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ABSTRACT

Light trucks and sport utility vehicles (SUVs) have become extremely popular in the United States in recent years, but this shift to larger passenger vehicles has placed new demands upon the gear lubricant. The key challenge facing vehicle manufacturers in North America is meeting government-mandated fuel economy requirements while maintaining durability. Gear oils must provide long-term durability and operating temperature control in order to increase equipment life under severe conditions while maintaining fuel efficiency.

This paper describes the development of a full-scale light duty axle test that simulates a variety of different driving conditions that can be used to measure temperature reduction properties of gear oil formulations. The work presented here outlines a test methodology that allows gear oil formulations to be compared with each other while accounting for axle changes due to wear and conditioning during testing. Results are shown from a variety of different axle configurations and loading conditions. This test method shows the importance of accounting for changes in the axle when comparing test results whenever severe conditions are experienced.

INTRODUCTION

Within the last few years, there has been a renewed desire to make fuel economy improvements in North America's light trucks and sport utility vehicles (SUV's). Vehicle manufacturers have set aggressive fuel efficiency improvement objectives for these vehicles. Because of this, gear lubricants have been targeted to contribute fuel economy improvements over the current products used in these applications.

This is not as easy as it may seem. In addition to acceptable fuel economy, gear lubricants are required to protect axle components under a variety of stressed conditions. These include high speed scuffing, low speed, high torque wear, corrosion and oxidation. In light truck and racing applications, gear oils must provide long-term durability and operating temperature control under extreme conditions, such as trailer towing or extended high speed applications. Higher operating temperatures for prolonged periods can adversely affect metallurgical properties and reduce fluid film thickness, both of which can lead to premature equipment failures. In our view, operating temperature is an important indicator of durability.

While fuel economy is now the driving force in next generation lubricant development, it is clearly recognized that any improvements in fuel economy must not be at the expense of axle durability or performance.

Fuel economy improvements can be measured via the U.S. EPA 55/45 driving cycles[1]. Automotive manufacturers use this test to certify a vehicle's fuel economy. This test can also be used to show fuel economy improvements in gear oil lubricants.

Many manufacturers feel that stabilized operating temperature under the proper controlled conditions is an important indicator of the durability performance of a lubricant under severe conditions. In the case of operating temperature assessment, there exists no standard test method or methodology. Typically, when applied in a laboratory test stand a single axle is broken-in and then used repeatedly to evaluate many lubricants. Under severe conditions, the stabilized operating temperatures for a given reference oil decreases each time it is run in an axle. As the number of test runs on an axle increases the stabilized operating temperature of the reference oil is lower. This poses a problem when evaluating candidate lubricants. With a changing target, how can a lubricant be accurately evaluated?

This paper describes a laboratory test method that accounts for test-to-test changes in the axle and gives the lubricant formulator an accurate way of comparing test results. In addition, common pitfalls of this method and operating guidelines will be described.

The remainder of this paper is divided into four parts. First, the test stand used to develop and utilize the test procedure is described. Second, the test methodology is discussed in detail. The third section focuses on presenting test results that demonstrate the usefulness of the test methodology. Finally, the last section summarizes the paper's findings and offers some conclusions.

PART 1 - AXLE TEST STAND CONFIGURATION

This full-scale axle dynamometer test stand was designed and set up to simulate a variety of operating conditions. A schematic of the test stand is shown in Figure 1. This figure illustrates the axle rig and its major components. Figure 2 shows a picture of the test stand.

Figure 1: Schematic of Axle Test Stand

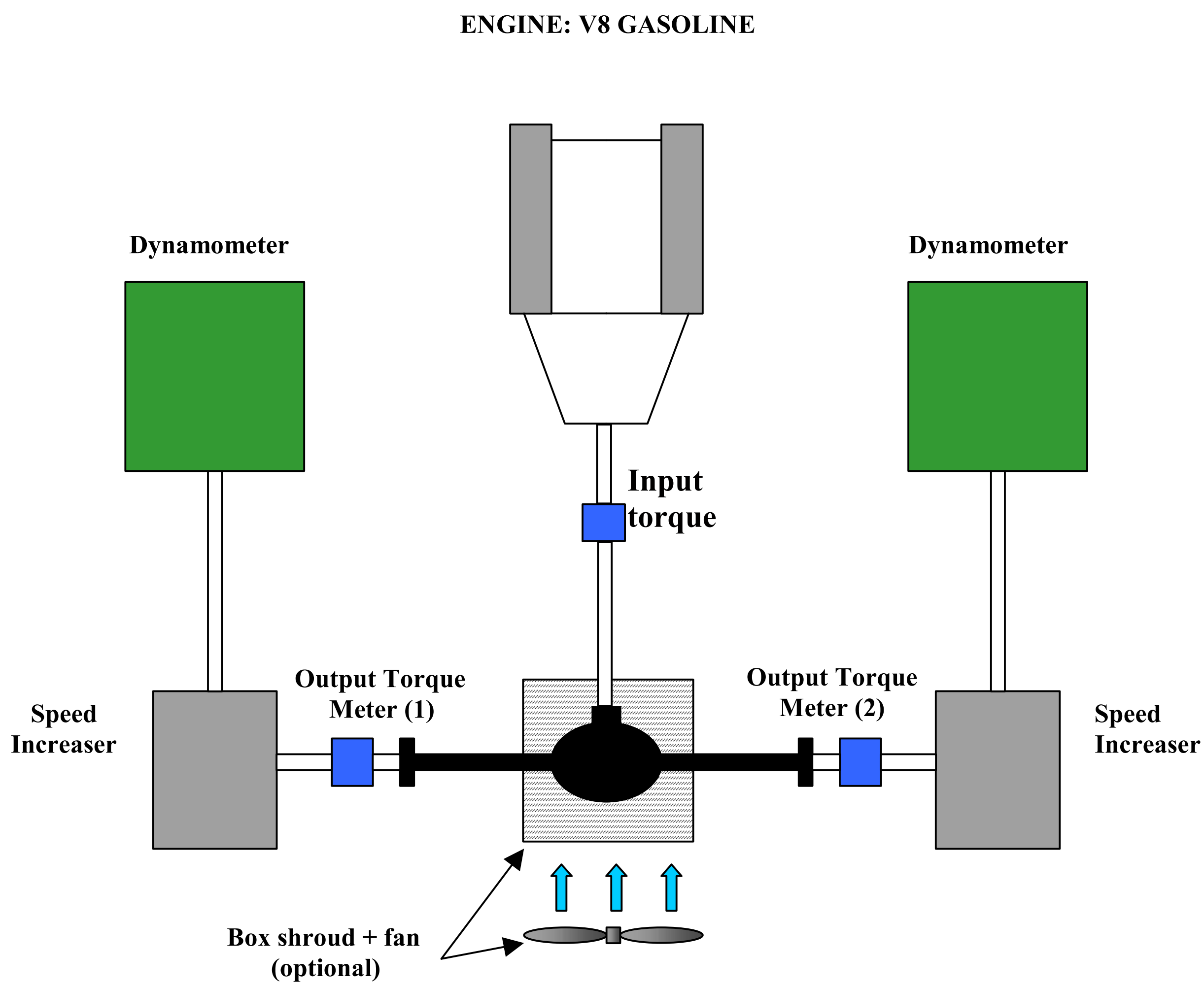
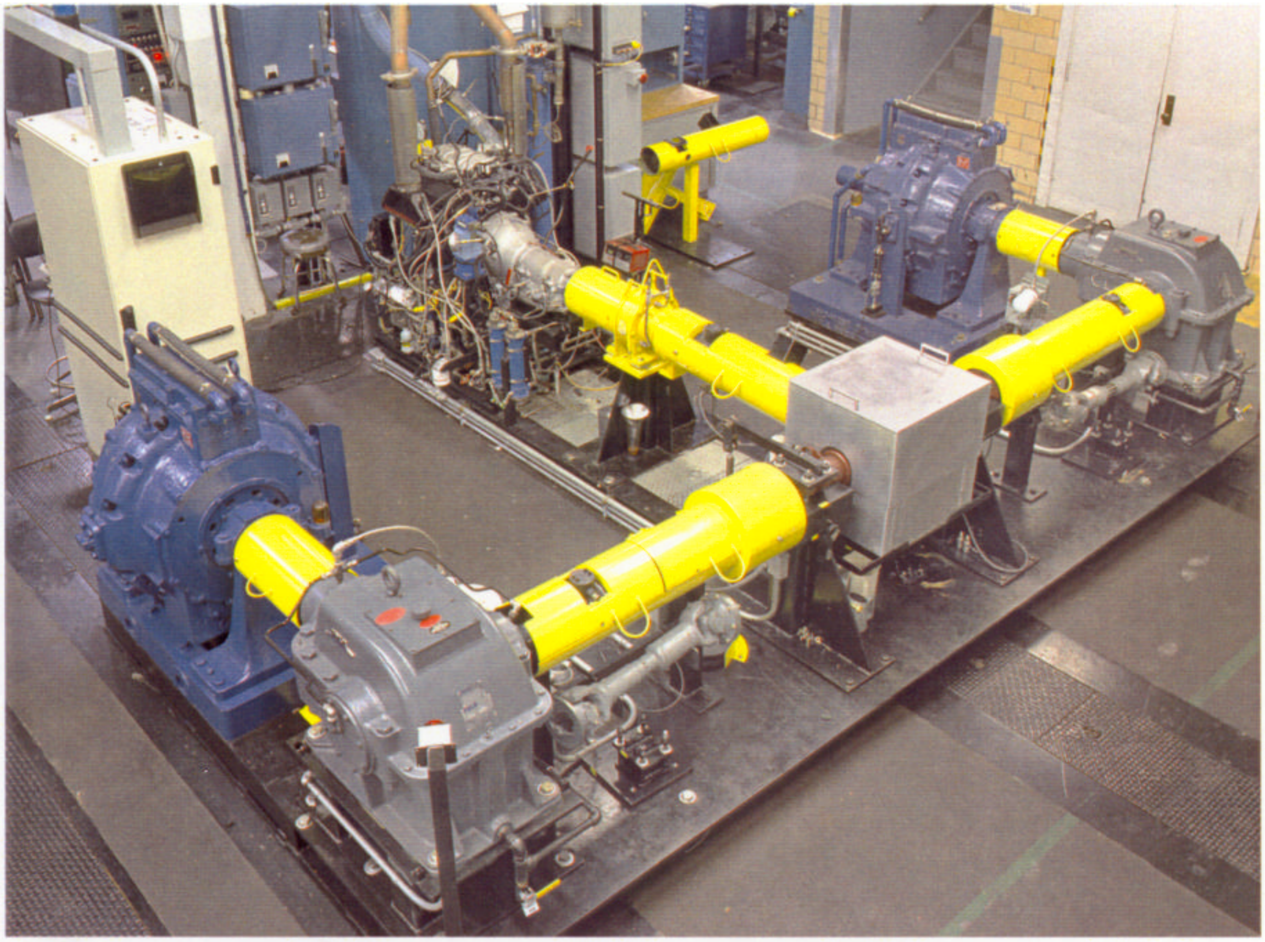


Figure 2: Photograph of Test Stand



STAND CONFIGURATION - Power is supplied to the axle by a gasoline fueled 7.4 liter V8 engine through a heavy duty 4-speed automatic transmission that can be automatically shifted by the data acquisition and control (DAC) system. The axle used for lubricant evaluation is rigidly mounted to the stand. The power driven through the axle is absorbed by two air gap eddy current dynamometers. A speed increaser is placed between the axle wheel end and the dynamometer to boost output speed to the dynamometer for low speed applications. The stand used is flexible and with a quick change of torque meters and/or axle fixtures is able to accommodate a wide range of axle sizes, from small passenger vehicle axles to large on highway truck axles.

TORQUE METERS - A single in-line torque meter integral to the drive shaft measures the input pinion torque to the axle. Two in-line torque meters measure the output torque from the axle to the dynamometers. One output torque meter has been placed between each axle wheel end and speed increaser.

In addition, the torque meters used are the enhanced accuracy, DC operated models. This was done to increase and maintain a high degree of accuracy and repeatability. These torque meters are periodically dead weight calibrated to insure accurate torque measurements.

AXLE COOLING AND TEMPERATURE MONITORING - Behind the axle a fan is positioned to provide airflow across the axle. This was done to simulate the actual airflow cooling experienced in field tests. The fan speed, size and position were selected to produce temperatures in the axle which match field test data for the axle being tested.

In addition, two water spray nozzles are positioned around the axle. These spray nozzles are used for two purposes. First, they are used to control the lubricant temperature during axle break-in. Second, they provide protection against high axle lubricant temperatures. Depending upon the lubricant under evaluation, this test procedure has the potential of experiencing very high axle lubricant temperatures. To protect the axle, high temperature limits have been put in place for each test stage.

Another major concern is the measurement of the ambient air and axle lubricant temperatures. Thus, care was taken to properly position the thermocouples. The axle lubricant temperature is measured by a thermocouple positioned directly next to the axle ring gear. The thermocouple is held in place by a specially modified axle cover. The ambient air temperature is measured by placing a thermocouple in the air stream produced by the fan. Both thermocouples are periodically calibrated to insure accurate temperature measurements.

DATA ACQUISITION AND CONTROL SYSTEM - A DSP Redline ADAPT / MRTP system is used to control the operation of the stand and to acquire data throughout the test. In addition to the ambient and lubricant temperatures, this system monitors and records additional temperatures (engine oil, transmission oil, dyno, gear box, fuel, and coolant), torques (input and two outputs), speeds (engine, pinion, axle shafts, and dynos) and axle efficiency (ratio of output torque to input torque) throughout the test. Data is logged periodically.

This system controls the operation of the stand with five control loops.

- Two control loops are used to maintain the desired pinion speed. This is done by modulating each dynamometer current to achieve a desired pinion rpm.
- The load on the pinion is maintained by adjusting the engine throttle.
- A fourth control loop is used to control the axle lubricant temperature during axle break in and to prevent high temperatures from damaging the axle during lubricant evaluations.
- Finally, a fifth control loop is used to insure that the automatic transmission is running each test stage in the appropriate gear.

It is important that the automatic transmission is operating in the proper gear. Some of the test stages during this test run at relatively high loads. Premature failure will occur if the transmission does not operate in the appropriate gear for a given test stage.

PART 2 - TEST METHOD

In general, the evaluation of the lubricant's durability was assessed by determining its stabilized operating temperature and axle efficiency at a number of discrete speed / torque conditions. The test procedure used is described below.

REFERENCE OILS - Reference oils are critical to this test methodology. For the development of this test procedure and evaluation of lubricants, two reference oils were used. The fluids used as reference oils are as follows:

Good Reference: Synthetic SAE 75W-140

Poor Reference: Synthetic SAE 75W-90

The good reference has been shown to provide outstanding performance in a wide variety of severe service applications. This fluid provided excellent temperature reduction in a controlled severe duty field test. This reference oil is used to break-in the axle and is periodically tested on a given axle to track any changes that might occur in stabilized operating temperatures.

The poor reference was also field tested and did not provide the same level of durability or temperature reduction in severe conditions as the good reference. Testing has shown however that this lubricant provides measurable fuel economy benefits. This reference oil is used to verify that the test procedure can distinguish between oils that provide different levels of performance in the field.

AXLE BREAK-IN - Before an axle can be used for lubricant evaluation, a break-in procedure is run. This procedure consists of a series of controlled load and speed conditions. The axle lubricant temperature is controlled throughout the break-in procedure where it is not allowed to exceed 250°F (121°C). The good reference oil is used for the break-in procedure.

Running an adequate break-in is critical in preparing the axle for accurate lubricant evaluations. Once broken in an axle can run multiple candidate lubricant evaluations.

TEST STAGES - Following the break-in procedure, candidate lubricants are evaluated by determining the stabilized operating temperature and efficiency at five combinations of speed and loads (stages) to approximate different severe operating conditions. Table 1 outlines the test conditions used.

Table 1

Durability and Operating Temperature Test Conditions

STAGE	GENERAL CONDITION	CORRELATION
I	High torque / low speed	Heavy Load - Start-Up
II	Moderate torque / high speed	High Speed - Flat Surface
III	Moderate torque / moderate-high speed	Heavy Load - Flat Surface
IV	Moderate-high torque / moderate speed	Heavy Load - Moderate Grade
V	High Torque / low-moderate speed	Heavy Load - Steep Grade

Each of the load stages is run until a stabilized lubricant temperature is achieved. This typically takes 1.5 to 2.5 hours. Once a stabilized temperature is reached, the next test stage is started. This cycle is repeated until all test stages have been evaluated. At the completion of each test stage, the ambient air temperature, stabilized lubricant temperature and stabilized axle efficiency is recorded[(2)].

AMBIENT AIR TEMPERATURE ADJUSTMENTS - It has been observed that changes in ambient air temperature affect the stabilized operating temperature of the axle lubricant. Since this test method was run in a laboratory where the ambient air temperature may vary, changes in ambient air temperatures must be accounted for. Adjusting the axle lubricant temperature to account for ambient air temperature changes is done by normalizing the axle lubricant temperature relative to an ambient air temperature of 80°F with the following equation:

$$T_{corrected} = T_{axle} + (80°F - T_{ambient})$$

Where,

$T_{corrected}$ = lubricant temperature (°F) corrected for the ambient air temperature.

T_{axle} = measured lubricant temperature (°F).

$T_{ambient}$ = measured ambient air temperature (°F).

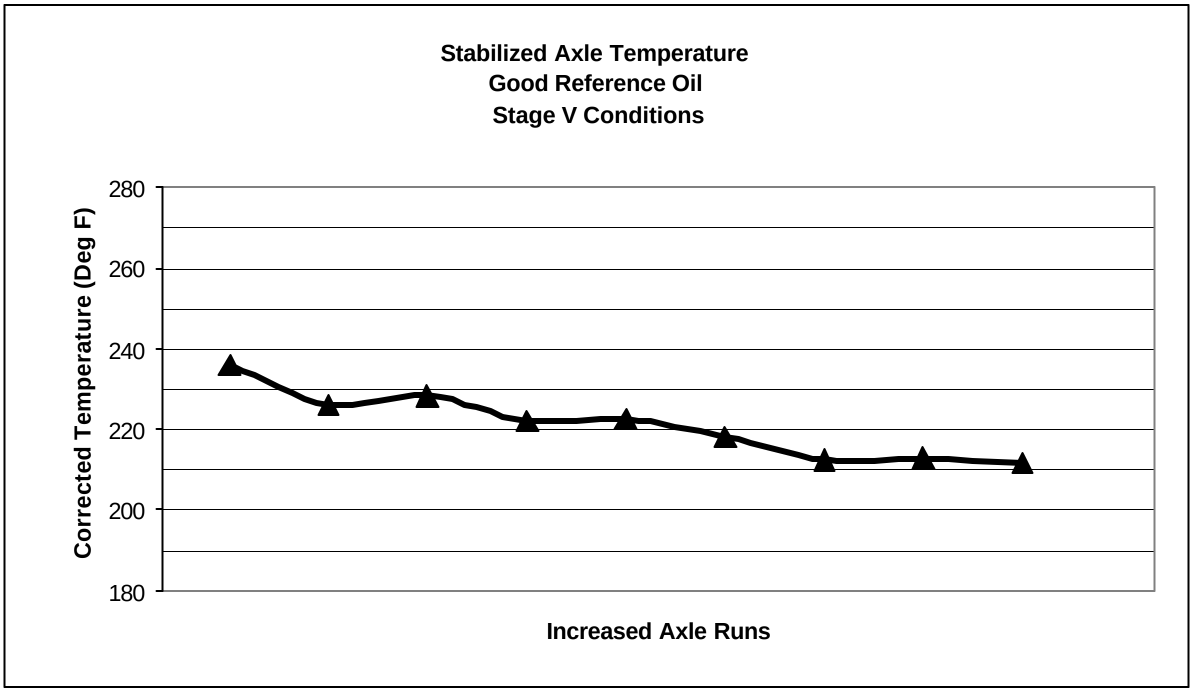
Before applying any of the methodology described below, the axle lubricant temperature is adjusted to account for ambient air temperature differences.

REFERENCE TEMPERATURE CHANGES - As the number of tests run on an axle increases, the stabilized operating temperature for a given load condition of any single oil is lower. This fact poses a problem when evaluating a candidate lubricant.

To solve this problem in the past, reference oil is tested periodically and the candidate result is compared to the last reference test result. However, if the reference test temperature gets lower after each test run, comparing the candidate to the last reference result will make the candidate seem better than it actually is relative to the reference.

Figure 3 shows the change in stabilized operating temperatures for stage V conditions on a test axle when the good reference oil is tested. The stabilized operating temperature goes down as the number of test runs on the axle increases. For this test procedure, this trend occurs on all 5 test stages.

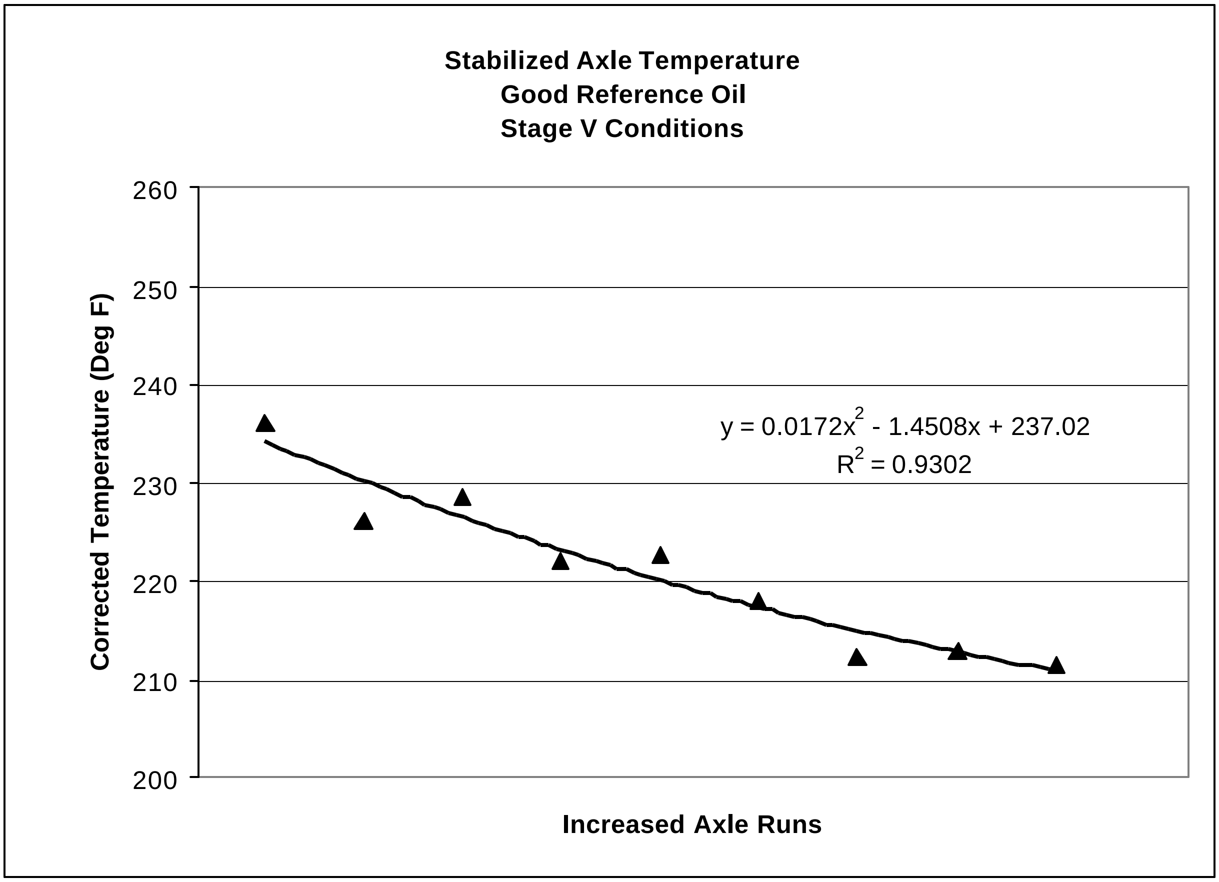
Figure 3: Stabilized Operating Temperature For the Good Reference Oil Over the Life of a Test Axle Under Stage V Conditions



REFERENCE TARGET TEMPERATURE - To make a fair comparison between a reference and a candidate, the reference oil's stabilized operating temperature used for comparison should be adjusted for the number of runs made on the axle. This adjustment must be done for each test stage and lubricant evaluated on an axle. The adjusted reference oil temperature or "reference target temperature" can then be compared to the candidate oil's stabilized operating temperature for the load stage in question.

Based on the reference test data, an equation for each test stage can be generated taking into account the reduction in the reference stabilized operating temperature as the number of test runs increases on an axle. This must be done for each axle tested. Once generated, candidate results can be accurately compared to reference oil performance. Figure 4 shows a curve fitted to the stabilized operating temperatures of the good reference oil for Stage V test conditions.

Figure 4: Curve Fitted To Stabilized Operating Temperature Results for Good Reference Oil on a Test Axle Under Stage V Conditions

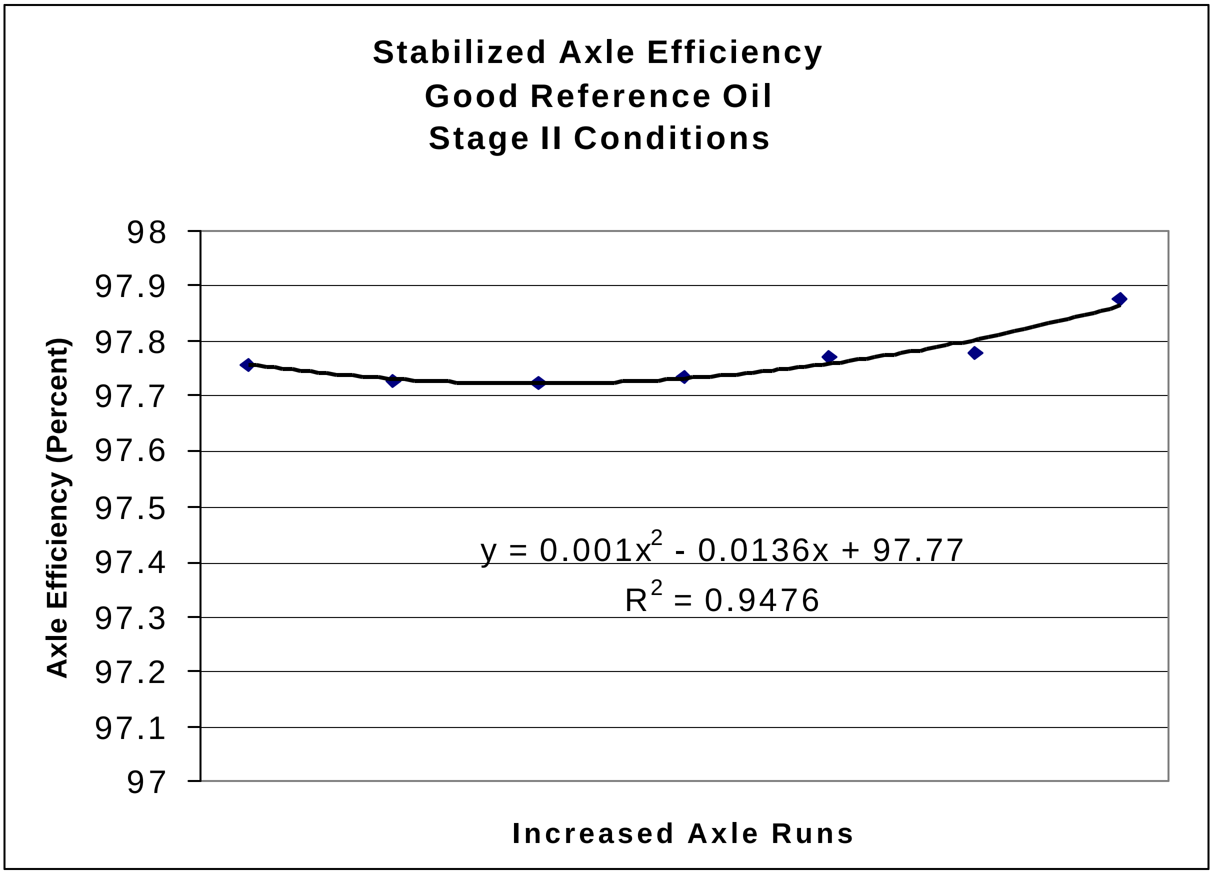


From the equation developed in Figure 4, a reference target temperature can be calculated for each test run on the axle for each test stage. Candidate test results can now be accurately compared to reference test results.

In addition, this method allows the formulator to more accurately compare results that were tested on different axles since your comparison is relative to the reference oil.

AXLE EFFICIENCY CHANGES - Just as with the stabilized temperature, a similar effect occurs with the axle efficiency measurements on test axles. The axle efficiency gradually increases as the number of tests on an axle increases. Figure 5 shows the changes in the axle efficiency and the reference target efficiency equation developed from the test results.

Figure 5: Stabilized Axle Efficiency Values For the Good Reference Oil Over Life of a Test Axle Under Stage II Conditions



It has been our experience with this test procedure that the stabilized axle efficiency for any test stage is inversely proportional to the stabilized operating temperature. The higher the efficiency, the lower the operating temperature. Thus our primary focus in the paper is on the operating temperatures and not the axle efficiencies. The test methodology described in this paper can be applied to both.

ASSESSMENT OF TEST REPEATABILITY - Test repeatability can be estimated from the reference test results on each axle. This is done by comparing the differences between the actual stabilized operating temperature and the calculated reference target temperature for each reference test in an axle for a given test stage. For example, the test repeatability was calculated to be 5.9°F for Stage V conditions shown in Figure 4. Our experience has been that repeatability estimates range from 0.5 to 8.0° F depending upon the test stage run, axle used and lubricants tested.[3, 4]

The test repeatability on any given axle is greatly affected by the quality of the candidate oils tested. Running a poor quality oil affects the results of the tests that run on the axle after it finishes. This introduces additional variability in the test stand. Thus it is important to run good quality oils to minimize variability.

PART 3 - TEST RESULTS

Test results presented in this paper are focused on demonstrating the validity of this test procedure for use as a tool to evaluate the temperature reducing capabilities of lubricants under severe operating conditions. This section is divided into three parts.

FIELD TEST CORRELATION - The test stages described earlier were developed from field tests data. They are designed to represent actual conditions experienced by vehicles in use. Results produced by the test stand were compared to results from the field. Modifications were made to the stand axle airflow system until the stand's test results matched the field test results. The comparisons were made between known oils run in field test vehicles and the test stand. For this test, we compared the laboratory test results for both the poor and good reference oils with the same oils run in the field test.

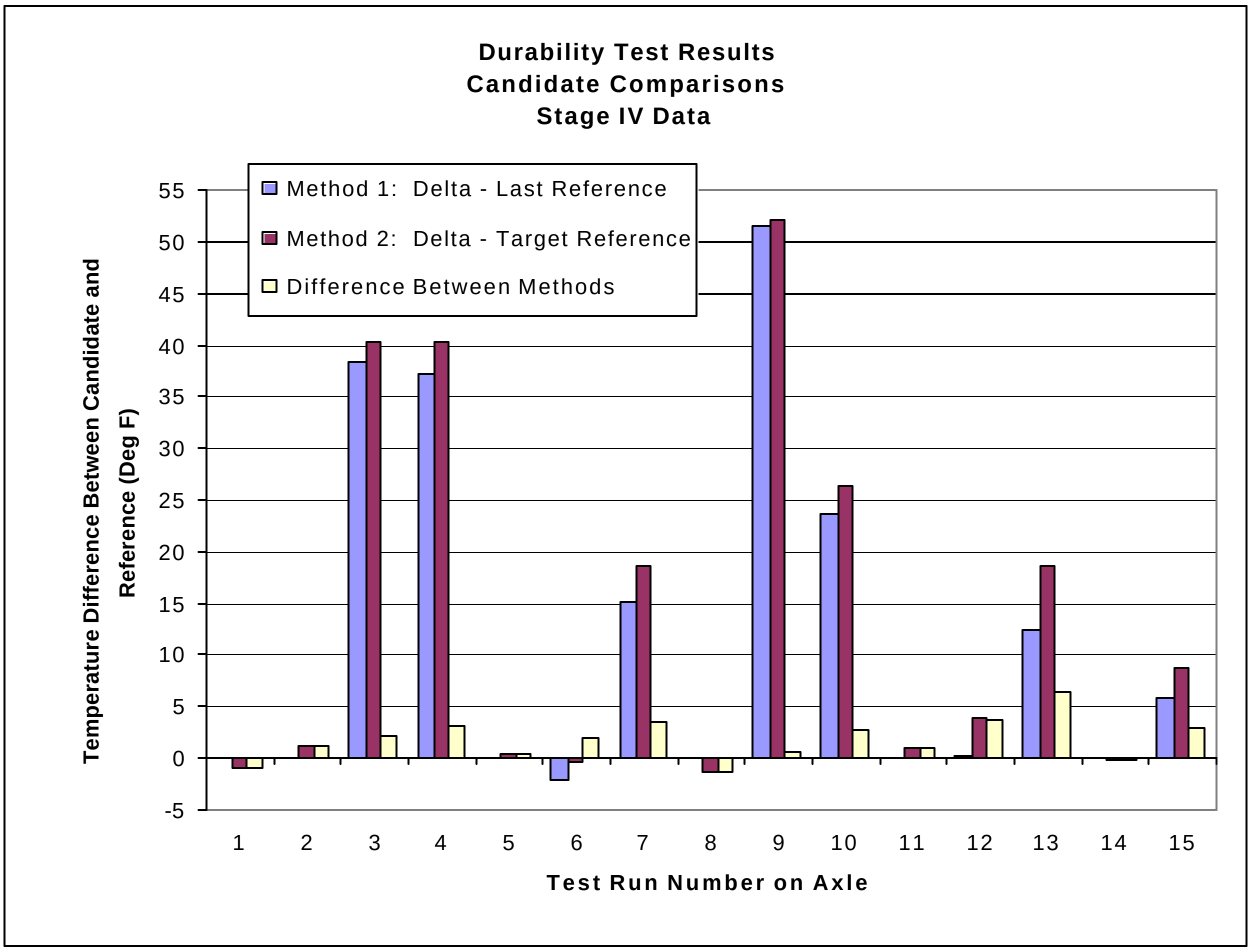
COMPARISON METHOD DIFFERENCES - From the equations developed above, a reference target temperature can be calculated for each test run. Figure 6 shows the improvement in oil assessments that can be made by using the reference target method. Figure 6 shows a comparison between two evaluation methods.

Both methods compare candidate test results with the good reference oil test results for a single test stage. Test runs 1,2,5,8,11 and 14 were good reference runs.

Method 1 is comparing the candidate oil stabilized lubricant temperature to the last reference oil stabilized temperature result.

Method 2 is comparing a candidate oil stabilized lubricant temperature to the calculated reference target temperature for the candidate's axle run number.

Figure 6: Comparison of Two Methods of Data Evaluation



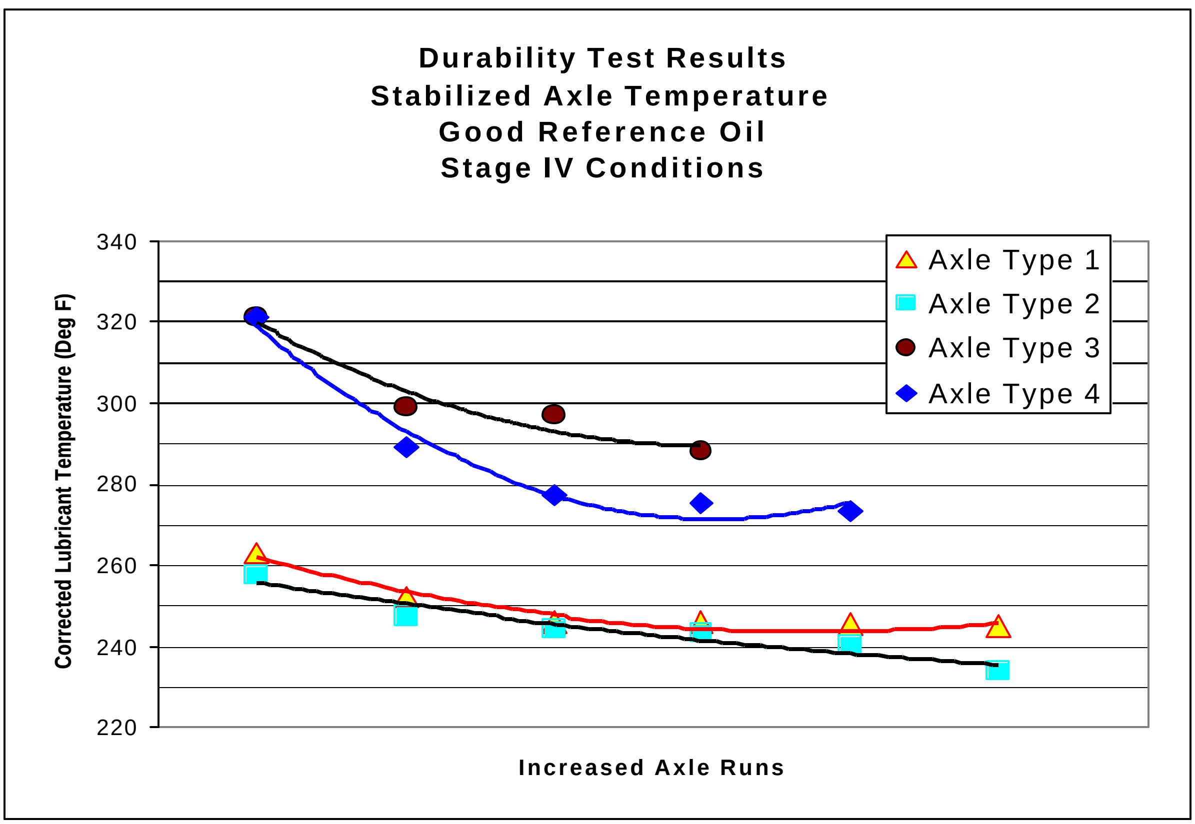
Positive deltas indicate that the test in question ran at a higher operating temperature than the reference. Likewise, a negative delta indicates that the test ran at a cooler temperature than the reference. Note that some values for method 1 are zero. In all cases, method 2 makes the candidate test results look better than reality.

In some cases, the differences between the methods can be large. Test run number 13 in Figure 6 shows a large difference between the two methods. This is due to a large change in temperature results between reference oil tests (test runs 11 and 14). Method 1 did not accurately account for the change in the axle and introduced a large error in the candidate evaluation. Method 2 did account for the change and produced a much more accurate candidate assessment for test run number 13. Using the reference target technique (method 2) will produce a much more accurate assessment of the lubricant's performance than method 1. The greater the change in the axle from test to test, the more important the reference target technique becomes.

The test repeatability for the data used in Figure 6 was 2.6°F using the target reference evaluation technique (method 2). Note that the difference between the two methods is greater than the test repeatability for 6 of the 9 candidate evaluations.

DIFFERENT AXLE TYPES - This procedure was applied to several different axle designs. In every case the application of the methodology improved the quality of candidate evaluations. This method allowed the formulator to make correct choices when developing lubricants that can provide operating temperature control under a variety of conditions. Figure 7 shows the results of good reference oil runs in four different axle designs. They all show a reduction in temperature as the number of test runs on the axle increases.

Figure 7: Change in Temperature Response for the Good Reference Oil Running Test Stage IV Conditions on a Number of Different Axle Types



PART 4 - SUMMARY

The use of the test methodology described in this paper allows for more accurate gear lubricant evaluations when running severe duty test conditions. Applying these techniques should translate to faster development of superior quality lubricants that will provide acceptable durability performance when operated under severe conditions.

The results have shown the usefulness of this test procedure in evaluating lubricants. Hopefully, this test procedure will aid in the development of a more fuel-efficient lubricant, as measured by the U.S. EPA 55/45 driving cycles that will also provide acceptable durability in severe operating conditions.

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