FUEL EFFICIENT GEAR OIL – PART V

INTERIM REPORT
TFLRF No. 490

by
Mary R. Stevens
Greg A. Hansen

U.S. Army TARDEC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX

for
Allen S. Comfort
U.S. Army TARDEC
Force Projection Technology
Warren, Michigan

Contract No. W56HZV-15-C-0030 (WD013)

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U.S. Army TARDEC Fuels and Lubricants
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14. ABSTRACT The U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC) continued work and testing on the stationary axle efficiency test stand to determine the effect of Fuel Efficient Gear Oils (FEGO) on vehicle fuel economy. A Federal Test Method (FTM) was finalized and fifteen candidate tests were performed, following the finalized FTM procedure. The FTM procedure results show good differentiation in efficiency between different axle lubricants of similar viscosities. The reference runs show consistent, repeatable results. The low torque conditions of the efficiency tests show the greatest amount of efficiency improvement. The low viscosity fluids showed the greatest overall efficiency values, suggesting that fuel economy would increase with decreased lubricant viscosity.		
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EXECUTIVE SUMMARY

The U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC) desires to increase the fuel economy of its ground vehicle fleet and has designed a stationary axle efficiency test stand to determine the efficiency of Fuel Efficient Gear Oils (FEGO). A Federal Test Method (FTM) procedure was developed and finalized. A total of fifteen candidate tests were completed to prove out the FTM procedure. The following goals were developed:

- Provide a lower cost alternative for evaluating gear lubricant efficiency as compared to full scale vehicle testing.
- Finalize a standardized Federal Test Method (FTM) to be used for future product qualification.
- Provide improved testing accuracy and precision to discriminate between similar gear oils, with a special focus on similar viscosity oils and different additive packages.
- Develop a numerical calculation and weighting system to apply to the FTM procedure to predict fuel economy improvements from gear lubricants.

The stationary axle stand test protocol development was completed. The DAQ system was improved and the stand was converted to allow for a fixed axle temperature versus a fixed cooling rate. The FTM procedure was modified to adjust the fixed axle temperature at the low power conditions to 140 °F, instead of 175 °F. The FTM procedure was finalized.

A total of fifteen tests were conducted to analyze the finalized FTM procedure. Two different oil viscosities were tested. The testing showed good differentiation in efficiency between the reference oils and the candidate fluids of similar viscosities. The testing also showed repeatability between different reference test runs. The low torque conditions showed the greatest amount of efficiency improvement in the efficiency test cycle. The low viscosity fluids showed the greatest overall efficiency values, suggesting that fuel economy would increase with decreased lubricant viscosity. Different weighting systems were developed to determine a single numerical value for each fluid in an attempt to predict the vehicle efficiency improvements of each candidate fluid over the reference fluids.

FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period June 2017 through December 2018 under Contract No. W56HZV-15-C-0030. The U.S. Army Tank Automotive RD&E Center, Force Projection Technology, Warren, Michigan administered the project. Mr. Eric Sattler (RDTA-SIE-ES-FPT) served as the TARDEC contracting officer's technical representative. Mr. Allen Comfort of TARDEC served as project technical monitor.

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ACRONYMS AND ABBREVIATIONS

°C – degrees Celsius

°F – degrees Fahrenheit

FEGO – Fuel Efficient Gear Oil

FMTV – Family of Medium Tactical Vehicle

FTM – Federal Test Method

GPM – Gallons Per Minute

HET – Heavy Equipment Transporter

HMMWV – High Mobility Multipurpose Wheeled Vehicle

Hz - hertz

kHz - kilohertz

kph – kilometer per hour

ft-lb – pound feet

mph – miles per hour

MTV – Medium Tactical Vehicle

Nm – newton meter

OMS/MP – Operational Mode Summary/Mission Profile

rpm – revolutions per minute

sec - seconds

SwRI – Southwest Research Institute

TARDEC – Tank Automotive Research Development and Engineering Center

TFLRF – TARDEC Fuels and Lubricants Research Facility

kNm – kilo newton meter

DAQ – Data Acquisition

hp – horse power

1.0 BACKGROUND AND OBJECTIVES

The U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC) desires to increase the fuel economy of its ground vehicle fleet and has designed a stationary axle test stand to investigate the impact of Fuel Efficient Gear Oils (FEGO) on overall vehicle efficiencies. TARDEC designed and constructed the test stand at the U.S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI) in San Antonio, Texas. The following goals were developed:

- Provide a lower cost alternative for evaluating gear lubricant efficiency as compared to full scale vehicle testing.
- Finalize a standardized Federal Test Method (FTM) to be used for future product qualification.
- Provide improved testing accuracy and precision to discriminate between similar gear oils, with a special focus on similar viscosity oils and different additive packages.
- Develop a numerical calculation and weighting system to apply to the FTM procedure to predict fuel economy improvements from gear lubricants.

This report covers the progression of the stationary axle test stand process refinement, the completion of the FTM procedure, and the candidate efficiency testing that was conducted using the MTV axle. Previous work was reported under TFLRF Interim Report No. 484 (AD1039630).

2.0 STATIONARY AXLE STAND PROCESS REFINEMENT

Continuing from work completed in IR 484, critical variables of the stationary axle stand were investigated and analyzed in order to improve on the repeatability of the efficiency testing. The variables that were examined included the oil formulation, axle operating conditions, temperature control strategy, data acquisition (DAQ) control system, and torque and speed measurements.

As described in IR 484, the DAQ control system and temperature control strategy were both modified. The DAQ system adjustments included increasing the gate time to 0.5 seconds, which increased the resolution for the torque measurements. Digital low-pass filters were also applied to the input/output speed and torque measurements to reduce any signal noise. Both of these changes showed an improvement in the repeatability of the efficiency results and are reflected in the FTM procedure.

The temperature control strategy was also modified. The control method was changed from a fixed cooling rate, which was designed to replicate real-world operation, to a fixed axle oil temperature. A fixed axle oil temperature allows for a direct comparison between two fluids, as well as increased repeatability and precision of the test method.

The axle operating conditions and the oil formulations were examined using the fifteen tests conducted following the finalized FTM procedure. The oil formulations in the test matrix included fluids of differing viscosities and additive packages.

3.0 FEDERAL TEST METHOD COMPLETION

At the completion of WD 33 (W56HZV-09-C-0100), a draft FTM procedure was developed. The FTM was refined and updated prior to testing candidate fluids. The major change made to the FTM procedure was a change in the axle differential oil temperature set point for four of the ten steps in the efficiency test procedure.

The previous FTM draft procedure operated all ten of the efficiency steps at an axle differential oil temperature of 175 °F. After investigation of the temperature controllability and operation, and due to stand limitations, the temperature set point for the low power steps were adjusted. For the low power steps, the temperature set point was changed to 140 °F. The temperature set point for the other steps in the efficiency procedure remained at 175 °F. The speed, load, and temperature test conditions for each step are listed in Table 1. This procedure is also outlined in the finalized FTM procedure (Method xxx). The finalized FTM procedure can be found in the Appendix B.

Table 1. Federal Test Method Speed & Load Points

Step	Step Name	Nominal Speed [mph]	Pinion Speed [rpm]	Pinion Load [ft-lb]	Axle Input Power [hp]	Axle Differential Fluid Temperature [°F]
1	FTM_25_450r	25	1469	450	126	175
2	FTM_35_250r	35	2100	250	100	175
3	FTM_25_325r	25	1469	325	91	175
4	FTM_45_175r	45	2600	175	87	175
5	FTM_15_400r	15	865	400	66	175
6	FTM_55_104r	55	3207	104	64	175
7	FTM_35_67r	35	2100	67	27	140
8	FTM_25_54r	25	1469	54	15	140
9	FTM_15_45r	15	865	45	7.5	140
10	FTM_5_80r	5	294	80	4.5	140

4.0 CANDIDATE AXLE OIL EFFICIENCY TESTING

After the completion of the finalized FTM procedure, a total of fifteen efficiency tests were conducted, including two baseline fluids and six candidate fluids. The finalized FTM test procedure was used for each efficiency test run. Table 2 shows the run order of the baseline and candidate fluids used for the testing matrix.

Table 2. Efficiency Test Matrix

Run Order	Fluid Code	Lab Oil Code	Viscosity
1	Baseline 80W90	LO 330868	80W90
2	FEGO Candidate 75W90 (LZ)	LO 332220	75W90
3	Baseline 80W90	LO 330868	80W90
4	Afton 75W90	LO 310411	75W90
5	Baseline 80W90	LO 330868	80W90
6	BASF XFE 75W85	LO 351433	75W85
7	Baseline 80W90	LO 330868	80W90
8	BASF XFE 75W90	LO 351434	75W90
9	Baseline 80W90	LO 330868	80W90
10	Baseline 85W140	LO 364270	85W140
11	FEGO Candidate 75W140 (LZ)	LO 332374	75W140
12	Baseline 85W140	LO 364270	85W140
13	BASF XFE 75W110	LO 351656	75W110
14	Baseline 85W140	LO 364270	85W140
15	Baseline 80W90	LO 330868	80W90

A total of five runs were completed for each fluid. A table of test results was compiled and the mean, standard deviation, and variance (of the five test runs) were calculated for each fluid. Each candidate test was compared to a baseline test. The baseline test was always completed before the candidate test. For the comparisons, an F-test was first conducted to determine if the baseline and candidate tests had equal variances. Next, a T-test was conducted to determine the statistical significance of the difference in means of the baseline and candidate tests. The results of the F-test determined which T-test should be used.

Tables (3, 5, 7, 9, 11, 13) show the results of the candidate fluid over the baseline fluid. The columns in the aforementioned tables show the estimated efficiency improvement (or reduction in efficiency if negative) of the candidate over the baseline fluid, along with the 95% confidence interval. Tables (4, 6, 8, 10, 12, 14) show whether or not there is a statistical difference between the two fluids tested (determined by the T-test).

The plots associated with each table that show a graphical representation of the efficiency improvement of the candidate fluid over the baseline fluid are included in Appendix A of the report.

After the completion of each candidate fluid test, an additional single baseline run was completed. The baseline run was compared to the five pre-baseline runs in order to determine the validity of the candidate test. For a candidate test to be considered valid, the post-reference test run had to return a result that was statistically equivalent to the five pre-reference test runs. A repeatability range was calculated based on the standard deviation of the five pre-reference runs. If the post-reference test fell within the repeatability range, the candidate test was considered valid. A result of "No" in the "Statistical Difference Between Oils" column (Tables 4, 6, 8, 10, 12, 14) proved that the post-reference test fell within the repeatability range as calculated by the five pre-reference runs. The repeatability range was calculated for each step. If ≥ 50% of the steps resulted in "No", the candidate test was considered valid.

It should be noted that although the repeatability tests showed that all of the post-reference tests were statistically equivalent to the pre-references tests for the fluids tested in the matrix, a higher level of uncertainty is associated with running only one post-reference test. A repeatability range was also calculated for each step. Depending on the test conditions and the standard deviations for certain steps, this method may result in unfavorable results. Also, if the test stand hardware or instrumentation drifts over time in any direction, performing only one post-reference test may result in a falsely failed candidate test. This method does not take into account any natural drift in the stand and does not account for any test steps that may produce a very low standard deviation due to the test operating conditions.

The results of the post-reference test compared to the pre-reference tests to determine validity are shown in the tables following the candidate test results.

Table 3. Efficiency Improvement of Candidate LO332220 (75W90)

		Step #	Statistical Difference Between Oils	Estimated Efficiency Change	95% Confidence Interval
LO332220	Candidate Improvement Over Baseline	FTM_25_450r	Yes	0.549%	± 0.014%
		FTM_35_250r	Yes	0.582%	± 0.029%
		FTM_25_325r	Yes	0.582%	± 0.023%
		FTM_45_175r	Yes	0.578%	± 0.065%
		FTM_15_400r	Yes	0.551%	± 0.017%
		FTM_55_104r	Yes	0.625%	± 0.125%
		FTM_35_67r	Yes	1.012%	± 0.197%
		FTM_25_54r	Yes	1.149%	± 0.186%
		FTM_15_45r	Yes	1.018%	± 0.144%
		FTM_5_80r	Yes	0.875%	± 0.101%

Table 4. Post-Reference Validity Check LO332220 (75W90)

Step #	Statistical Difference Between Oils
FTM_25_450r	NO
FTM_35_250r	NO
FTM_25_325r	NO
FTM_45_175r	NO
FTM_15_400r	NO
FTM_55_104r	NO
FTM_35_67r	NO
FTM_25_54r	NO
FTM_15_45r	NO
FTM_5_80r	NO

Candidate test LO332220 is considered valid based on the reference validity check results.

Table 5. Efficiency Improvement of Candidate LO310411 (75W90)

		Step #	Statistical Difference Between Oils	Estimated Efficiency Change	95% Confidence Interval
LO310411	Candidate Improvement Over Baseline	FTM_25_450r	Yes	0.546%	± 0.019%
		FTM_35_250r	Yes	0.637%	± 0.031%
		FTM_25_325r	Yes	0.618%	± 0.027%
		FTM_45_175r	Yes	0.646%	± 0.041%
		FTM_15_400r	Yes	0.568%	± 0.019%
		FTM_55_104r	Yes	0.679%	± 0.059%
		FTM_35_67r	Yes	1.118%	± 0.096%
		FTM_25_54r	Yes	1.188%	± 0.092%
		FTM_15_45r	Yes	1.070%	± 0.096%
		FTM_5_80r	Yes	0.901%	± 0.063%

Table 6. Post-Reference Validity Check LO310411 (75W90)

Step #	Statistical Difference Between Oils
FTM_25_450r	YES
FTM_35_250r	YES
FTM_25_325r	YES
FTM_45_175r	NO
FTM_15_400r	NO
FTM_55_104r	YES
FTM_35_67r	NO
FTM_25_54r	YES
FTM_15_45r	NO
FTM_5_80r	NO

Candidate test LO310411 is considered valid based on the reference validity check results.

Table 7. Efficiency Improvement of Candidate LO351433 (75W85)

		Step #	Statistical Difference Between Oils	Estimated Efficiency Change	95% Confidence Interval
LO351433	Candidate Improvement Over Baseline	FTM_25_450r	Yes	0.556%	± 0.012%
		FTM_35_250r	Yes	0.658%	± 0.015%
		FTM_25_325r	Yes	0.636%	± 0.011%
		FTM_45_175r	Yes	0.654%	± 0.024%
		FTM_15_400r	Yes	0.579%	± 0.013%
		FTM_55_104r	Yes	0.742%	± 0.053%
		FTM_35_67r	Yes	1.260%	± 0.052%
		FTM_25_54r	Yes	1.503%	± 0.075%
		FTM_15_45r	Yes	1.424%	± 0.074%
		FTM_5_80r	Yes	1.092%	± 0.051%

Table 8. Post Reference Validity Check LO351433 (75W85)

Step #	Statistical Difference Between Oils
FTM_25_450r	NO
FTM_35_250r	NO
FTM_25_325r	NO
FTM_45_175r	NO
FTM_15_400r	NO
FTM_55_104r	YES
FTM_35_67r	YES
FTM_25_54r	YES
FTM_15_45r	NO
FTM_5_80r	YES

Candidate test LO351433 is considered valid based on the reference test validity results.

Table 9. Efficiency Improvement of Candidate LO351434 (75W90)

		Step #	Statistical Difference Between Oils	Estimated Efficiency Change	95% Confidence Interval
LO351434	Candidate Improvement Over Baseline	FTM_25_450r	Yes	0.540%	± 0.015%
		FTM_35_250r	Yes	0.540%	± 0.020%
		FTM_25_325r	Yes	0.582%	± 0.025%
		FTM_45_175r	Yes	0.442%	± 0.030%
		FTM_15_400r	Yes	0.583%	± 0.017%
		FTM_55_104r	Yes	0.253%	± 0.041%
		FTM_35_67r	Yes	0.629%	± 0.058%
		FTM_25_54r	Yes	0.947%	± 0.040%
		FTM_15_45r	Yes	1.017%	± 0.049%
		FTM_5_80r	Yes	0.924%	± 0.048%

Table 10. Post-Reference Validity Check LO351434 (75W90)

Step #	Statistical Difference Between Oils
FTM_25_450r	NO
FTM_35_250r	NO
FTM_25_325r	NO
FTM_45_175r	NO
FTM_15_400r	YES
FTM_55_104r	NO
FTM_35_67r	YES
FTM_25_54r	YES
FTM_15_45r	NO
FTM_5_80r	YES

Candidate test LO351434 is considered valid based on the reference test validity results.

Table 11. Efficiency Improvement of Candidate LO332374 (75W140)

		Step #	Statistical Difference Between Oils	Estimated Efficiency Change	95% Confidence Interval
LO332374	Candidate Improvement Over Baseline	FTM_25_450r	Yes	0.714%	± 0.023%
		FTM_35_250r	Yes	0.705%	± 0.031%
		FTM_25_325r	Yes	0.760%	± 0.032%
		FTM_45_175r	Yes	0.647%	± 0.077%
		FTM_15_400r	Yes	0.796%	± 0.028%
		FTM_55_104r	Yes	0.748%	± 0.177%
		FTM_35_67r	Yes	1.424%	± 0.208%
		FTM_25_54r	Yes	1.694%	± 0.257%
		FTM_15_45r	Yes	1.786%	± 0.140%
		FTM_5_80r	Yes	1.320%	± 0.070%

Table 12. Post-Reference Validity Check LO332374 (75W140)

Step #	Statistical Difference Between Oils
FTM_25_450r	NO
FTM_35_250r	NO
FTM_25_325r	NO
FTM_45_175r	NO
FTM_15_400r	NO
FTM_55_104r	NO
FTM_35_67r	NO
FTM_25_54r	NO
FTM_15_45r	NO
FTM_5_80r	NO

Candidate test LO332374 is considered valid based on the reference test validity results.

Table 13. Efficiency Improvement of Candidate LO351656 (75W110)

		Step #	Statistical Difference Between Oils	Estimated Efficiency Change	95% Confidence Interval
LO351656	Candidate Improvement Over Baseline	FTM_25_450r	Yes	0.678%	± 0.013%
		FTM_35_250r	Yes	0.785%	± 0.009%
		FTM_25_325r	Yes	0.755%	± 0.014%
		FTM_45_175r	Yes	0.863%	± 0.021%
		FTM_15_400r	Yes	0.676%	± 0.017%
		FTM_55_104r	Yes	1.054%	± 0.039%
		FTM_35_67r	Yes	2.017%	± 0.054%
		FTM_25_54r	Yes	2.388%	± 0.058%
		FTM_15_45r	Yes	2.374%	± 0.092%
		FTM_5_80r	Yes	1.303%	± 0.048%

Table 14. Post-Reference Validity Check LO351656 (75W110)

Step #	Statistical Difference Between Oils
FTM_25_450r	NO
FTM_35_250r	YES
FTM_25_325r	NO
FTM_45_175r	NO
FTM_15_400r	YES
FTM_55_104r	NO
FTM_35_67r	NO
FTM_25_54r	NO
FTM_15_45r	NO
FTM_5_80r	NO

Candidate test LO351656 is considered valid based on the reference test validity results.

At the completion of all candidate and baseline tests, one additional baseline 80W90 test was run. This test was compared to the initial 80W90 reference tests to determine if any changes were present in the stand. The repeatability results show that all steps in the post-reference test were within the repeatability limits of the first 80W90 reference test sequence. These results demonstrate that there is repeatability between the baseline oils, even over an extended period of time, and after many different fluid tests were conducted on the same hardware set.

Table 15. Post-Reference Validity Check Baseline 80W90

Step #	Statistical Difference Between Oils
FTM_25_450r	NO
FTM_35_250r	NO
FTM_25_325r	NO
FTM_45_175r	NO
FTM_15_400r	NO
FTM_55_104r	NO
FTM_35_67r	NO
FTM_25_54r	NO
FTM_15_45r	NO
FTM_5_80r	NO

Based on the results of the test matrix, each candidate fluid showed a statistical difference in comparison to the baseline fluid, and each candidate showed a positive efficiency improvement over the baseline. The high viscosity oils (75W140 and 75W110) showed a greater improvement over the high viscosity baseline fluid (85W140), especially at the low torque conditions. Comparisons of the lower viscosity fluids (75W90 and 75W85) also showed that the efficiency improvement was larger at the low torque conditions as compared to the higher torque conditions. These results show that there is good differentiation in efficiency between different axle lubricants because of the clear differentiation between reference and candidate test fluids.

Figures 1 and 2 show the shift of each baseline fluid over time for every test procedure power step. Figure 1 shows the baseline 80W90 fluid. In general, each step demonstrates a flat efficiency trend. Baseline run #4 shows that the efficiency increased slightly for most steps, especially the lower power condition steps (steps 6, 7, and 8). For run #5 and run #6, the baseline efficiency dropped back down to match the first three baseline runs. Although the efficiency value for each step increased for baseline run #4, the test was still considered within repeatability limits as compared to the previous baseline run #3. Figure 2 shows the baseline 85W140 fluid. Only three runs were conducted with this fluid, but the results show that the baseline testing for this fluid was also steady over time.

Over the course of this program, the baseline fluids tracked well with one another, which is critical to the repeatability of this efficiency testing. Even with a minor efficiency change, each baseline run remained within the repeatability limits of the test.

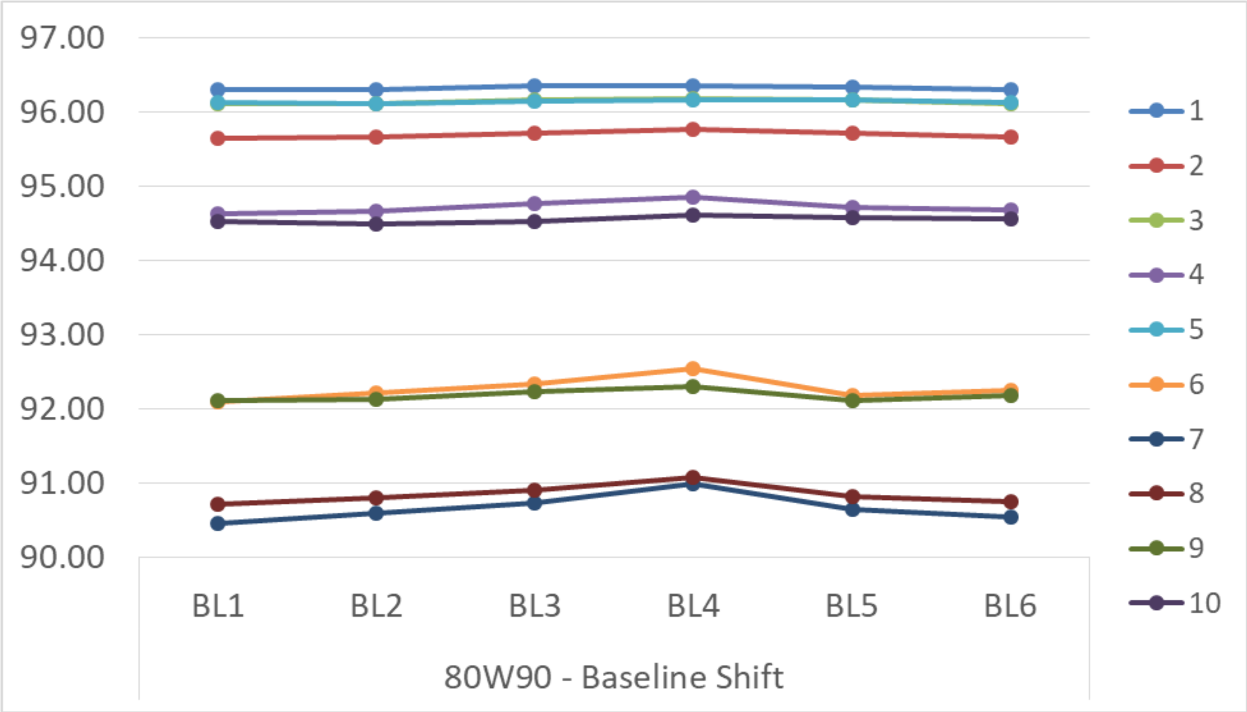

Figure 1. 80W90 Baseline LO330868 Shift

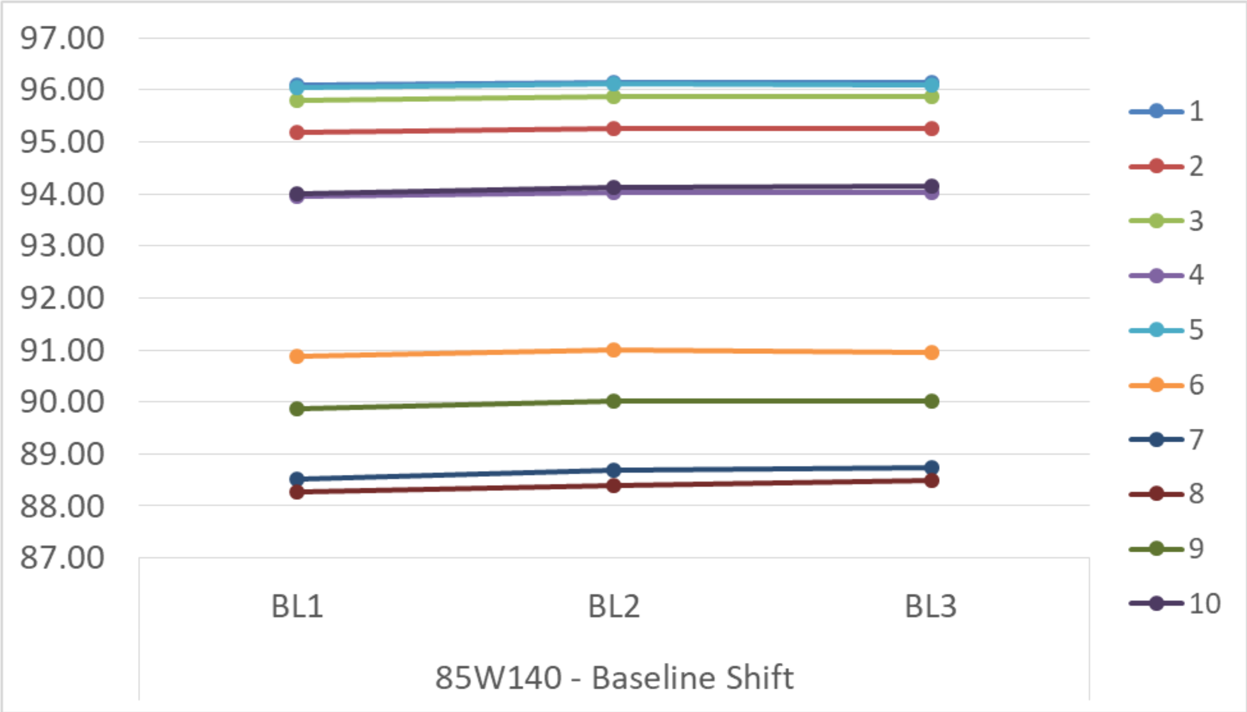

Figure 2. 85W140 Baseline LO364270 Shift

At the conclusion of the testing, different weighting systems were studied to determine the best way to calculate the overall efficiency gain/loss of the candidate fluid over the baseline fluid. Three different weighting systems were developed: a system based on a HMMWV (light duty) vehicle data set, a system based on a HET (heavy duty) vehicle data set, and an even weighting/straight average system. The HMMWV and HET weighting systems were calibrated from the results of SAE J1321 testing completed at SwRI.

Each weighting system was used to develop one numerical result that can demonstrate the efficiency difference of the candidate fluid over the baseline fluid. The HMMWV and HET weighting systems used a different weight for each step, based on the operating conditions established in the SAE J1321 testing on each of those vehicles. The weights for each step are listed in Table 16.

Table 17 shows the total efficiency value for each fluid and for each weighting system. The table also shows the percent efficiency increase over the candidate fluid with its associated reference fluid test. Overall, the even weighting system consistently showed the greatest differentiation between the candidate and reference fluids, while the HMMWV weighting system consistently showed the lowest differentiation between the candidate fluid and reference fluid. All 3 weighting systems gave the same ranking of the fluids performance.

Although the weighting systems provide a single numerical result for each fluid tested, attention to the development of the systems should be taken into consideration. Each system was developed using real-world SAE J1321 data from a HMMWV and HET. The axle used for the efficiency bench testing is from a MTV. The single numerical result generated with the HMMWV, HET, or even weighting systems may not directly correlate to results seen in a SAE J1321 test using a MTV.

The efficiency test procedure, as stated in the FTM procedure, was partially developed using MTV vehicle testing and benchmarking results. Results from a SAE J1321 test using a MTV and a drive cycle closely related to the efficiency test procedure as listed in the FTM procedure would be ideal in order to directly relate the results from the bench efficiency test procedure to a real-world application. These real-world results would be critical in developing an accurate weighting system for the FTM procedure.

Table 16. Weighting Systems Overview

Step	HMMWV Weighting	HET Weighting	Even Weighting
1	14.48%	10.25%	10%
2	27.15%	19.23%	10%
3	14.48%	10.25%	10%
4	7.26%	12.34%	10%
5	14.48%	10.26%	10%
6	4.12%	7.01%	10%
7	0.89%	1.51%	10%
8	11.91%	20.25%	10%
9	1.66%	2.83%	10%
10	3.57%	6.07%	10%
Total	100.00%	100.00%	100.00%

Table 17. Numerical Results for Weighting Systems

			Even Weighting		HMMWV Weighting		HET Weighting	
Run Number	Oil Code	Viscosity	Efficiency (%)	% Eff Increase	Efficiency (%)	% Eff Increase	Efficiency (%)	% Eff Increase
1	LO330868	80W90	93.870		94.924		94.188	
2	LO332220	75W90	94.622	0.801	95.587	0.699	94.918	0.774
3	LO330868	80W90	93.906		94.942		94.221	
4	LO310411	75W90	94.703	0.849	95.642	0.737	94.991	0.817
5	LO330868	80W90	93.985		95.007		94.295	
6	LO351433	75W85	94.895	0.969	95.773	0.806	95.166	0.924
7	LO330868	80W90	94.082		95.066		94.379	
8	LO351434	75W90	94.728	0.686	95.671	0.636	95.016	0.675
9	LO330868	80W90	93.937		94.980		94.253	
10	LO364270	85W140	92.862		94.252		93.253	
11	LO332374	75W140	93.922	1.141	95.141	0.943	94.249	1.068
12	LO364270	85W140	92.961		94.327		93.339	
13	LO351656	75W110	94.251	1.387	95.340	1.074	94.547	1.294
14	LO364270	85W140	92.978		94.340		93.361	
15	LO330868	80W90	93.916		94.947		94.224	

5.0 RESULTS AND CONCLUSIONS

- The stationary axle efficiency stand set-up was completed. The FTM procedure was finalized, which provides a good measure of axle efficiency. The FTM procedure testing matrix showed good differentiation in efficiency between different axle lubricants. Reference runs showed consistent, repeatable results. Each candidate run showed clear differentiation between the associated reference runs.
- The testing that followed the FTM procedure development showed the largest improvement in efficiency at the low torque conditions. The higher viscosity oils showed the largest efficiency improvement (as compared with each respective baseline fluid), especially at the low torque conditions.
- The lower viscosity oils show the highest axle efficiency values. Low viscosity oils are expected to provide the highest level of fuel economy improvement in vehicle testing.
- The axle did appear to continually shift in total efficiency as the testing progressed. A repeatability study was conducted on all pre-reference tests and compared with the post-reference test to determine if the candidate test was valid. Each candidate test conducted in the matrix was deemed valid based on the repeatability validity studies of the pre and post reference test results. The repeatability study should be statistically reviewed to determine if it will account for all shifts in reference test efficiencies over time.
- Three numerical weighting systems were developed and applied to the results of the fifteen efficiency tests performed. The weighting systems each calculated a single numerical efficiency result for every fluid. The results showed that each candidate fluid showed a greater efficiency in comparison to the reference fluid results. None of the weighting systems were derived from an SAE J1321 with an MTV, but instead from SAE J1321 data with an HMMWV and a HET. The axle used in the efficiency testing was an MTV axle, therefore the results from the weighting systems may not directly correlate to real-world results.

6.0 RECOMMENDATIONS

- Determine which weighting system to apply to the FTM procedure or determine if a new weighting system should be used that directly relates to the MTV axle.
- The finalized FTM procedure uses a temperature set point for each operating condition. In real-world operation, axle fluid is not held at a constant fixed temperature. Future work should include investigating the impact of a fixed cooling rate versus a fixed axle temperature and how the temperature of real-world operation of axle fluids impacts the rankings of the efficiency results from a fixed axle temperature stationary stand.
- Determine if the repeatability range for pre-reference and post-reference testing is the best way to determine the validity of the candidate testing. One post-reference test may provide a higher amount of uncertainty in determining the validity of previous tests. The number of steps that must fall within the repeatability to determine if a post-reference is acceptable should also be investigated. If one numerical result can be calculated from a total of five runs, the repeatability range could be adjusted to encompass all ten steps in a run with a single numerical result versus comparing each step individually.

7.0 REFERENCES

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APPENDIX A. TEST RESULTS

Table A-1. Run 1 Results

LO330868					
	Run 1	Run 2	Run 3	Run 4	Run 5
FTM_25_450r	96.307	96.283	96.289	96.290	96.298
FTM_35_250r	95.654	95.607	95.654	95.650	95.669
FTM_25_325r	96.124	96.087	96.117	96.112	96.128
FTM_45_175r	94.624	94.554	94.623	94.634	94.668
FTM_15_400r	96.149	96.126	96.120	96.115	96.131
FTM_55_104r	92.073	91.986	92.142	92.123	92.181
FTM_35_67r	90.360	90.249	90.544	90.527	90.620
FTM_25_54r	90.654	90.507	90.819	90.738	90.827
FTM_15_45r	92.123	91.978	92.105	92.080	92.231
FTM_5_80r	94.643	94.507	94.463	94.433	94.575

Table A-2. Run 2 Results

LO332220					
	Run 1	Run 2	Run 3	Run 4	Run 5
FTM_25_450r	96.838	96.827	96.845	96.849	96.854
FTM_35_250r	96.236	96.202	96.230	96.242	96.234
FTM_25_325r	96.698	96.671	96.696	96.708	96.705
FTM_45_175r	95.199	95.125	95.195	95.245	95.232
FTM_15_400r	96.688	96.666	96.674	96.685	96.681
FTM_55_104r	92.738	92.572	92.717	92.817	92.787
FTM_35_67r	91.553	91.291	91.420	91.557	91.540
FTM_25_54r	91.985	91.674	91.802	91.925	91.905
FTM_15_45r	93.277	92.993	93.063	93.148	93.122
FTM_5_80r	95.471	95.412	95.363	95.348	95.401

Table A-3. Run 3 Results

LO330868					
	Run 1	Run 2	Run 3	Run 4	Run 5
FTM_25_450r	96.302	96.306	96.298	96.275	96.299
FTM_35_250r	95.662	95.657	95.670	95.640	95.654
FTM_25_325r	96.117	96.106	96.112	96.079	96.099
FTM_45_175r	94.696	94.676	94.678	94.639	94.658
FTM_15_400r	96.114	96.106	96.118	96.103	96.105
FTM_55_104r	92.257	92.263	92.217	92.188	92.191
FTM_35_67r	90.645	90.644	90.575	90.535	90.551
FTM_25_54r	90.843	90.845	90.819	90.726	90.770
FTM_15_45r	92.092	92.162	92.151	92.097	92.106
FTM_5_80r	94.472	94.479	94.537	94.460	94.482

Table A-4. Run 4 Results

LO310411					
	Run 1	Run 2	Run 3	Run 4	Run 5
FTM_25_450r	96.822	96.835	96.843	96.857	96.851
FTM_35_250r	96.251	96.281	96.300	96.318	96.317
FTM_25_325r	96.688	96.712	96.727	96.740	96.739
FTM_45_175r	95.260	95.306	95.333	95.340	95.339
FTM_15_400r	96.648	96.676	96.689	96.691	96.684
FTM_55_104r	92.829	92.891	92.938	92.933	92.918
FTM_35_67r	91.594	91.674	91.718	91.775	91.777
FTM_25_54r	91.872	91.984	91.993	92.038	92.059
FTM_15_45r	93.050	93.185	93.222	93.288	93.212
FTM_5_80r	95.294	95.396	95.407	95.428	95.413

Table A-5. Run 5 Results

LO330868					
	Run 1	Run 2	Run 3	Run 4	Run 5
FTM_25_450r	96.342	96.338	96.339	96.349	96.361
FTM_35_250r	95.732	95.709	95.705	95.705	95.707
FTM_25_325r	96.176	96.161	96.161	96.158	96.161
FTM_45_175r	94.776	94.755	94.750	94.748	94.755
FTM_15_400r	96.153	96.152	96.142	96.134	96.145
FTM_55_104r	92.358	92.329	92.338	92.301	92.357
FTM_35_67r	90.793	90.710	90.709	90.674	90.757
FTM_25_54r	90.999	90.897	90.878	90.844	90.948
FTM_15_45r	92.316	92.243	92.198	92.135	92.246
FTM_5_80r	94.562	94.519	94.513	94.468	94.540

Table A-6. Run 6 Results

LO351433					
	Run 1	Run 2	Run 3	Run 4	Run 5
FTM_25_450r	96.896	96.903	96.902	96.911	96.895
FTM_35_250r	96.370	96.382	96.377	96.363	96.359
FTM_25_325r	96.797	96.810	96.805	96.799	96.788
FTM_45_175r	95.430	95.434	95.402	95.388	95.399
FTM_15_400r	96.712	96.729	96.732	96.734	96.717
FTM_55_104r	93.113	93.135	93.078	93.037	93.029
FTM_35_67r	91.995	91.999	92.010	91.980	91.960
FTM_25_54r	92.418	92.411	92.444	92.407	92.399
FTM_15_45r	93.633	93.655	93.691	93.654	93.623
FTM_5_80r	95.555	95.605	95.646	95.634	95.622

Table A-7. Run 7 Results

LO330868					
	Run 1	Run 2	Run 3	Run 4	Run 5
FTM_25_450r	96.345	96.337	96.342	96.346	96.356
FTM_35_250r	95.772	95.755	95.758	95.757	95.755
FTM_25_325r	96.182	96.172	96.184	96.177	96.175
FTM_45_175r	94.842	94.848	94.850	94.846	94.841
FTM_15_400r	96.172	96.158	96.167	96.159	96.160
FTM_55_104r	92.508	92.553	92.542	92.552	92.559
FTM_35_67r	90.996	90.986	90.983	90.994	90.989
FTM_25_54r	91.103	91.070	91.070	91.090	91.074
FTM_15_45r	92.358	92.258	92.294	92.318	92.317
FTM_5_80r	94.579	94.600	94.631	94.608	94.626

Table A-8. Run 8 Results

LO351434					
	Run 1	Run 2	Run 3	Run 4	Run 5
FTM_25_450r	96.863	96.891	96.894	96.891	96.887
FTM_35_250r	96.269	96.315	96.303	96.307	96.302
FTM_25_325r	96.724	96.773	96.769	96.771	96.765
FTM_45_175r	95.246	95.305	95.288	95.301	95.296
FTM_15_400r	96.720	96.751	96.753	96.756	96.752
FTM_55_104r	92.742	92.801	92.799	92.836	92.803
FTM_35_67r	91.567	91.690	91.638	91.607	91.593
FTM_25_54r	91.991	92.082	92.047	92.004	92.018
FTM_15_45r	93.315	93.364	93.352	93.298	93.300
FTM_5_80r	95.484	95.566	95.584	95.528	95.503

Table A-9. Run 9 Results

LO330868					
	Run 1	Run 2	Run 3	Run 4	Run 5
FTM_25_450r	96.342	96.338	96.333	96.320	96.313
FTM_35_250r	95.738	95.737	95.723	95.672	95.662
FTM_25_325r	96.176	96.175	96.163	96.129	96.115
FTM_45_175r	94.751	94.766	94.751	94.638	94.624
FTM_15_400r	96.176	96.172	96.165	96.148	96.125
FTM_55_104r	92.255	92.275	92.253	92.041	92.055
FTM_35_67r	90.750	90.822	90.789	90.482	90.377
FTM_25_54r	90.990	91.010	90.959	90.597	90.508
FTM_15_45r	92.347	92.276	92.237	91.835	91.824
FTM_5_80r	94.580	94.615	94.602	94.468	94.638

Table A-10. Run 10 Results

LO364270					
	Run 1	Run 2	Run 3	Run 4	Run 5
FTM_25_450r	96.060	96.110	96.101	96.092	96.099
FTM_35_250r	95.148	95.215	95.200	95.193	95.195
FTM_25_325r	95.754	95.831	95.817	95.805	95.805
FTM_45_175r	93.844	93.999	93.975	93.974	93.979
FTM_15_400r	96.016	96.075	96.059	96.044	96.046
FTM_55_104r	90.622	90.967	90.942	90.902	90.944
FTM_35_67r	88.229	88.658	88.592	88.481	88.595
FTM_25_54r	87.920	88.473	88.366	88.255	88.327
FTM_15_45r	89.694	90.011	89.940	89.864	89.892
FTM_5_80r	93.994	94.091	94.032	93.947	93.946

Table A-11. Run 11 Results

LO332374					
	Run 1	Run 2	Run 3	Run 4	Run 5
FTM_25_450r	96.788	96.807	96.806	96.812	96.817
FTM_35_250r	95.886	95.898	95.896	95.894	95.900
FTM_25_325r	96.544	96.562	96.560	96.569	96.574
FTM_45_175r	94.583	94.596	94.585	94.613	94.626
FTM_15_400r	96.821	96.843	96.839	96.856	96.862
FTM_55_104r	91.603	91.617	91.606	91.652	91.642
FTM_35_67r	89.863	89.974	89.982	89.926	89.928
FTM_25_54r	89.935	89.876	90.039	89.958	90.002
FTM_15_45r	91.728	91.589	91.600	91.688	91.723
FTM_5_80r	95.338	95.290	95.293	95.338	95.352

Table A-12. Run 12 Results

LO364270					
	Run 1	Run 2	Run 3	Run 4	Run 5
FTM_25_450r	96.150	96.144	96.136	96.143	96.131
FTM_35_250r	95.250	95.242	95.247	95.259	95.247
FTM_25_325r	95.879	95.864	95.863	95.876	95.862
FTM_45_175r	94.009	93.998	94.017	94.039	94.020
FTM_15_400r	96.131	96.118	96.109	96.114	96.108
FTM_55_104r	90.954	90.981	91.002	91.023	91.015
FTM_35_67r	88.659	88.642	88.677	88.740	88.679
FTM_25_54r	88.427	88.347	88.370	88.407	88.406
FTM_15_45r	90.099	90.003	89.971	90.011	90.017
FTM_5_80r	94.201	94.141	94.087	94.124	94.137

Table A-13. Run 13 Results

LO351656					
	Run 1	Run 2	Run 3	Run 4	Run 5
FTM_25_450r	96.800	96.818	96.824	96.823	96.827
FTM_35_250r	96.029	96.042	96.034	96.029	96.036
FTM_25_325r	96.604	96.626	96.630	96.624	96.632
FTM_45_175r	94.880	94.899	94.886	94.871	94.863
FTM_15_400r	96.767	96.792	96.798	96.801	96.800
FTM_55_104r	92.077	92.070	92.049	92.020	92.028
FTM_35_67r	90.750	90.720	90.677	90.673	90.662
FTM_25_54r	90.845	90.807	90.758	90.760	90.728
FTM_15_45r	92.502	92.426	92.392	92.344	92.308
FTM_5_80r	95.433	95.463	95.460	95.440	95.410

Table A-14. Run 14 Results

LO364270					
	Run 1	Run 2	Run 3	Run 4	Run 5
FTM_25_450r	96.147	96.119	96.135	96.141	96.137
FTM_35_250r	95.265	95.243	95.263	95.259	95.262
FTM_25_325r	95.885	95.856	95.868	95.873	95.866
FTM_45_175r	94.045	94.020	94.052	94.043	94.038
FTM_15_400r	96.126	96.091	96.102	96.101	96.097
FTM_55_104r	90.931	90.927	91.002	90.972	90.984
FTM_35_67r	88.811	88.802	88.814	88.647	88.647
FTM_25_54r	88.575	88.466	88.530	88.407	88.439
FTM_15_45r	90.215	90.009	90.050	89.917	89.933
FTM_5_80r	94.279	94.190	94.166	94.089	94.085

Table A-15. Run 15 Results

LO330868					
	Run 1	Run 2	Run 3	Run 4	Run 5
FTM_25_450r	96.290	96.300	96.303	96.301	96.306
FTM_35_250r	95.653	95.658	95.658	95.655	95.658
FTM_25_325r	96.108	96.114	96.116	96.115	96.120
FTM_45_175r	94.672	94.682	94.695	94.679	94.684
FTM_15_400r	96.115	96.124	96.126	96.123	96.124
FTM_55_104r	92.252	92.257	92.272	92.251	92.251
FTM_35_67r	90.540	90.533	90.553	90.524	90.542
FTM_25_54r	90.787	90.748	90.753	90.746	90.747
FTM_15_45r	92.198	92.156	92.167	92.169	92.186
FTM_5_80r	94.570	94.563	94.552	94.544	94.559

Table A-16. Baseline versus Candidate LO332220

	Baseline LO330868				Candidate LO332220		
	Mean	St Dev	Variance		Mean	St Dev	Variance
FTM_25_450r	96.293	0.009	0.000		96.843	0.010	0.000
FTM_35_250r	95.647	0.023	0.001		96.229	0.016	0.000
FTM_25_325r	96.114	0.016	0.000		96.696	0.015	0.000
FTM_45_175r	94.621	0.042	0.002		95.199	0.047	0.002
FTM_15_400r	96.128	0.013	0.000		96.679	0.009	0.000
FTM_55_104r	92.101	0.075	0.006		92.726	0.095	0.009
FTM_35_67r	90.460	0.151	0.023		91.472	0.116	0.013
FTM_25_54r	90.709	0.133	0.018		91.858	0.122	0.015
FTM_15_45r	92.103	0.091	0.008		93.121	0.106	0.011
FTM_5_80r	94.524	0.085	0.007		95.399	0.048	0.002

Table A-17. Baseline versus Candidate LO310411

	Baseline LO330868				Candidate LO310411		
	Mean	St Dev	Variance		Mean	St Dev	Variance
FTM_25_450r	96.296	0.012	0.000		96.841	0.014	0.000
FTM_35_250r	95.657	0.011	0.000		96.293	0.028	0.001
FTM_25_325r	96.103	0.015	0.000		96.721	0.022	0.000
FTM_45_175r	94.669	0.022	0.000		95.316	0.034	0.001
FTM_15_400r	96.109	0.007	0.000		96.678	0.017	0.000
FTM_55_104r	92.223	0.036	0.001		92.902	0.044	0.002
FTM_35_67r	90.590	0.052	0.003		91.708	0.077	0.006
FTM_25_54r	90.801	0.052	0.003		91.989	0.073	0.005
FTM_15_45r	92.122	0.032	0.001		93.191	0.088	0.008
FTM_5_80r	94.486	0.030	0.001		95.387	0.054	0.003

Table A-18. Baseline versus Candidate LO351433

	Baseline LO330868				Candidate LO351433		
	Mean	St Dev	Variance		Mean	St Dev	Variance
FTM_25_450r	96.346	0.010	0.000		96.901	0.006	0.000
FTM_35_250r	95.712	0.012	0.000		96.370	0.009	0.000
FTM_25_325r	96.163	0.007	0.000		96.800	0.009	0.000
FTM_45_175r	94.757	0.011	0.000		95.411	0.020	0.000
FTM_15_400r	96.145	0.008	0.000		96.725	0.010	0.000
FTM_55_104r	92.337	0.024	0.001		93.078	0.046	0.002
FTM_35_67r	90.729	0.047	0.002		91.989	0.019	0.000
FTM_25_54r	90.913	0.061	0.004		92.416	0.017	0.000
FTM_15_45r	92.227	0.067	0.004		93.651	0.026	0.001
FTM_5_80r	94.520	0.035	0.001		95.612	0.035	0.001

Table A-19. Baseline versus Candidate LO351434

	Baseline LO330868				Candidate LO351434		
	Mean	St Dev	Variance		Mean	St Dev	Variance
FTM_25_450r	96.345	0.007	0.000		96.885	0.012	0.000
FTM_35_250r	95.759	0.007	0.000		96.299	0.018	0.000
FTM_25_325r	96.178	0.005	0.000		96.760	0.021	0.000
FTM_45_175r	94.845	0.004	0.000		95.287	0.024	0.001
FTM_15_400r	96.163	0.006	0.000		96.746	0.015	0.000
FTM_55_104r	92.543	0.020	0.000		92.796	0.034	0.001
FTM_35_67r	90.990	0.005	0.000		91.619	0.047	0.002
FTM_25_54r	91.082	0.015	0.000		92.028	0.036	0.001
FTM_15_45r	92.309	0.037	0.001		93.326	0.030	0.001
FTM_5_80r	94.609	0.021	0.000		95.533	0.042	0.002

Table A-20. Baseline versus Candidate LO332374

	Baseline LO364270				Candidate LO332374		
	Mean	St Dev	Variance		Mean	St Dev	Variance
FTM_25_450r	96.092	0.019	0.000		96.806	0.011	0.000
FTM_35_250r	95.190	0.025	0.001		95.895	0.005	0.000
FTM_25_325r	95.802	0.029	0.001		96.562	0.011	0.000
FTM_45_175r	93.954	0.063	0.004		94.601	0.018	0.000
FTM_15_400r	96.048	0.022	0.000		96.844	0.016	0.000
FTM_55_104r	90.875	0.143	0.021		91.624	0.022	0.000
FTM_35_67r	88.511	0.170	0.029		89.935	0.047	0.002
FTM_25_54r	88.268	0.210	0.044		89.962	0.063	0.004
FTM_15_45r	89.880	0.118	0.014		91.666	0.067	0.004
FTM_5_80r	94.002	0.061	0.004		95.322	0.029	0.001

Table A-21. Baseline versus Candidate LO351656

	Baseline LO364270				Candidate LO351656		
	Mean	St Dev	Variance		Mean	St Dev	Variance
FTM_25_450r	96.141	0.008	0.000		96.819	0.011	0.000
FTM_35_250r	95.249	0.006	0.000		96.034	0.006	0.000
FTM_25_325r	95.869	0.008	0.000		96.623	0.011	0.000
FTM_45_175r	94.016	0.015	0.000		94.880	0.014	0.000
FTM_15_400r	96.116	0.009	0.000		96.792	0.014	0.000
FTM_55_104r	90.995	0.028	0.001		92.049	0.025	0.001
FTM_35_67r	88.679	0.037	0.001		90.696	0.037	0.001
FTM_25_54r	88.391	0.032	0.001		90.780	0.046	0.002
FTM_15_45r	90.020	0.047	0.002		92.394	0.075	0.006
FTM_5_80r	94.138	0.041	0.002		95.441	0.021	0.000

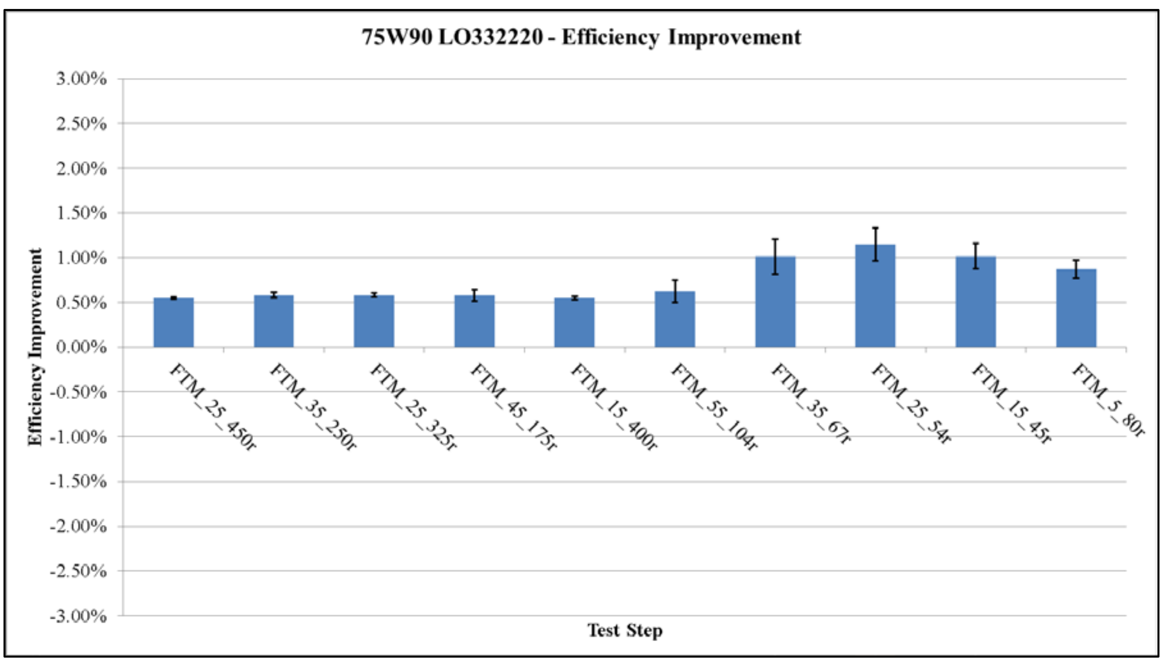


Figure A-1. Efficiency Improvement of LO332220 over Baseline 80W90

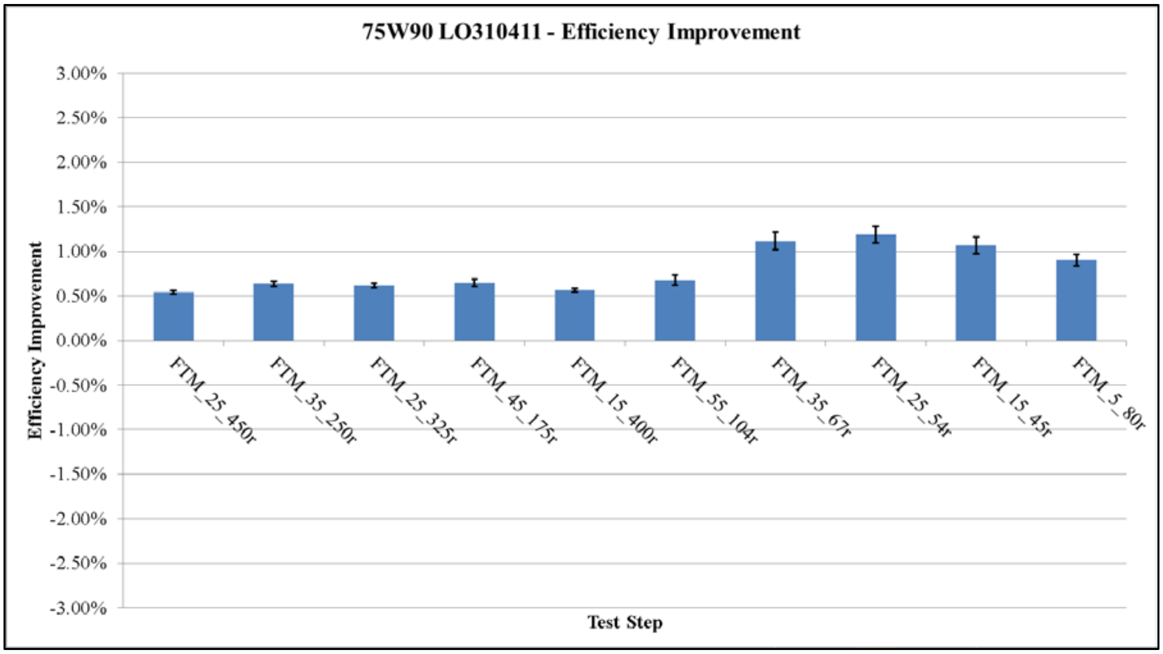


Figure A-2. Efficiency Improvement of LO310411 over Baseline 80W90

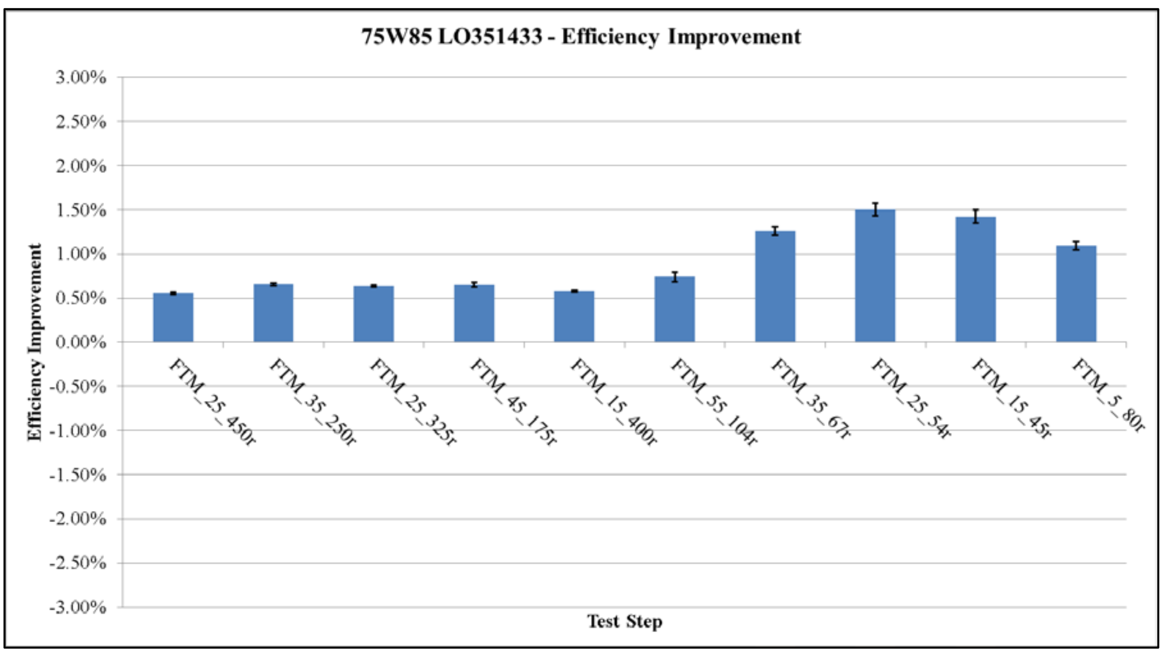


Figure A-3. Efficiency Improvement of LO351433 over Baseline 80W90

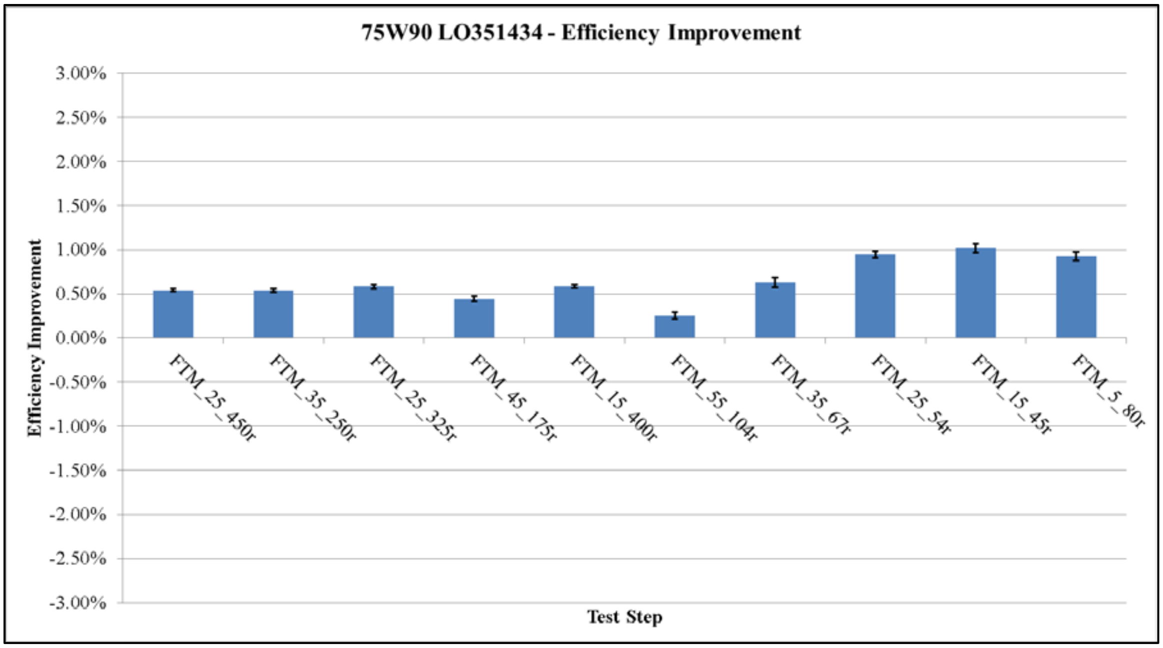


Figure A-4. Efficiency Improvement of LO351434 over Baseline 80W90

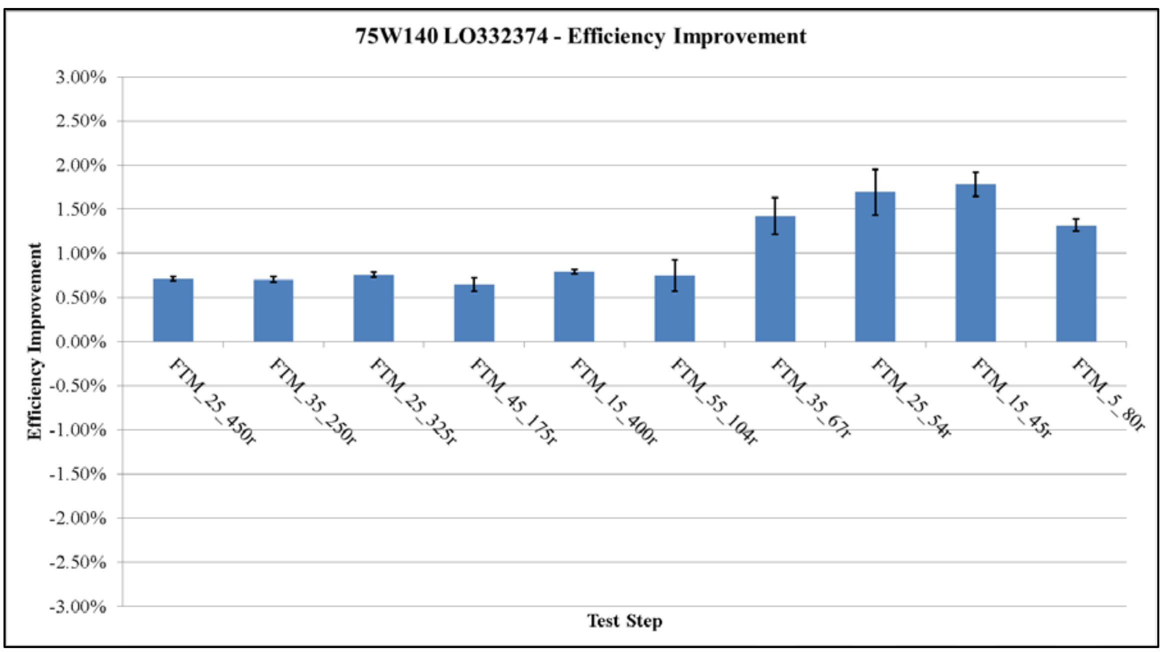


Figure A-5. Efficiency Improvement of LO332374 over Baseline 85W140

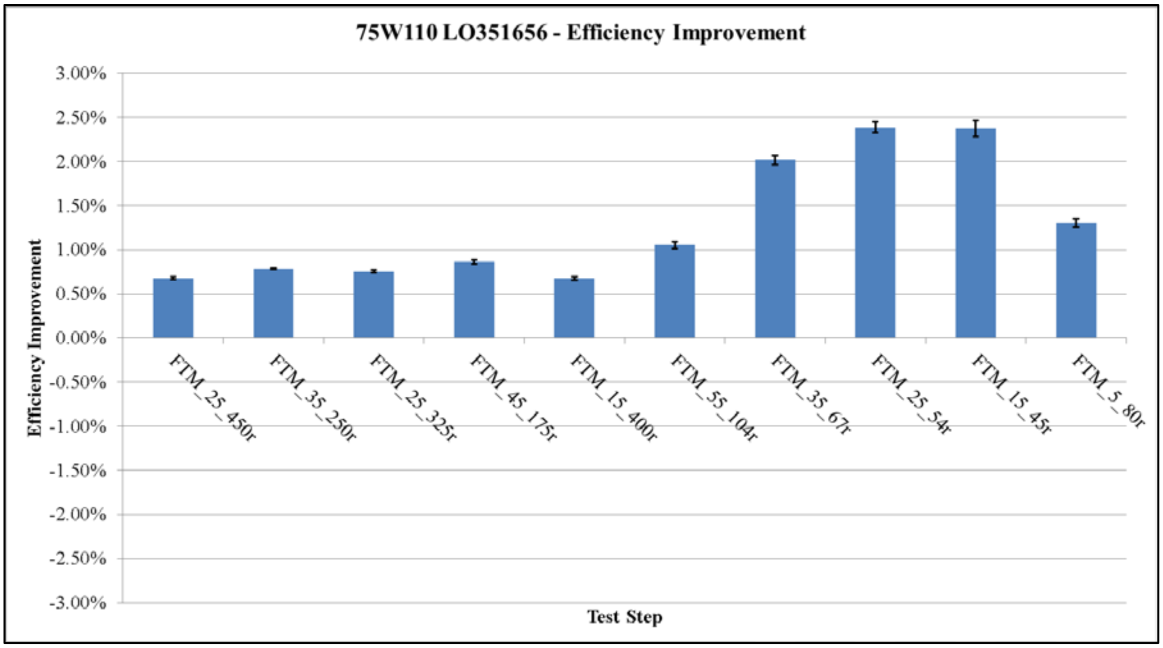


Figure A-6. Efficiency Improvement of LO351656 over Baseline 85W140

APPENDIX B. FINALIZED FTM PROCEDURE

FED-STD-791D

Method xxxx.x
Date

EFFICIENCY OF AXLE GEAR LUBRICANTS

1. SCOPE

1.1. This method is used for determining the relative mechanical efficiency improvement provided by a candidate axle gear lubricant against a reference lubricant under controlled laboratory conditions.

2. SUMMARY

2.1. A medium tactical vehicle axle is used to measure the efficiency change between axle gear lubricants under controlled laboratory conditions. At the start of the test segment, a minimum of 5 baseline runs are conducted using the reference fluid to determine baseline axle efficiency. The axle is then double flushed with the candidate axle gear lubricant, and a minimum of 5 candidate runs are conducted following the same operating procedure. At the completion of the candidate testing, the axle is double flushed with the reference lubricant, and a single test run is conducted using the reference oil to determine test validity. A test is considered valid if the post-candidate reference run returns data that is statistically equivalent to the pre-candidate reference runs. If valid, the pre-candidate reference test data is compared to the candidate test data to determine the change in measured efficiency of the axle. Combined statistical analysis is conducted on all of the reference and candidate runs to determine efficiency change and confidence interval for each operating condition.

3. SAMPLE SIZE

3.1. A total of 38 L (10 gallons) of candidate lubricant is required to double flush the axle and oil temperature control loop.

4. REFERENCES, STANDARDS, and APPARATUS

4.1. References

4.1.1. SAE Standard J2360, Automotive Gear Lubricants for Commercial and Military Use.

4.2. Test Apparatus

4.2.1. The axle test apparatus is a T-type test stand where the axle is driven by an electric AC motor, and the two outputs of the axle are coupled using speed increasing gear boxes and absorbed by an identically sized AC motor/generator. Speed control is provided by the input motor, while load control is provided by the output absorber (controlling against input torque measurement). Speed is measured through incrementing encoders mounted at the input and output motors, and torque is measured using high accuracy digital torque flanges mounted directly at the axle's input and output interfaces to reduce any outside influence from the remainder of the test stand on the resulting efficiency calculation.

4.3. Test Axle Description

4.3.1. The axle used for testing is the rearmost axle from the 5-ton M1083A1 cargo truck from the Family of Medium Tactical Vehicles (FMTV). The axle is produced by Meritor and is identified by the part number: RR15611NFDF32-780.

4.3.2. The axle is a typical beam type axle with an open differential and an overall gear ratio of 7.8:1 (3.9:1 ring and pinion ratio, and 2:1 wheel end reduction). The axle has a common oil sump between the center differential section and wheel end hub reductions.

4.3.3. The factory input pinion yoke is replaced by a custom machined input yoke that allows for direct mounting of the input torque flange.

4.3.4. Special output hubs are machined to bolt to the axle's wheel studs and provide mounting for the output torque flange.

4.4. Test Stand Detailed System Description

4.4.1. Axle input power and output absorption is provided by two 250hp AC electric motor/generators controlled through two variable frequency drives (VFD).

4.4.2. A total of two speed increasing gear boxes are utilized to increase each axle wheel end output speed and reduce torque prior to the absorbing motor. The gearboxes have a mechanical gear ratio of 7.259:1, and contain an integrated lubrication and cooling circuit.

4.4.3. Input torque is measured using a 1 kNm digital torque flange with a minimum 0.05 accuracy class.

4.4.4. Output torque at each wheel end is measured using 3 kNm digital torque flanges with a minimum of 0.05 accuracy class.

4.4.5. A three-way ball valve is installed into the rear axle fill port to allow the test stand operator to select if the differential housing is open to atmosphere for fluid level setting, or in the recirculate position for the heater control loop return flow. This valve must be installed in such a way that when vented for fluid level setting, the resulting fluid level in the axle is level with the lower portion of the original fill port (reference photo below).

Figure 1. Rear Axle Fill Port Three-Way Ball Valve

4.4.6. Differential oil temperature control is provided through the use of an external heater control loop with the ability to heat or cool the axle gear oil during operation depending on loading conditions. The heater control loop has a nominal recirculation flow rate of 5gpm. Gear oil is removed from the bottom of the differential at the drain port, circulated through heater and trim heat exchanger, and returned back to the axle at the rear fill port during operation.

4.4.7. Gear oil temperature measurement is captured using a closed tip thermocouple entering into the center housing of the axle at the drain port location. The thermocouple should enter into the differential housing at a distance of 1″ ± 0.25″ referenced from the flat external boss of the drain port on the lower differential housing (reference photo below).

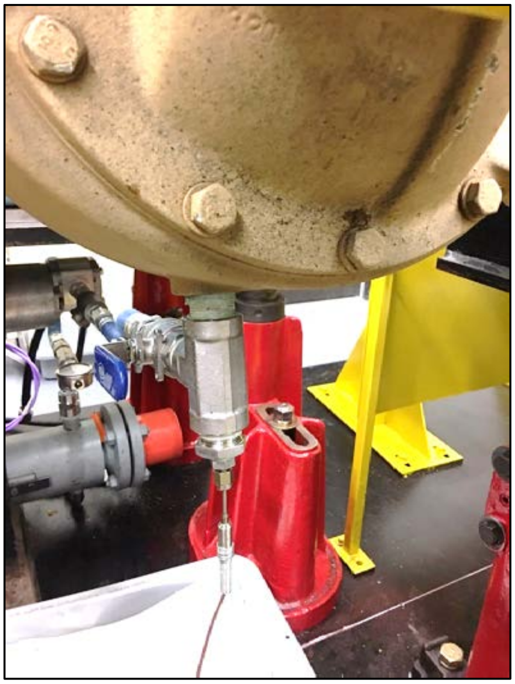


Figure 2. Axle Drain Port Location

4.5. Instrumentation

4.5.1. The following parameters are the minimum required measurements to be recorded during testing:

- Input speed
- Output speed
- Input torque
- Left output torque
- Right output torque
- Differential gear oil temperature
- Heater control loop return temperature
- Ambient temperature

4.6. Data Acquisition

4.6.1. A data acquisition and control system must be utilized to simultaneously record all testing parameters and provide speed and torque control for the axle under test. The data acquisition system must be capable of logging data at the specified 2Hz for the stabilized data recording steps during the efficiency test. It is recommended that the data acquisition system be able to monitor and control the system at an update rate of 100Hz to ensure precise control of the system.

4.6.2. The data acquisition and control system must also be capable of controlling limits for over/under oil temperature, and over/under torque and speed.

4.7. Test Stand Diagram

4.7.1. A detailed diagram of the test stand and heater control loop is provided in Appendix A.

5. MATERIALS

5.1. A sufficient volume of reference lubricant is required to double flush the axle and heater control loop for the pre-candidate and post-candidate test reference runs. This is equivalent to approximately 8 gallons, plus two times the capacity of the external heater control loop volume.

6. PROCEDURE

6.1. Fluid Change:

NOTE: If the axle fluid is being changed from one lubricant to another, a double flush procedure should always be used! The procedure below outlines the process to complete a SINGLE flush. Complete steps 6.1.1 through 6.1.6 twice to complete a double flush.

6.1.1. If starting with the axle already drained, proceed to step 6.1.3. If starting with the axle full, start the test stand and operate the axle at approximately 1500 rpm and 200 ft-lb until the differential fluid temperature is ≥ 175 °F.

6.1.2. Once the temperature has reached 175 °F, bring the test stand to a stop while keeping the fluid temperature elevated (i.e. do not apply cooling). Once stopped, drain the axle and heater control loop and dispose of the drained fluid. Refer to Figure 2 for drain port location.

6.1.3. Ensure that the circulation pump is off, and position the three way valve at the rear fill port of the axle to the vent position (open to atmosphere). Refer to Figure 1 for three-way valve location. Add fluid to the axle housing through the upper vent port until the fluid level is even with the rear housing fill port (this is noted by a trickle of fluid from the vented three way valve on the axle).

6.1.4. Move the three way valve at the rear fill port of the axle to the recirculation position (Figure 1), and turn on the circulation pump and allow the fluid to flow through the heater system for a minimum of 2 minutes to purge air from the heater system.

6.1.5. Turn off the circulation pump and reposition the three way valve at the rear fill port of the axle to the vent position, and add fluid to the axle housing through the upper vent port until the fluid level is topped back off to the rear housing fill port level.

6.1.6. Once complete, position the three way valve at the rear fill port of the axle back to the recirculation position for testing.

6.2. Efficiency Testing:

6.2.1. Start the test stand and ramp the axle to step one test conditions (see Table 1.) and hold until the differential oil temperature reaches 175 °F +/- 1 °F.

6.2.2. Once the differential oil reaches temperature, progress the axle through the speed, load, and temperature points outlined in Table 1 while logging (at a minimum) input torque, output torque left and right, input speed, output speed, and axle differential fluid temperature.

6.2.3. The axle differential fluid temperature set point is reduced to 140 °F for the low torque operating conditions.

6.2.4. Operation at each step should consist of two sub-steps, first a stabilization sub-step to allow the axle to stabilize at the specified test conditions, then second, a specified data recording sub-step.

6.2.5. During the stabilization sub-step, the pinion speed should be held at +/- 2 rpm of the speed set point and the pinion load should be held at +/- 5 lb-ft of the load set point.

6.2.6. During the stabilization sub-step, the axle should be operated at the specified test condition in Table 1 for a minimum of 5 minutes, and the moving average of the axle differential fluid temperature should be at the temperature set point +/- 0.25 °F before continuing to the recording step. The moving average should be calculated over a 60 second interval with a 1 second sample time. Overall data logging rate during the stabilization step should be 0.2 Hz (5 sec).

6.2.7. During the recording sub-step, the axle should be operated at the specified test condition for 60 seconds at a logging rate of 2 Hz (0.5 sec). Once complete the axle can be ramped to the next step/test condition for stabilization.

Table 1. Federal Test Method Speed & Load Points

Step	Nominal Speed [mph]	Pinion Speed [rpm]	Pinion Load [ft-lb]	Axle Differential Fluid Temperature [°F]
1	25	1469	450	175
2	35	2100	250	175
3	25	1469	325	175
4	45	2600	175	175
5	15	865	400	175
6	55	3207	104	175
7	35	2100	67	140
8	25	1469	54	140
9	15	865	45	140
10	5	294	80	140

6.2.8. The axle should be operated through all 10 steps to complete 1 cycle. For each individual test, 10 cycles should be completed for data averaging.

7. CALCULATIONS

7.1. Efficiency of Individual Test Run

7.1.1. All final calculations are completed using the data from the data recording sub-step captured after stabilization at each speed and load. To determine efficiency results for the reference or candidates tests, input and output power and efficiency for each step of all 10 cycles should be calculated as follows:

$$Power_{In} = \frac{(Speed_{In} * Torque_{In})}{5252}$$

$$Power_{Out} = \frac{Speed_{Out} * (Torque_{Out\ Left} + Torque_{Out\ Right})}{5252}$$

$$Efficiency = \frac{Power_{Out}}{Power_{In}} * 100$$

$$where: Power\ [hp], Speed\ [rpm], Torque\ [lbft]$$

7.1.2. From these calculations, a matrix of resulting efficiency can be tabulated for each baseline or candidate run. An example table is shown below, where "xx" denotes the calculated efficiency for all 10 cycles of the baseline or candidate run. (Note: cycle 1 is not included in the final analysis to reduce any impacts in efficiency measurement from long thermal transients that persist in the tested hardware after the initial warm-up).

	Baseline or Candidate Single Run Results								
	Cycle								
STEP	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
FTM_25_450r	xx	xx	xx	xx	xx	xx	xx	xx	xx
FTM_35_250r	xx	xx	xx	xx	xx	xx	xx	xx	xx
FTM_25_325r	xx	xx	xx	xx	xx	xx	xx	xx	xx
FTM_45_175r	xx	xx	xx	xx	xx	xx	xx	xx	xx
FTM_15_400r	xx	xx	xx	xx	xx	xx	xx	xx	xx
FTM_55_104r	xx	xx	xx	xx	xx	xx	xx	xx	xx
FTM_35_67r	xx	xx	xx	xx	xx	xx	xx	xx	xx
FTM_25_54r	xx	xx	xx	xx	xx	xx	xx	xx	xx
FTM_15_45r	xx	xx	xx	xx	xx	xx	xx	xx	xx
FTM_5_80r	xx	xx	xx	xx	xx	xx	xx	xx	xx

7.1.3. The composite result for a single baseline or candidate run is then calculated by taking the average efficiency over cycles 2 through 10 for each step of the individual run. An example composite result table for a single run is shown below.

Baseline or Candidate Run Composite Result	
STEP	Run #
FTM_25_450r	xx
FTM_35_250r	xx
FTM_25_325r	xx
FTM_45_175r	xx
FTM_15_400r	xx
FTM_55_104r	xx
FTM_35_67r	xx
FTM_25_54r	xx
FTM_15_45r	xx
FTM_5_80r	xx

7.1.4. Recall, a minimum of 5 runs must be conducted for each baseline or candidate test. After all 5 runs are completed, a baseline or candidate test results table can be formed. An example is shown below.

	Baseline or Candidate Test Result				
STEP	Run 1	Run 2	Run 3	Run 4	Run 5
FTM_25_450r	xx	xx	xx	xx	xx
FTM_35_250r	xx	xx	xx	xx	xx
FTM_25_325r	xx	xx	xx	xx	xx
FTM_45_175r	xx	xx	xx	xx	xx
FTM_15_400r	xx	xx	xx	xx	xx
FTM_55_104r	xx	xx	xx	xx	xx
FTM_35_67r	xx	xx	xx	xx	xx
FTM_25_54r	xx	xx	xx	xx	xx
FTM_15_45r	xx	xx	xx	xx	xx
FTM_5_80r	xx	xx	xx	xx	xx

7.2. Statistical Analysis – Comparison of Reference Test to Candidate Test

7.2.1. Once all baseline and candidate test data is gathered, statistical analysis can be conducted to determine overall efficiency change and confidence interval.

7.2.2. For both the baseline and candidate test results, calculate the mean, standard deviation, and variance for each individual step.

	Baseline				Candidate		
STEP	Mean	Std Dev	Variance		Mean	Std Dev	Variance
FTM_25_450r	xx	xx	xx		xx	xx	xx
FTM_35_250r	xx	xx	xx		xx	xx	xx
FTM_25_325r	xx	xx	xx		xx	xx	xx
FTM_45_175r	xx	xx	xx		xx	xx	xx
FTM_15_400r	xx	xx	xx		xx	xx	xx
FTM_55_104r	xx	xx	xx		xx	xx	xx
FTM_35_67r	xx	xx	xx		xx	xx	xx
FTM_25_54r	xx	xx	xx		xx	xx	xx
FTM_15_45r	xx	xx	xx		xx	xx	xx
FTM_5_80r	xx	xx	xx		xx	xx	xx

7.2.3. For each step, conduct an F-Test to determine if the baseline and candidate tests have equal variances.

7.2.4. Based on the results of 7.2.3, conduct an appropriate T-Test for each step between the baseline and candidate test results to establish the statistical significance (95% confidence interval) of the difference in means between the reference and candidate results. The results should be complied in a single table as shown below.

	Candidiate Improvement		
STEP	% change	Statistically Significant?	Confidence Interval
FTM_25_450r	xx	Y/N	± xx
FTM_35_250r	xx	Y/N	± xx
FTM_25_325r	xx	Y/N	± xx
FTM_45_175r	xx	Y/N	± xx
FTM_15_400r	xx	Y/N	± xx
FTM_55_104r	xx	Y/N	± xx
FTM_35_67r	xx	Y/N	± xx
FTM_25_54r	xx	Y/N	± xx
FTM_15_45r	xx	Y/N	± xx
FTM_5_80r	xx	Y/N	± xx

8. REPORTING

8.1. At the completion of testing, report the baseline and candidate test result tables calculated in step 7.1.4, the candidate improvement table calculated in step 7.2.4, and the post-candidate reference run result to document test validity.

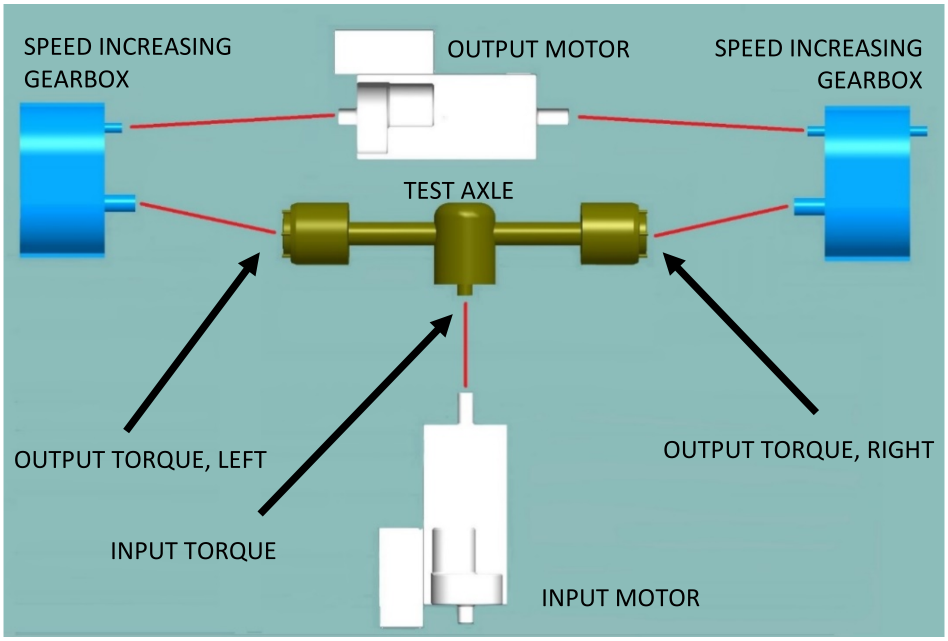
9. PRECISION

9.1. Precision data has not been developed for this method. Since candidate testing includes the completion of reference runs for data comparison, statistical analysis of the reference and candidate results effectively captures and reflects the repeatability of the test stand measurement.

Method Prepared By:
Army – 2018

APPENDIX A of FINALIZED FTM PROCEDURE

1. Axle test stand block diagram:



2. Heater recirculation loop block diagram: