2018 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
POWER & MOBILITY (P&M) TECHNICAL SESSION
AUGUST 7-9, 2018 - NOVI, MICHIGAN

Development of a Laboratory Based Test Methodology to Identify Axle Lubricants with Limited Slip Capability

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ABSTRACT

Modern vehicles use various methods to improve traction. One way to control torque to the drive wheels and improve traction is the limited slip differential (LSD). These differentials prevent loss of traction in the event that a driving wheel loses grip. A popular arrangement is the clutch-type LSD. Clutch-type LSDs use alternating friction and reaction plates lubricated by gear oils with specific frictional properties that allow for smooth and quiet operation. It is essential that vehicles designed with LSDs use gear oils with the appropriate frictional characteristics, but each manufacturer relies on proprietary test methods to identify compatible gear oils for their LSDs. This lack of standardization limits the availability of compatible oils. To deal with this problem, the Army is developing a laboratory based test method using the SAE No. 2 friction test machine to identify fully formulated gear oils compatible with LSDs found in military equipment.

INTRODUCTION

Modern vehicles use a diverse set of mechanical and electronic methods to improve traction under adverse driving conditions. These include locking differentials, limited slip differentials, and a variety of electronically controlled torque vectoring or active differentials. One of the most popular ways to control torque to the drive wheels, without the complexity involved in active differentials, is the limited slip differential (LSD). These differentials are an essential device that allows normal differential action for negotiating corners, but prevents loss of traction in the event that a driving wheel loses grip. Although there are different types of limited slip differentials, the clutch-type LSD, shown in Figure 1, is most pertinent to military applications (e.g., Stryker Combat Vehicle). It relies on the smooth operation of oil-lubricated frictional clutches to control wheel torque. Typically multi-plate in construction, clutch-type LSDs depend on alternating friction and reaction plates lubricated by gear oils with specific frictional properties that allow for smooth and controlled torque transfer and mitigation of the stick-slip phenomena which presents itself as unwanted chatter or squeal. Such "chatter" can range from a minor NVH issue, to such severity that it can cause damage to the vehicle's driveline. Thus, it's essential that vehicles designed with limited slip differentials use gear oils with the correct frictional characteristics. Although many standardized test methods have been developed by industry to test the compatibility of transmission and wet brake clutches with oils, vehicle manufacturers still rely on proprietary methods to identify compatible gear oils for their limited slip differentials. The lack of such a standardized test limits the availability of compatible oils, and OEMs resort to special top-treatments specific for their LSD applications. Given the diversity of equipment suppliers to the military, this situation complicates the job of maintenance personnel and logisticians who have to deal with multiple suppliers of top-treatments. In an effort to deal with this problem, the Army is developing a laboratory based test methodology to identify fully formulated gear oils that are compatible with currently used LSD found in military equipment. This work is intended to support the final development of a Federal Test Method (FTM) to ensure candidate fuel efficient gear oils (FEGO) are compatible with the LSD found in military ground equipment.

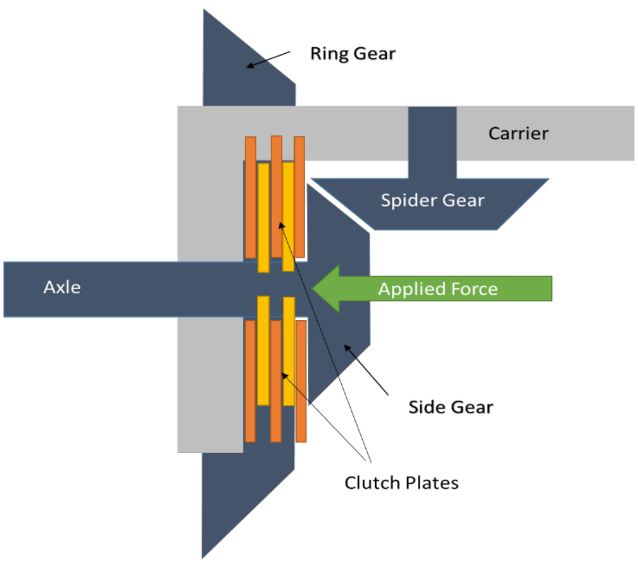

Figure 1: Cross-Section of Limited Slip Differential

LIMITED SLIP TEST CONCEPTS

Since the clutch-type LSD uses an oil lubricated clutch pack to control differential wheel speed and torque, frictional characteristics of the oil become critical. The following test concepts were considered for the evaluation of LSD and oil compatibility:

- Full vehicle testing using a driving protocol that stresses limited slip differential operation
- Development of a stationary axle friction test stand for the specific purpose of LSD clutch and lubricant compatibility
- Frictional testing of military relevant clutch material using a commercial test rig (e.g., SAE No. 2 test stand)
- Friction and wear evaluations using bench top test apparatus(es)

The advantages and disadvantages of these different concepts are explored in the sections that follow.

Full Vehicle Tests

There are many variations used in full vehicle evaluations to test the compatibility between the LSD and the oil (e.g., big wheel/small wheel and split-mu) but they all are designed to stress the oil's ability to prevent unwanted torsional variations (i.e., prevent severe stick-slip between clutches). In the split-mu test method, a vehicle outfitted with a new differential and test oil is driven on a slippery surface such that one side of the vehicle experiences very low traction and wheel spin. The vehicle traverses a short distance under these high slip conditions. This process is repeated several times before the vehicle is driven for a specified cool down period and another cycle of "spin outs" are completed. A chatter or moan evaluation is done at each cycle end consisting of a set of low speed turns while coasting to a stop [1]. Such full vehicle tests have the advantage of using the exact hardware as they will be fielded so there are no concerns that the hardware and overall axle dynamics are not representative of the real world. On the other hand, these tests are time consuming, expensive, and require a test vehicle(s) and new differentials for every oil evaluated.

Stationary Axle Limited Slip Test Stand

Consideration was also given to the development of a dedicated stationary axle LSD test stand. Such a test stand could consist of an electric input motor coupled to the input pinion of the test axle and electric motors (configured as generators) for each wheel end acting as absorbing units. The test stand could be computer controlled and programmed to cycle through operating conditions which stress the LSD and oil compatibility. The advantages of this concept is that it would provide the ability to test various size axles in a repeatable way, using hardware that is used in vehicle applications. Thus, some of the natural vehicle dynamics are preserved. The main disadvantage of this concept is the high initial cost to design and build the stand. In addition, the dynamics of the real vehicle are not exactly duplicated because tires and suspension components are not included.

Commercial Friction Test Rig

Similar to clutch-type LSD, compatibility between clutch and fluid for an automatic stepped transmission is critical for its operation. The frictional properties of automatic transmission fluids (ATF) are frequently evaluated in a commercial test rig called the SAE No. 2 Friction Test Machine [2]. The typical SAE No. 2 test rig consists of an electric motor with a test head installed on the motor output shaft. The test head houses the friction plates splined to the rotating output shaft and reaction plates splined to the stationary test head. The motor rotates the friction plates while the clutch (i.e., friction/reaction plates) is applied through a pressure actuation system. Test fluid can be continuously circulated through the test head or the test head can be filled with a specific quantity of fluid. Torque during a clutch engagement is continuously monitored and used to determine the coefficient of friction at various slip speeds and apply pressures. A basic schematic of an SAE No. 2 test rig is shown in Figure 2. SAE No. 2 test rigs are widely available at commercial test labs and therefore the cost of testing is reasonable. The test rigs have good repeatability and are flexible in terms of speed and loading conditions. The main disadvantage of this concept is that it does not duplicate the dynamics of the full driveline.

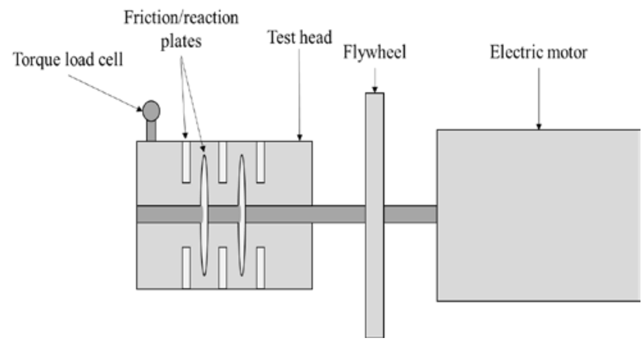

Figure 2: Basic Components of an SAE No. 2 Friction Test Machine

Bench Top Friction Testing

The final test concept considered was a bench top/scale friction apparatus. A typical example of such an apparatus is the pin-on-disc or disc-on-disc test configuration shown in Figure 3. Advantages of a bench top test are the low cost and generally short duration. Test samples can be generic or machined from actual parts. However, such tests completely lack the dynamics of the application, and therefore are used only as a screening tool prior to more comprehensive rig or vehicle testing.

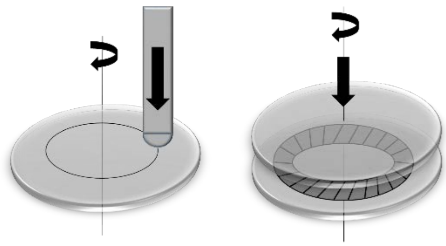

Figure 3: Pin-on-disc and Disc-on-disc Bench Test Configuration

CONCEPT CHOICE AND DEVELOPMENT

Based on the low development costs, wide availability, and proven capability to simulate friction responses in similar operation (e.g., transmission clutches), the choice made was to develop an LSD and oil compatibility test using the SAE No. 2 Friction Test Machine.

Initial investigations into this test concept centered on the possibility of using the actual friction and reaction plates from a limited slip differential in common use in Army vehicles. Unfortunately, the internal diameter of the discs were found to be too small to accommodate the output shaft of the SAE No. 2 test rig. Therefore, alternative friction and reaction plates were sought. The LSD manufacturer recommended alternative friction and reaction plates using similar materials but of larger size. A comparison of these with the actual LSD plates was conducted before proceeding with developmental testing. The results of this comparison, which included basic surface texture properties (e.g., roughness, skew, mean spacing, etc.), measured with an optical profilometer, are shown in Table 1.

Reaction Plate		
	Actual (1)	Alternative (2)
Ra, µm (3)	0.167	0.199
RSm, mm (3)	0.07	0.07
Rsk	-2.333	-1.696
Rku	13.894	8.419
Friction Plate		
	Actual (1)	Alternative (2)
Ra, µm (3)	7.752	6.685
RSm, mm (3)	0.15	0.13
Rsk	-0.115	0.088
Rku	3.155	2.598

(1) Actual plate from the LSD
(2) Alternative plate identified by the LSD manufacturer
(3) Height discrimination: 5%; Spacing discrimination: 1%

Table 1: Surface Texture Properties of Clutch Plates

Referring to Table 1, Ra is the *roughness average*, RSm is the *mean spacing of profile irregularities*, Rsk is the *skewness*, and Rku is the *kurtosis* [3]. Similarities between these parameters suggest that that clutch plates from the actual LSD and the alternative are very similar in terms of overall roughness magnitude, roughness spacing, and roughness shape. Based on the similarity of surface texture and metallurgy, the alternative plates were determined to be an acceptable substitute for use in the further development of the compatibility test.

Test Conditions

Test conditions were defined for the SAE No. 2 Friction Test Machine to ensure testing was conducted in a manner relevant to real-world application but still within the limitations of the test rig. Key properties of interest were the application pressure of the clutch pack, clutch plate sliding velocities, and temperature. The LSD manufacturer provided the following parameters based on test procedures the manufacturer used during durability and application testing:

- Clutch preload torque: 110 ft·lbf
- Typical sliding velocity: 10 rpm
- Full clutch pack pressure: 700 lbf/in^2
- Estimated coefficient of friction: 0.14

Real world sliding velocity within the LSD clutch will vary widely depending on operating conditions. For example, using the tire diameter, wheel hub reduction ratio, and top speed of a Stryker Combat Vehicle, sliding velocities between the differential carrier and the output axle (i.e., the sliding velocity experienced by the clutch pack) could vary from 0 to approximately 150 rpm. Noting that the alternative plates used in the SAE No. 2 test rig are slightly less than twice the radius of the plates used in the Stryker Combat Vehicle LSD, this suggests a maximum sliding velocity of roughly 80 rpm.

The clutch preload torque is a measure of the torque that must be applied to the LSD assembly to breakaway the clutches from static condition. Using the parameters above and the inner and outer radius of the clutch plates, the equation

$$F_n = \frac{T}{cof * \left(\frac{r_o + r_i}{2}\right) * N}$$

Where:

F_n = normal force
T = torque
cof = coefficient of friction
r_o = radius (outer)
r_i = radius (inner)
N = number of frictional surfaces

can be used to estimate the minimum applied force required in the SAE No. 2 test to match the breakaway torque provided by the LSD manufacturer. The required applied force was calculated to be approximately 1000 lbf (4.448 kN). Although this applied force represents the minimum expected, the decision made was to use this load as a starting value in the development of a test method.

Differential fluid temperature varies as a function of vehicle speed, load, and ambient conditions. During previous testing conducted using vehicles from the Family of Medium Tactical Vehicles (FMTV), axle temperatures were measured and recorded [4]. From this data a test temperature of 200°F (93.3°C) was found to be representative of a typical axle temperature during use. This temperature was selected for use in the LSD oil compatibility test method.

Proposed Test Cycle

Based on the parameters described in the previous section, a test method was developed for use with the SAE No. 2 test rig. The proposed method consists of a series of repeating cycles that age the oil and clutch plates followed by performance checks which assess frictional conditions indicating chatter. Prior to installation in the SAE No. 2 test rig, the friction plates are soaked in the test oil for one hour. The “Aging Segment” consists of operating at a continuous slip speed of 40 rpm for one hour, using an applied force of 1000 lbf (i.e., 294.6 kPa applied pressure), and controlling fluid temperature to 200°F. A “Performance Segment” is then conducted which starts with a 5 minute hold at 0 rpm, 1000 lbf load, and 200°F, followed by the chatter test where the speed is ramped from 0 rpm to 80 rpm over 20 seconds, then immediately ramped down from 80 rpm to 0 rpm over 20 seconds, and finishes with another 5 minute hold at 0 rpm, 1000 lbf load, and 200°F fluid temperature. At the end of the 5 minute hold a static breakaway test is completed by ramping to 0.7 rpm while maintaining a 1000 lbf load. Note that during the cycle the applied load is continually maintained, which is representative of actual clutch operation due to preload. The complete cycle (i.e., Aging and Performance Segments) is repeated until either excessive chatter is observed or 100 cycles are completed. Note that early testing was stopped at 50 cycles but, as discussed later, this was found to be inadequate and was increased to 100 cycles. Figure 4 is a simplified schematic of the proposed method.

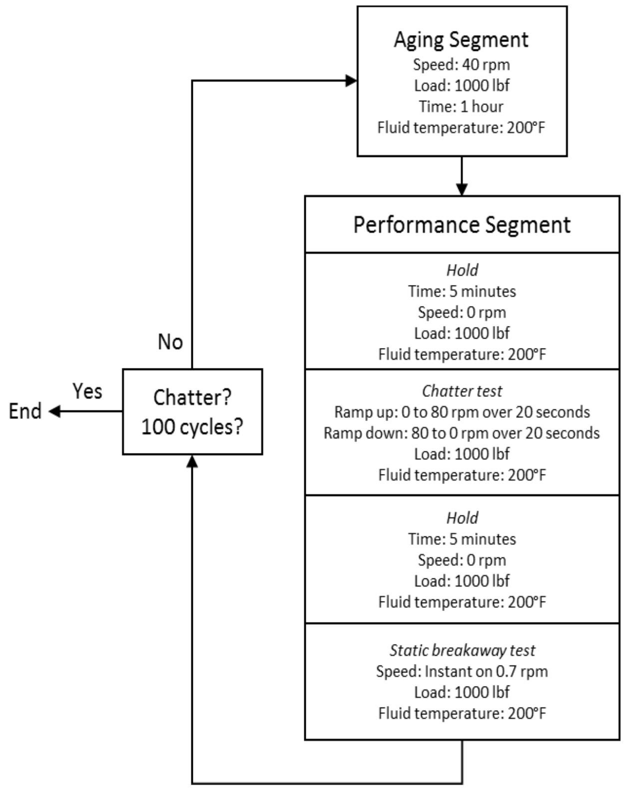

Figure 4: Schematic of the Proposed LSD Oil Compatibility Test Method

RESULTS AND DISCUSSION

Reference Oils

As a starting point, two differential gear oils, a "good" oil and "poor" oil were identified and obtained for initial testing. The "good" oil was a commercially available synthetic 75W-90 with limited-slip capability. This oil is currently used in an Army wheeled vehicle that requires limited-slip properties. The "poor" oil is a commercially available 80W-90 gear oil with no limited-slip properties. It is SAE J2360 qualified [5] and is typical of gear oils used in the majority of Army tactical wheeled vehicles.

A commercial SAE No. 2 Friction Test Machine was used and special fixtures fabricated to fit the clutch plates in the test head. The clutch pack configuration was:

PP – RP – FP – RP – Spacer – Cover

where PP = Pressure Plate, RP = Reaction Plate (stationary, splined to test head), and FP = Friction Plate (rotating, splined to input axle).

The test head was filled with 1000 mL of test fluid which completely fills the head and a small reservoir located approximately 2 inches above the test head.

Good Reference Oil

New friction and reaction plates were pre-soaked for one hour in test oil before installation in the test head. The test head was filled with test oil and the temperature was increased to 200°F before starting the test sequence outlined in Figure 4. The results for the chatter test are shown in Figures 5 and 6 for cycle number 5 and 50, respectively. It can be seen that the torque traces remain stable throughout the test, changing very little from cycle 5 to cycle 50. Furthermore, the torque and speed traces are relatively smooth with the exception of a small spike during the start of the 0 to 80 rpm ramp. This spike is due to static friction and represents the torque required for the clutch to start to slip; it can be associated with the clutch holding capacity. Also of interest is the shape of the torque curve during the ramp down from 80 rpm to 0 rpm. It can be shown that if the torque at the midpoint of the curve (i.e., 80 rpm or 20 seconds) is roughly equal to or greater than the torque just before 0 rpm (i.e., low speed torque), then the system will have a tendency to dampen torque fluctuations [6, 7, 8].

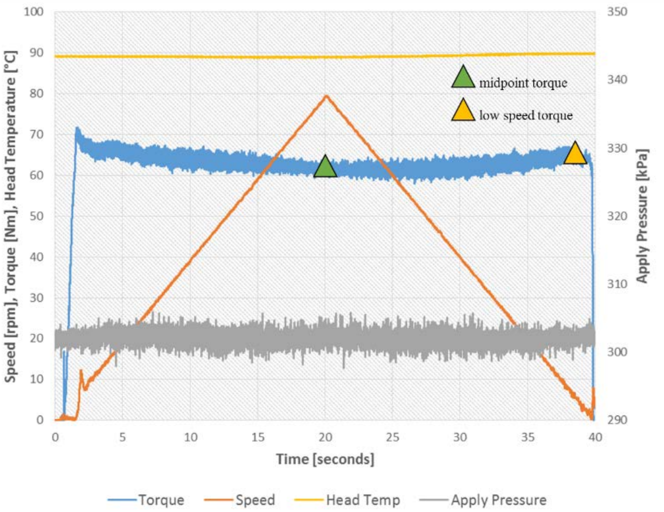

Figure 5: Speed Sweep of "Good" Reference Oil-Cycle 5

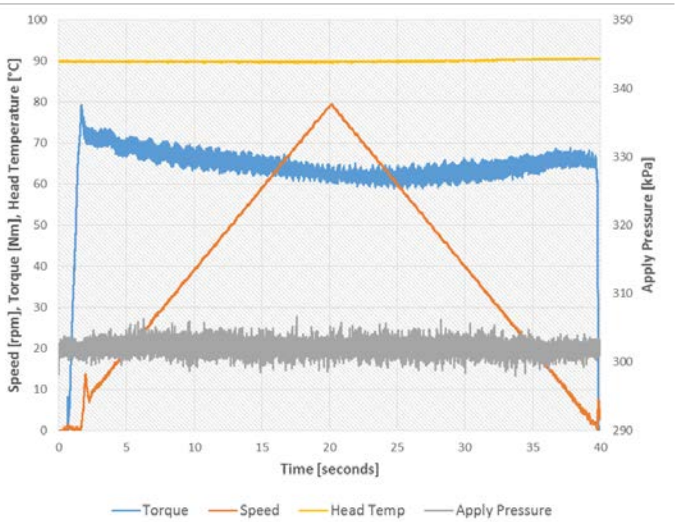

Figure 6: Speed Sweep of "Good" Reference Oil-Cycle 50

Poor Reference Oil

Following the procedure used for the "good" reference oil, the same test was conducted for the "poor" reference oil. The results from the chatter test are shown in Figures 7, 8, and 9 for cycles 5, 25, and 50, respectively.

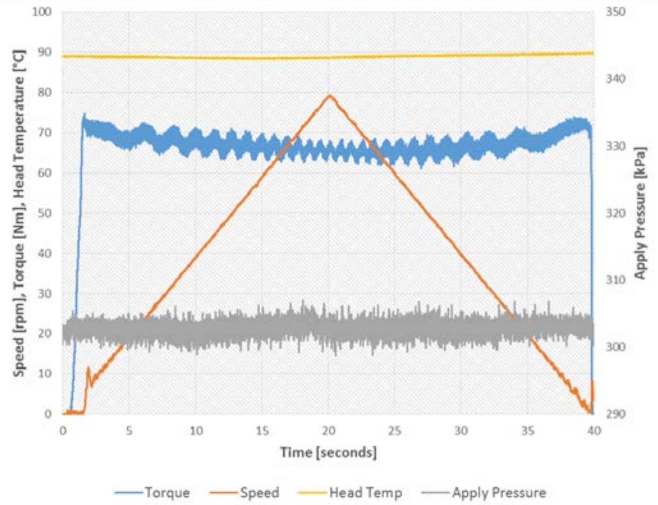

Figure 7: Speed Sweep of "Poor" Reference Oil-Cycle 5

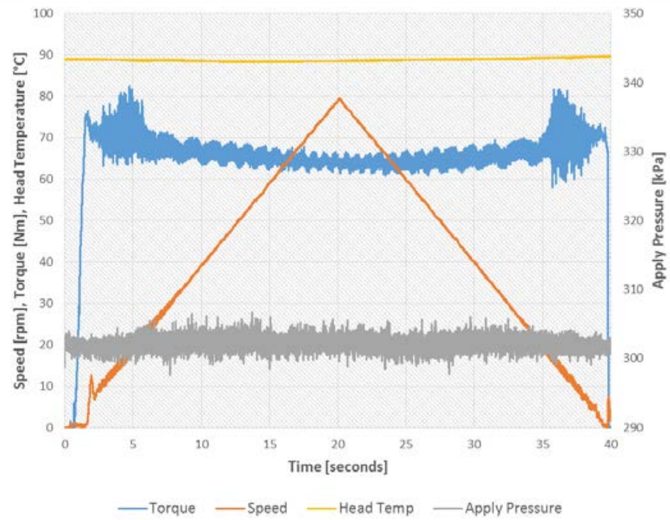

Figure 8: Speed Sweep of "Poor" Reference Oil-Cycle 25

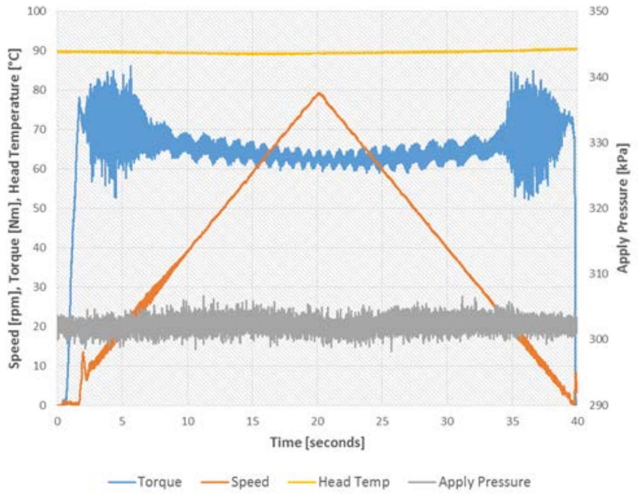

Figure 9: Speed Sweep of "Poor" Reference Oil-Cycle 50

Large torque oscillations (i.e., chatter) occurring between 5 rpm and 20 rpm can be seen in Figures 8 and 9 while speed was being ramped up and down. The chatter started near cycle 20 and continued to increase in magnitude until reaching the end of test at cycle 50. A low frequency oscillation is also present in Figure 7 and is likely caused by machining irregularities (e.g. waviness) in the clutches and not as a consequence of the oil.

Additional Oil Tests

Based on the test results of the "good" and "poor" reference oils it appeared that the proposed test methodology was able to differentiate between gear oils with and without limited slip capability. To further evaluate this, additional gear oils were required. Since it was known that the same additive company supplied the additive package for both the "good" and "poor" reference oils, the preference was to obtain fluids from a second supplier. Therefore, another gear oil additive supplier was contacted and provided two additional gear oils for testing. Both oils were 75W-90 formulations but one was formulated to be limited slip compatible and the other was not. Figures 10, 11, and 12 are the results from the gear oil without limited slip additive for cycles 5, 65, and 89, respectively.

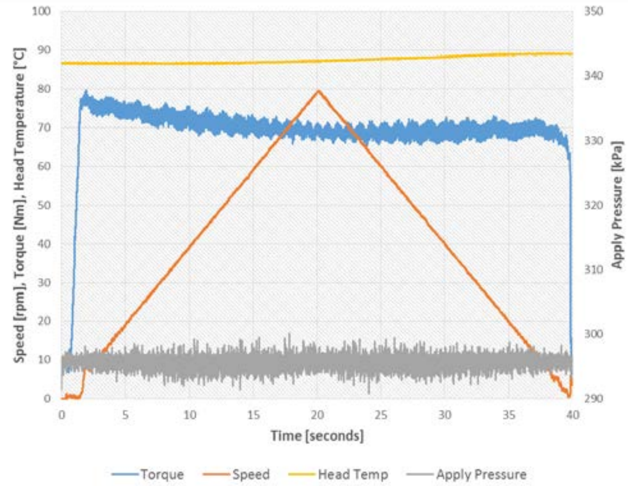

Figure 10: Speed Sweep of Non-LS Oil-Cycle 5

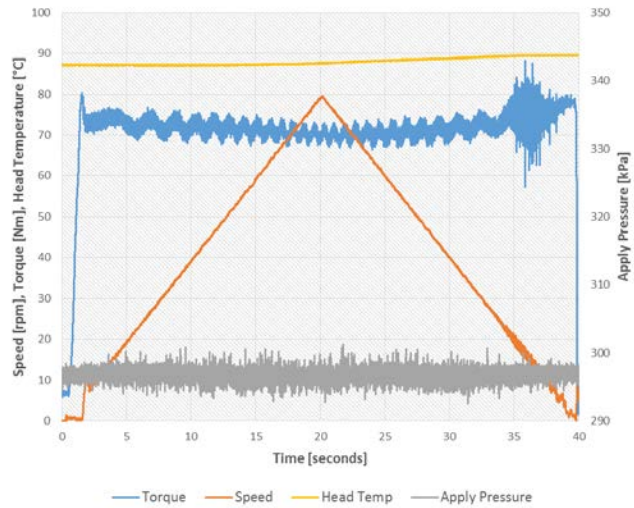

Figure 11: Speed Sweep of Non-LS Oil-Cycle 65

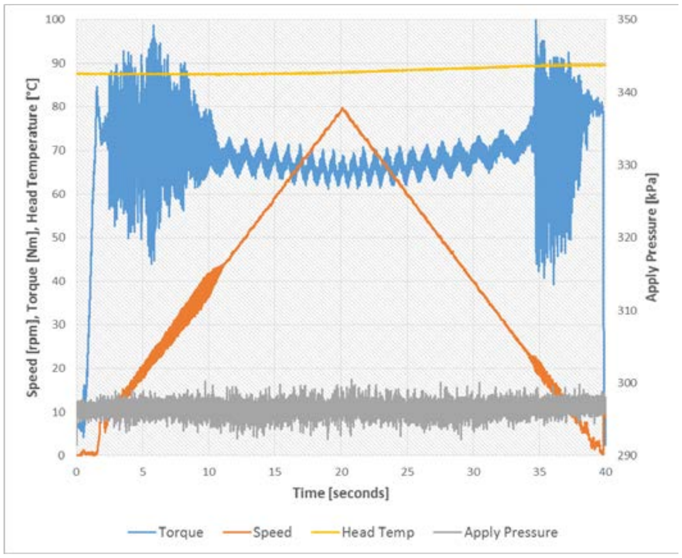

Figure 12: Speed Sweep of Non-LS Oil-Cycle 89

Pronounced torque oscillations were first detected at cycle 65 (figure 11). In contrast to the "poor" reference oil, this oil only started to chatter during the decreasing speed ramp. Again, chatter was most prevalent between 5 rpm and 20 rpm. As testing continued the amplitude of the torque oscillation grew until at cycle 89 (figure 12), the test was stopped due to excessive chatter. Between cycles 5 and 65, chatter also developed during the increasing speed ramp and lasted from 5 rpm to over 40 rpm. Based on these results it was clear that 50 cycles would not be adequate to identify gear oils with the propensity to chatter, so the test was extended to 100 cycles.

The results of testing the second oil identified as being limited-slip compatible are shown in figures 13 and 14 for cycles 5 and 100, respectively.

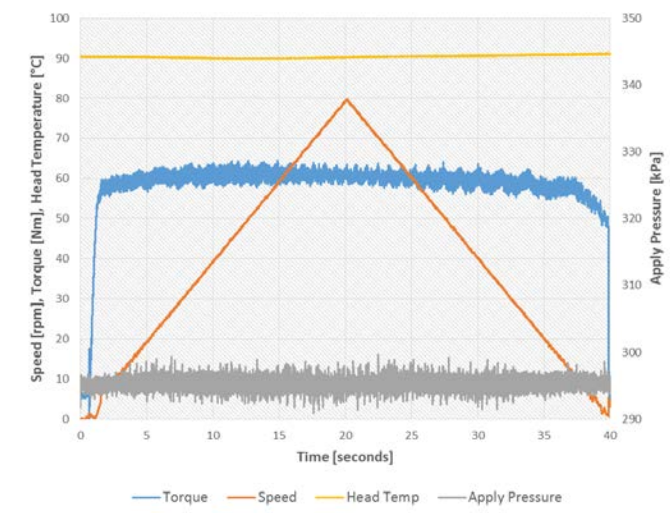

Figure 13: Speed Sweep of LS Oil-Cycle 5

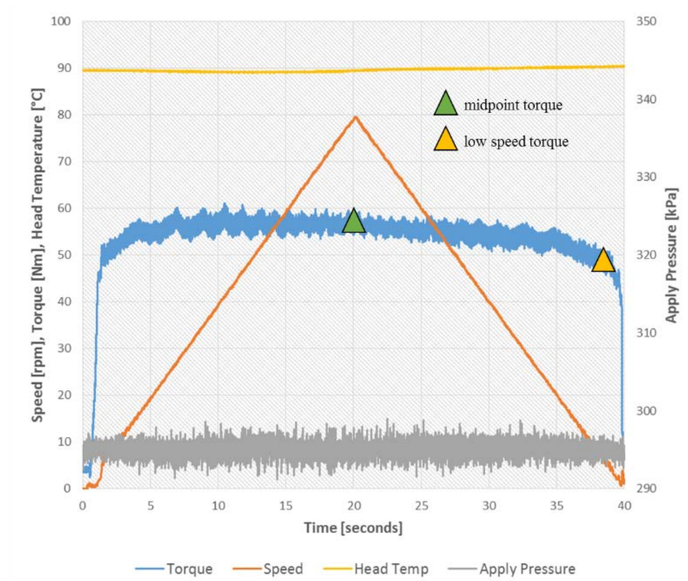

Figure 14: Speed Sweep of LS Oil-Cycle 100

The shape of the torque curves in Figures 13 and 14 are characteristic of a highly friction modified limited-slip gear oil. It can be seen that the midpoint torque is greater than the low speed torque, which as stated earlier is important for dampening undesirable torque oscillations and smooth clutch engagement. This behavior is a consequence of the friction modifier lowering the low speed and static coefficient of friction. It also lowers the kinetic coefficient of friction but to a much lesser extent. This can be seen by comparing the torque curves in Figures 10 and 14 and noting that the midpoint torque is reduced by approximately 10 Nm, while the low speed torque is reduced by more than 25 Nm.

Finally, two additional commercially available gear oils were obtained. The first oil was a top-tier, fully synthetic 75W-90 gear oil and the second was a fully synthetic 75W-90 claiming to be specifically formulated for fuel efficiency. Neither oil claimed limited-slip capability. Results showed that both oils exhibited chatter early on in the test (by cycle 5) and tests were terminated prior to reaching cycle 25 due to excessive chatter. Figure 15 shows the chatter test results for cycle 16 of the top-tier 75W-90 oil. The 75W-90 oil claiming fuel efficiency benefits showed similar results and is therefore not included.

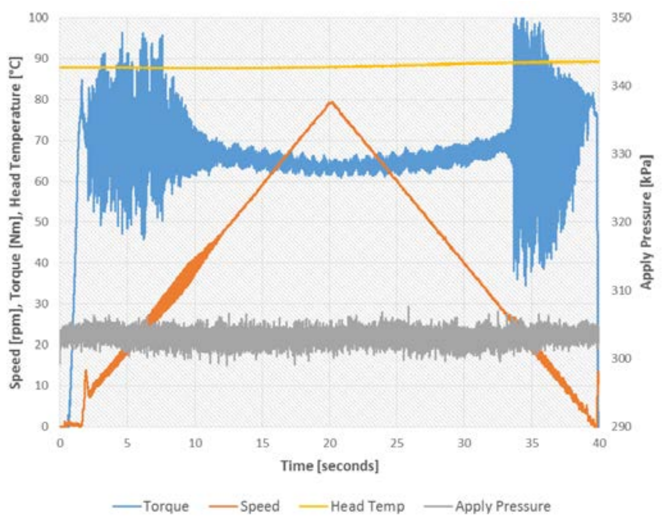

Figure 15: Speed Sweep of Top-Tier 75W-90-Cycle 16

Future Work

During actual use, a limited slip differential will operate under larger applied pressures and varying temperatures, therefore further testing is needed to understand how the developed test methodology responds to these changes. In addition, further testing will be needed to ensure that the results from the rig test are consistent with the behavior seen in a full vehicle. In order to verify this a Stryker Combat Vehicle (i.e., an eight wheeled armored personnel carrier) will be instrumented and tested at TARDEC's Power and Energy Vehicle Environmental Laboratory. The laboratory houses multiple dynamometers and is designed to allow real world vehicle performance and capability comparisons of wheeled and tracked vehicles.

SUMMARY AND CONCLUSIONS

Some commercial and military vehicles use limited slip differentials to improve traction and mobility when operating on slippery surfaces and under off-road conditions. Many automotive OEMs have proprietary in-house methods to evaluate gear oils for these applications. The lack of a standardized test methodology limits the availability of limited slip compatible oils and leads to supply limitations, vehicle downtime and higher prices. A test methodology was developed to identify gear oils that are compatible with clutch based limited slip differentials used in military vehicles. The test methodology uses a standard SAE No. 2 Friction Test Machine and friction and reaction plates similar to those used in actual military vehicles equipped with limited slip differentials. The test procedure includes an aging step which is designed to slowly degrade the clutch plates and oil, followed by a performance step, which measures the ability of the clutch and oil to limit stick-slip behavior. If left unaddressed, excessive stick-slip (or chatter) can lead to axle or vehicle damage. The proposed test methodology was used to evaluate several gear oils and results demonstrate the ability to differentiate between oils with and without limited slip capability. Further test development is needed to validate the methodology but these results are promising. The intent is that this methodology will form the basis for a Federal Test Method which can be used for the qualification of gear oils for military use.

REFERENCES

[1]Schenkenberger, C., Schiferl, E., Garling, G., Baker, M. et al., "Next Generation Torque

Control Fluid Technology, Part II: Split-Mu Screening Test Development," SAE Technical Paper 2006-01-3271, 2006, https://doi.org/10.4271/2006-01-3271.

[2]"SAE No. 2 Friction Test Machine μPVT Test", J2490_201208, https://doi.org/10.4271/J2490_201208.

[3]"Surface Texture (Surface Roughness, Waviness, and Lay)", ASME B46.1-2009.

[4]R.W. Warden, E.A Frame, "Axle Lubricant Efficiency", Interim Report TFLRF No. 444, May 2014.

[5]"Automotive Gear Lubricants for Commercial and Military Use", J2360_201204, https://doi.org/10.4271/J2360_201204.

[6]Bhushan, B, 2002, *Introduction to Tribology*, John Wiley & Sons, New York, 732 p.

[7]Kugimiya, T., Yoshimura, N. & Mitsui, J. Tribology Letters (1998) 5: 49. https://doi.org/10.1023/A:1019156716891

[8]Cameron, T., Hewette, C., McCombs, T., DeGonia, D. et al., "Traction and Clutch Effects on the Natural Frequency and Vibration Stability of Limited Slip Differential Axles," SAE Technical Paper 2007-01-2295, 2007, https://doi.org/10.4271/2007-01-2295