditions. In this way, many attempts were made to ensure similarity between the bench test and larger-scale engine tests.

RESULTS

Results will be displayed in several ways. First, the difference in Friction Mean Effective Pressure (FMEP) will be shown for the complete engine, followed by specific components. For clarity, the data will be shown in sets of three oils, comparing the impact of viscosity grade or FM treat rate separately.

Figure 8 shows a clear improvement in friction reduction when moving from high to low viscosity engine oils, which is not wholly unexpected. Interestingly, at low speeds (~1,000 rpm) the SAE 5W-30 oil is observed to offer the lowest friction. Under these conditions, the SAE 0W-16 may simply provide an insufficient oil film thickness and result in a transition into the boundary lubrication regime, while the thicker oil film of the higher viscosity SAE 5W-30 prevents this transition.

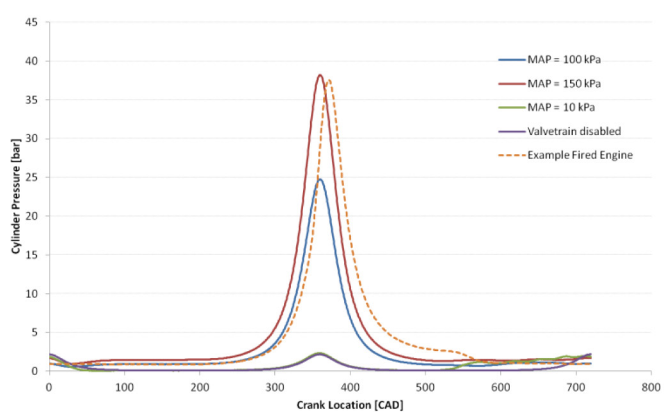

Figure 7. In-cylinder pressure resulting from pressurized intake manifold compared to fired engine pressure trace

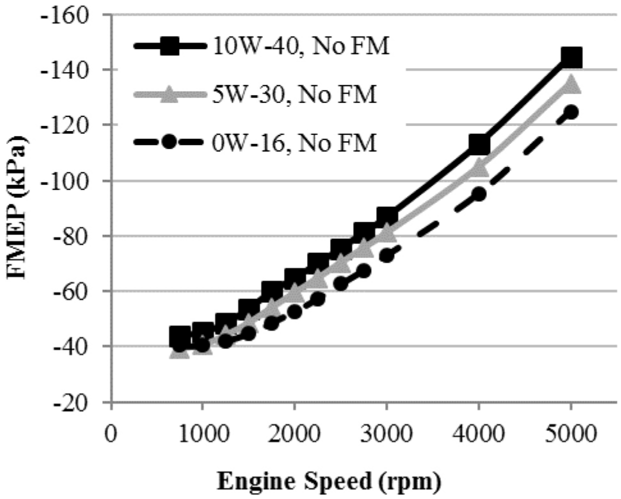

Figure 8. FMEP Complete engine, by oil viscosity grade

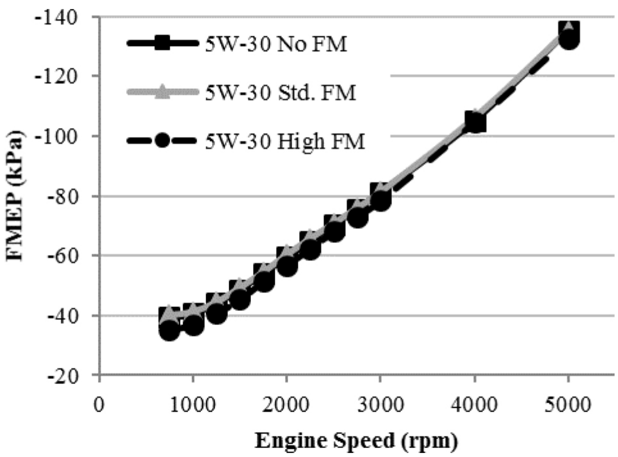

Figure 9. Complete engine friction, by FM treat rate

Figure 9 shows the FMEP vs. engine speed of all SAE 5W-30 oils, to determine the difference in FM treat rate. In this case, the difference between the oil without FM and the oil with the mid-FM level is statistically insignificant. However, the difference between either and the high FM containing oil is statistically significant. To better visualize the difference between the high FM oil and oil without FM, the percentage difference was calculated and is plotted in Figure 10. Due to the small absolute difference in FMEP at higher engine speeds, the percentage difference is less than at lower engine speeds.

In this form, the data clearly suggests a reduction in FMEP with the addition of FM into the engine oil. Furthermore, results are also well-aligned with lubrication theory in that the FM seems to be most effective at low speeds, which correlates to the boundary lubrication regime. The transition into the boundary lubrication regime, which is more apparent at lower engine speeds, is evident in Figure 11 and Figure 12. These plots show the pressurized manifold step, which increases the in-cylinder pressure, further enhancing the effect of the FM.

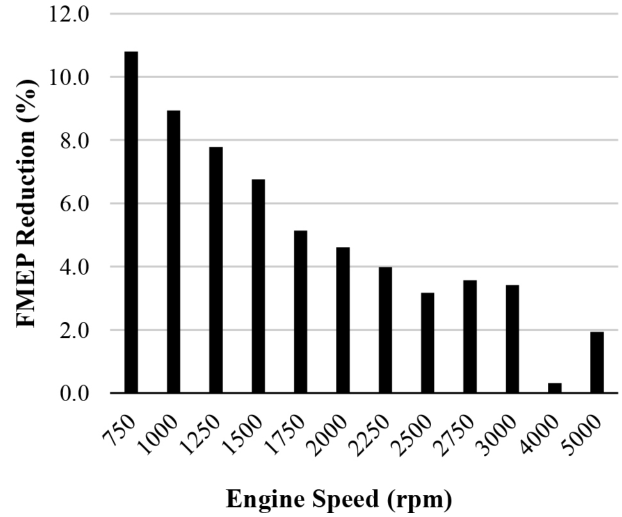

Figure 10. Complete engine FMEP reduction, No FM compared to High FM oils

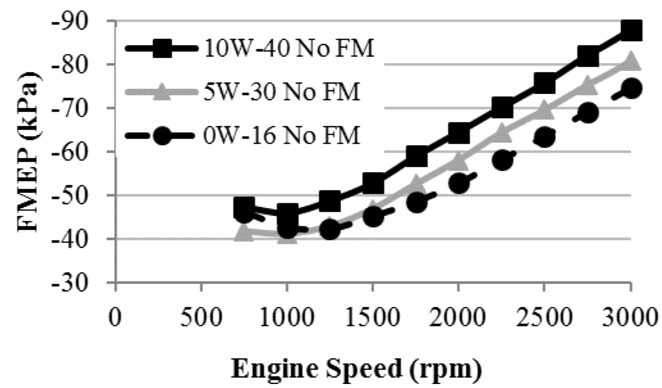

Figure 11. Engine FMEP with 150 kPa manifold pressure, by oil viscosity grade

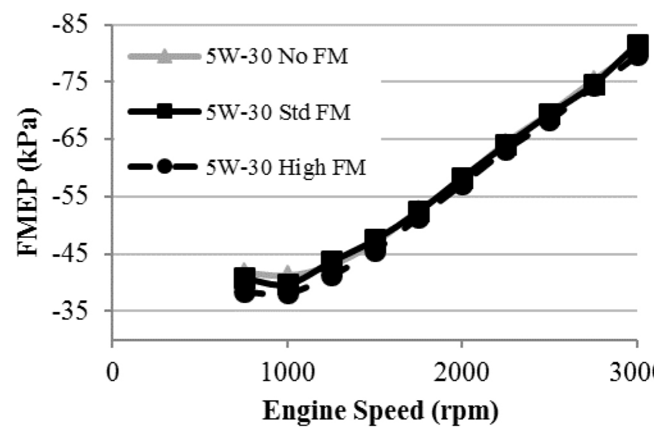

Figure 12. Engine FMEP with 150 kPa manifold pressure, by FM treat rate

When comparing viscosity grades, the SAE 0W-16 oil has the lowest friction at moderate engine speeds, but quickly increases to 10W-40 levels at speeds below 1000 rpm. The effect of FM is evident in Figure 12, with the FMEP decreasing with increasing FM treat rates. To better visualize the difference between the high FM oil and oil without FM, the percentage difference was calculated and is plotted in Figure 13. When viewed at the piston ring pack component level, Figure 14, the effect of the FM treat rate is also observed, particularly at low speeds. Figure 14 is calculated from Configuration 2 - Configuration 4 as ring flutter was observed in Configuration 3. Historically, the measured friction from the valvetrain has been insignificant with roller follower design. While there is work used to compress the spring, it is recovered on the backside of the valve when the spring expands, leaving only the small amount of friction between the valve and guide.

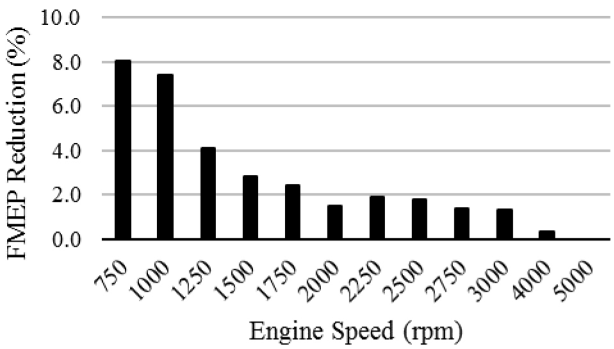

Figure 13. Engine FMEP Reduction with 150 kPa manifold pressure, No FM compared to High FM oils

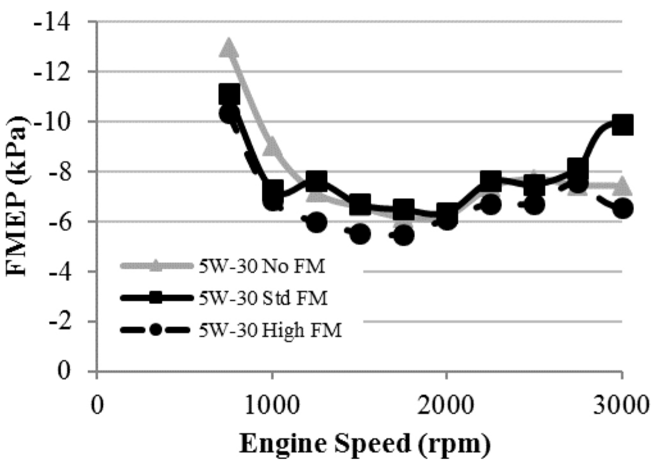

Figure 14. Component friction - piston rings, by FM treat rate

The total piston friction would normally be determined by adding the calculated piston ring friction (difference between pressurized and depressurized steps) to the sliding piston friction (removal of pistons). However, a significant engine imbalance issue was encountered, rendering data collection in this configuration impossible. Therefore, a tribometer was used to approximate the friction in the power cylinder. This tribometer was specifically designed to mimic the conditions experienced between the top piston compression ring and the bore near TDC. This region is important as it represents the boundary lubrication regime. The results of the tribometer test are shown in Figure 15.

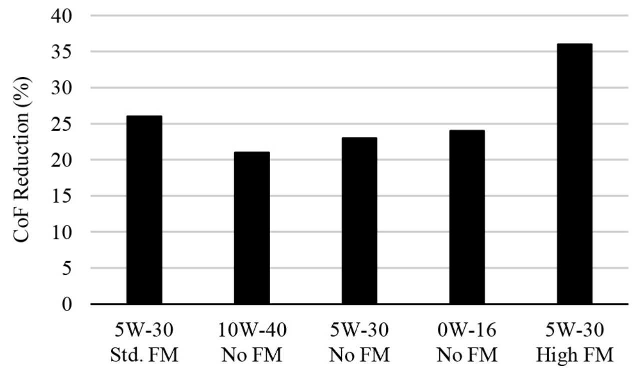

Figure 15. Ring-on-Bore CoF Reduction

In this plot, the highest reduction in coefficient of friction is realized in the SAE 5W-30 oil containing the high treat rate of FM. Next best is the ILSAC GF-5 baseline oil, which contains a standard treat rate of FM. Finally, the three oils that contain no FM all rank last. This indicates that FMs can be very effective at reducing friction between the piston ring and cylinder at or near TDC.

OPTIMIZING THE ENGINE OIL

Based on the findings of the current work and those of the previous work (22 and 23), it was speculated that the optimal engine oil for this vehicle would represent a balance in viscosity between the SAE 5W-30 and SAE 0W-16, and a precisely balanced additive system with moderate to high levels of FM. To evaluate this concept, a new oil was selected and evaluated in the newly developed motored engine friction test, the proposed ASTM Sequence VIE engine dynamometer test, and the chassis dynamometer test, using the 2012 Chevrolet Malibu®. To ensure a relevant comparisons and link with previous work, all tests used the same make and model engine and/or hardware. The optimized oil was blended to an SAE viscosity grade of 0W-20, and contained a moderate level of a proprietary organic FM. Several other changes to the formulation were also made which were based on findings beyond the scope of this experiment. As a result, the optimized SAE 0W-20 represents a commercially feasible, fully-formulated engine oil.

Since the SAE 0W-16 and the SAE 5W-30 + High FM had the highest fuel economy performance in most of the evaluations, they will be used to judge the relative performance of the new SAE 0W-20. Additionally, the GF-5 Baseline (SAE 5W-30 with standard FM) will also be shown for comparison. Combined FE is the result of a weighted average being applied to the three phases of the FTP-75 driving schedule and the single stage of the HwFET driving schedule (phase 4) as shown in Figure 16 and Figure 17.

The chassis dynamometer results are shown in Figure 18 as Combined FE. In this plot, error bars represent 2 standard deviations above and below the means. Although error bars overlap slightly between the ILSAC GF-5 Baseline and the SAE 5W-30 + high FM, a statistical analysis concluded that all oils, with the exception of the 0W-16 and the 5W-30 + High FM are significantly different, on a 95% confidence interval. This analysis was based on data from six tests with the ILSAC GF-5 Baseline and three with all other oils.

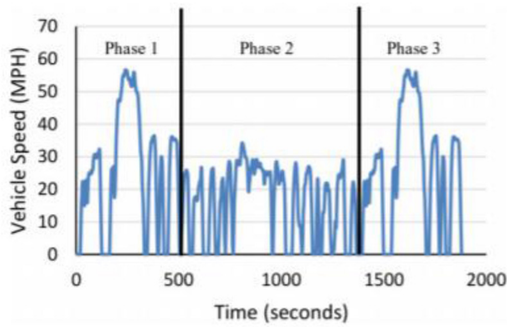

Figure 16. FTP-75 Driving Schedule

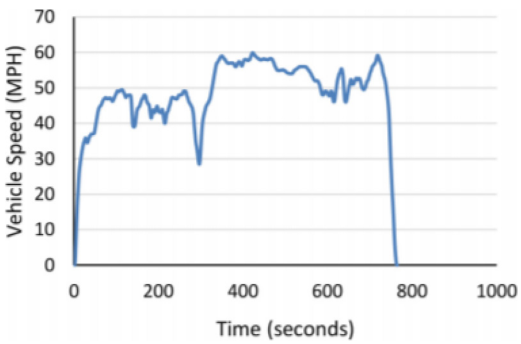

Figure 17. HwFET Driving Schedule

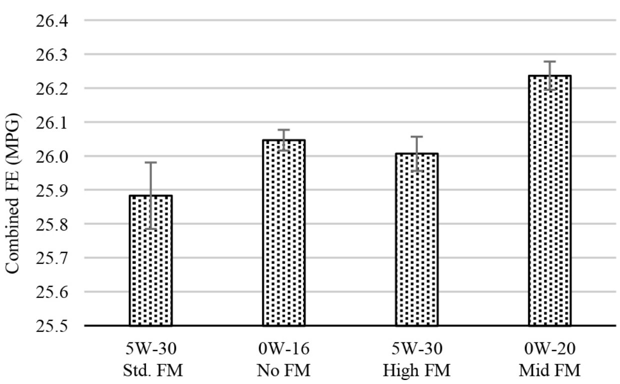

Figure 18. Chassis dynamometer Combined Fuel Economy

Fuel economy can also be viewed as fuel economy improvement (FEI), as a percentage, with respect to the ILSAC GF-5 baseline, and be displayed per phase. Figure 19 shows this data.

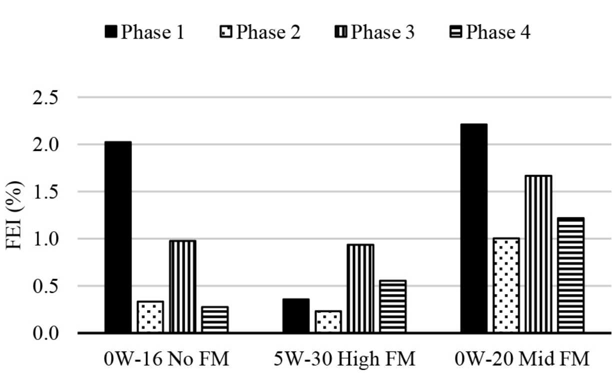

Figure 19. FEI by chassis dynamometer test phase

Displayed in this way, it is easy to see that the new 0W-20 performs the best over all phases of the FTP-75 and HwFET driving schedules. In the first phase, engine and oil temperatures are low and fuel economy improvement is largely a result of viscosity reduction. Conversely, in the fourth and final phase (this is the HwFET driving schedule) improvements in fuel economy are largely the result of friction modification and viscosity reduction. The new SAE 0W-20 therefore combines the best attributes of the low viscosity (SAE 0W-16) and the high FM treat rate of the SAE 5W-30.

The 0W-20 was also evaluated in the proposed Sequence VIE test, with the results shown in Figure 20.

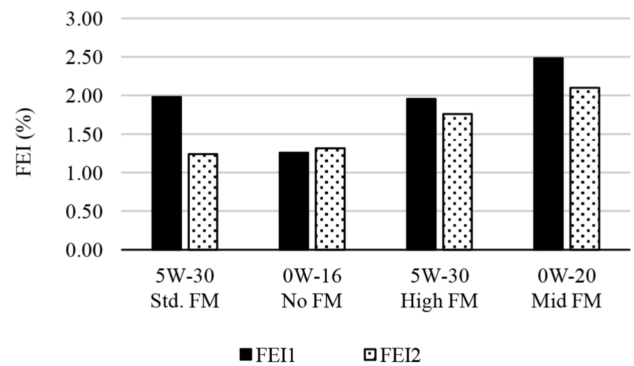

Figure 20. Sequence VIE FEI1 and FEI2

Fuel Economy Improvement (FEI) indicates the improvement in fuel economy relative to an industry-standard baseline. FEI1 represents the fresh oil fuel economy benefit, while FEI2 represents the fuel economy benefit after 6,500 miles of simulated aging. In both cases, the performance of each oil is compared to an industry-standard baseline. This reference oil is an SAE 20W-30 and is part of the Sequence VIE test protocol; it is not one of the oils prepared for the work in this paper and should not be confused with the ILSAC GF-5 Baseline oil. In the proposed VIE testing, the new SAE 0W-20 shows the best fuel economy performance, both in fresh (FEI1) and aged (FEI2) oils. Furthermore, the fuel economy improvement seems to be very durable, meaning there is not much degradation between fresh and aged oil fuel economy.

The proposed Sequence VIE engine dynamometer fuel economy test consists of six testing stages. Similarly to the chassis dynamometer testing, the Sequence VIE data can also be viewed by stage, Figure 21.

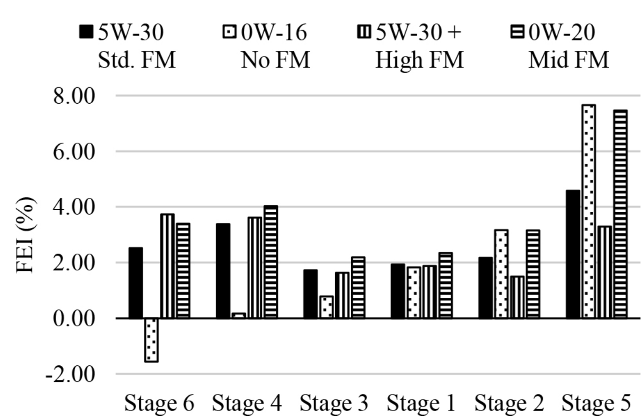

Figure 21. Sequence VIE FEI1 per test stage

In Figure 21, test stages have been arranged in an order which most closely represents the macroscopic lubrication regime. For example, the high temperatures, high loads and low engine speeds in stage 6 are most representative of the boundary lubrication regime. Stage 5 is characterized by high engine speeds, low loads and temperatures and is more representative of the hydrodynamic lubrication regime. The remaining stages fall in between, with the most boundary on the left and the most hydrodynamic on the right.

With the data arranged in this manner, it is easy to see the relative contributions of each lubricant to total fuel economy improvement. Again, we observe that the new SAE 0W-20 combines the best attributes of both low viscosity and friction modified oils. Fuel economy is maximized on both ends of the boundary/hydrodynamic lubrication spectrum.

SUMMARY/CONCLUSIONS

In this paper, the authors combine the results from two previous works that investigate the impact of engine oil viscosity and additive chemistry on fuel economy. The authors then expand this dataset with the evaluation of the exact same test oils in a newly developed FTT test. The results from the FTT test and specialty tribometer help explain some of the observations made in the first two papers (22, 23). With the combination of data from the vehicle dynamometer (FTP-75 and HwFET) testing, engine dynamometer (Sequence VIE) testing, FTT and specialty tribometer testing, a more holistic picture of fuel economy is formed, and a deeper understanding into fuel economy is obtained. Using this deeper understanding, a new engine oil is selected, which optimizes fuel economy improvement from both viscosity reduction and additive chemistry.

This new oil is then evaluated in the chassis dynamometer (FTP-75 and HwFET) test and the engine dynamometer (ASTM Sequence VIE) fuel economy test. The result is, by far, the best fuel economy performance of the oils tested. The standardized FTP-75 and HwFET chassis dynamometer test yields Combined FE. The ASTM Sequence VIE tests gives fuel economy improvement (FEI) data with respect to an industry standard baseline. In many cases, researchers and lubricant formulators may only pay attention to the final, reported results. However, analysis beyond these final, reported results should be conducted as the data yields important information about each lubricant's behavior in various lubrication regimes. This is an important distinction since the original oils either performed well in boundary lubrication or hydrodynamic lubrication, but not both. The final oil optimizes both viscosity and additive chemistry for excellent performance in every tested condition. Key findings are as follows:

- Even with the same hardware (GM 3.6 L engine) differences in test scale (vehicle vs. fired engine, vs. motored engine), can produce different results in terms of fuel economy.
- A discrepancy in results does not necessarily indicate that one test is 'wrong' or another is 'right', but that they may be evaluating slightly different phenomena.
- High precision FTT testing can be used to understand some of the differences observed between fired test procedures.
- Evaluating engine oils in different scale tests can allow the formulator to develop optimized engine oils that maximize fuel economy more universally than if only one test was used.

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DEFINITIONS/ABBREVIATIONS

CAFE - Corporate average fuel economy

FE - Fuel economy

FEI - Fuel economy improvement

FM - Friction modifier

FTP - Federal Test Procedure - FTP consists of two cycles (FTP-75 & HwFET)

FTP-75 - Chassis dynamometer test procedure consisting of three testing phases

HTHS - High Temperature High Shear

HwFET - Highway Fuel Economy Test

ILSAC - International Lubricants Standardization and Approval Committee

mpg - Miles per gallon (US Customary gallon)

mph - Miles per hour

NHTSA - National Highway Traffic Safety Administration

VM - Viscosity modifier