DEVELOPMENT OF AN ARMY STATIONARY AXLE EFFICIENCY TEST STAND – PART II

INTERIM REPORT
TFLRF No. 484

by
Adam C. Brandt
Edwin A. Frame

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-09-C-0100 (WD33)

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14. ABSTRACT The U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC) has initiated the construction and development of a stationary axle efficiency test stand to allow for laboratory based investigation of Fuel Efficient Gear Oils (FEGO) and their impact on vehicle efficiency. Development work using the stationary axle efficiency test stand was completed using hardware representative of light and medium duty tactical wheeled vehicles. Stationary axle efficiency testing was conducted following a draft Federal Test Method (FTM) using developmental and commercial oils. The most differentiation of efficiency between tested lubricants was achieved in the low speed/lower load operating conditions of the FTM cycle, while efficiency results at the higher speed/high load operating conditions showed significantly tighter grouping. Overall, results tended to show increased efficiency trending with reduced viscosity.			
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EXECUTIVE SUMMARY

The U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC) desires to increase the fuel efficiency of its ground vehicle fleet, and has initiated the construction and development of a stationary axle efficiency test stand to allow for laboratory based investigation of Fuel Efficient Gear Oils (FEGO) and their impact on vehicle efficiency. The test stand was designed and developed with the following goals:

- Provide a lower cost alternative for quantifying vehicle efficiency impact from new axle gear lubricants compared to full scale vehicle testing
- Provide improved testing accuracy and precision when assessing axle gear lubricants to improve ability to discriminate between similarly performing oils
- Be modular in design to provide sufficient motoring and absorption capabilities required to test a wide range of light to heavy duty driveline hardware representative of those fielded by the U.S. Army
- Support the future development of a standardized Federal Test Method intended to be used for future product qualification for the U.S. Army

Development work using the stationary axle efficiency test stand was completed using hardware representative of light and medium duty tactical wheeled vehicles. This included the High Mobility Multipurpose Wheeled Vehicle (HMMWV), and the 5-Ton Cargo variant of the Family of Medium Tactical Vehicles (FMTV). Results show that the stationary axle test stand provides excellent representation of real world results based on driving cycle replications of actual full scale SAE J1321 vehicle testing. Through development, the rearmost axle of the M1083A1 MTV was selected as a basis for a Federal Test Method (FTM) that specifies testing procedures to measure the efficiency improvement of an axle gear oil for use in military equipment. Table 1 shows the operating conditions for the MTV axle as defined by the current draft FTM.

Table 1. Final MTV FTM Cycle Operation Conditions

Step	Approximate Vehicle Velocity	Pinion Input Speed [rpm]	Pinion Input Load	Approximate Input Power	Differential Temperature
1	40kph (25mph)	1,469	610Nm (450lbft)	94kW (126hp)	79.4 °C (175 °F)
2	56kph (35mph)	2,100	338Nm (250lbft)	75kW (100hp)	
3	40kph (25mph)	1,469	440Nm (325lbft)	68kW (91hp)	
4	72kph (45mph)	2,600	237Nm (175lbft)	65kW (87hp)	
5	24kph (15mph)	865	542Nm (400lbft)	49kW (66hp)	
6	88kph (55mph)	3,207	141Nm (104lbft)	48kW (64hp)	
7	56kph (35mph)	2,100	91Nm (67lbft)	20kW (27hp)	
8	40kph (25mph)	1,469	73Nm (54lbft)	11kW (15hp)	
9	24kph (15mph)	865	61Nm (45lbft)	5kW (7hp)	
10	8kph (5mph)	294	108Nm (80lbft)	4kW (5hp)	

Stationary axle efficiency testing was conducted following the draft FTM using developmental and commercial oils. This included two different formulations of a 75W-90 product, a 75W-85, a 75W-110, and a 75W-140. Results of efficiency improvement for each individual oil are presented in Figure 1.

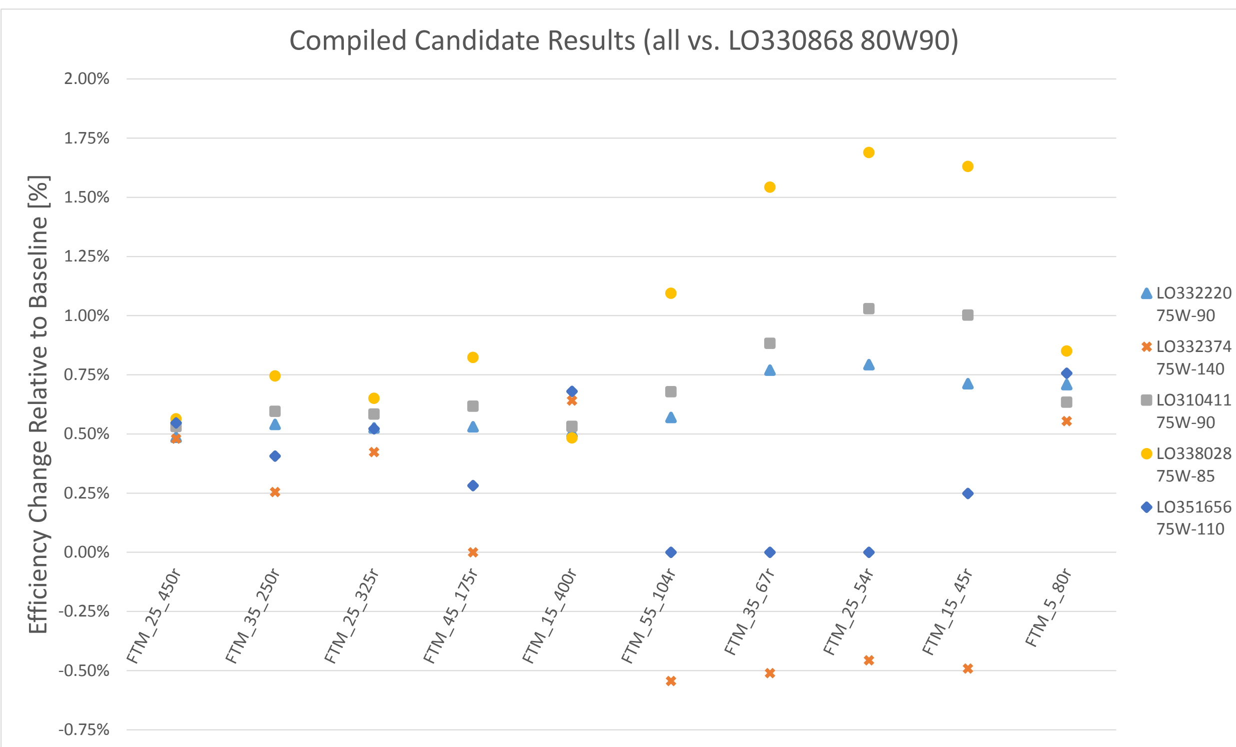

Figure 1. Complied FTM Results using MTV Axle

The greatest differentiation of efficiency between tested lubricants was achieved in the low speed/lower load operating conditions of the FTM cycle, while efficiency results at the higher speed/high load operating conditions showed significantly tighter grouping. Overall, results tended to show increased efficiency trending with reduced viscosity.

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 2014 through January 2017 under Contract No. W56HZV-09-C-0100. The U.S. Army Tank Automotive RD&E Center, Force Projection Technologies, 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

lbft – 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

1.0 BACKGROUND AND OBJECTIVE

The U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC) desires to increase the fuel efficiency of its ground vehicle fleet. One potential area for fuel consumption improvement is through optimization of driveline lubricating fluids. By improving the lubricating fluids to reduce mechanical losses, an increase in vehicle fuel efficiency can be achieved. TARDEC has previously conducted research to determine fuel consumption effects of fuel efficient axle gear lubricants in light, medium, and heavy duty tactical wheeled vehicles. Full scale vehicle fuel efficiency tests were conducted on the M1151A1 High Mobility Multipurpose Wheeled Vehicle (HMMWV), the M1083A1 5-ton cargo variant of the Family of Medium Tactical Vehicles (MTV), and the M1070 Heavy Equipment Transporter (HET). Results showed good potential for fuel efficiency gains through the use of “drop-in” fluids, while also highlighting the importance of fluid selection versus expected driving/duty cycle and vehicle application [1, 2, 3].

In conjunction with full scale vehicle testing, TARDEC also initiated the construction and development of a stationary axle efficiency test stand to allow for laboratory based investigation of Fuel Efficient Gear Oils (FEGO). This test stand was constructed at the U.S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF), located at Southwest Research Institute (SwRI) in San Antonio TX [4, 5], and was designed and developed with the following goals:

- Provide a lower cost alternative for quantifying vehicle efficiency impact from new axle gear lubricants compared to full scale vehicle testing
- Provide improved testing accuracy and precision when assessing axle gear lubricants to improve ability to discriminate between similarly performing oils
- Be modular in design to provide sufficient motoring and absorption capabilities required to test a wide range of light to heavy duty driveline hardware representative of those fielded by the U.S. Army
- Support the future development of a standardized Federal Test Method intended to be used for future product qualification for the U.S. Army

This report covers the continued progression of the stationary axle efficiency stand development, picking up on work last reported under TFLRF Interim Report No. 471, where the stationary axle test stand construction was completed, and preliminary shakedown and repeatability work was conducted using the MTV axle and a baseline 80W-90 gear oil.

2.0 BASELINE AND DEVELOPMENTAL OIL PROPERTIES

For all development work conducted on the axle efficiency test stand, the same oils used in the previously mentioned full scale vehicle testing were utilized. This includes a baseline 80W-90 gear oil, as well as a two synthetic 75W-90 and 75W-140 fuel efficient candidates. Table 2 outlines the basic chemical and physical properties of each oil. It is worth noting that three separate batches of baseline 80W-90 oil have been used over the course of the development process, and some minor changes in composition and performance of the baseline 80W-90 have been noted. The compositional changes can be noted in the table below, while performance changes are touched on in their respective sections in the report.

3.0 STATIONARY AXLE STAND REFINEMENT (ORIGINAL MTV INSTALLATION)

Continuing from work reported under IR471, additional changes were implemented to the stationary axle test stand in an effort to improve run to run repeatability of efficiency data. Changes focused on two primary areas, the data acquisition/signal handling systems, and the implementation of a differential oil temperature control system.

Table 2. Baseline and Developmental Gear Oil Chemical & Physical Properties

Test	ASTM Method	Units	LO246580 Baseline 80W-90	LO272251 Baseline 80W-90	LO330868 Baseline 80W-90	LO332374 Developmental 75W-140	LO332220 Developmental 75W-90
Elements	D5185		(Batch 1)	(Batch 2)	(Batch 3)		
Aluminum		ppm	<1	<1	<1	<1	<1
Antimony		ppm	<1	<1	<1	<1	<1
Barium		ppm	<1	<1	<1	<1	<1
Boron		ppm	105	236	233	224	151
Calcium		ppm	14	6	7	<1	3
Chromium		ppm	<1	<1	<1	<1	<1
Copper		ppm	<1	<1	<1	<1	<1
Iron		ppm	149	<1	<1	<1	<1
Lead		ppm	<1	<1	<1	<1	<1
Magnesium		ppm	4	<1	<1	<1	10
Manganese		ppm	<1	<1	<1	<1	<1
Molybdenum		ppm	<1	<1	<1	<1	<1
Nickel		ppm	<1	<1	<1	<1	<1
Phosphorus		ppm	949	947	942	1331	1812
Silicon		ppm	<1	<1	<1	<1	<1
Silver		ppm	<1	<1	<1	<1	<1
Sodium		ppm	<5	<5	<5	<5	<5
Tin		ppm	<1	<1	<1	<1	<1
Zinc		ppm	8	2	5	<1	2
Potassium		ppm	<5	<5	<5	<5	<5
Strontium		ppm	<1	<1	<1	<1	<1
Vanadium		ppm	<1	<1	<1	<1	<1
Titanium		ppm	<1	<1	<1	<1	<1
Cadmium		ppm	<1	<1	<1	<1	<1
Kinematic Viscosity	D445						
Test Temperature		°C	40	40	40	40	40
Viscosity		mm²/s	126.07	135.62	138.81	178.28	87.27
Kinematic Viscosity	D445						
Test Temperature		°C	100	100	100	100	100
Viscosity		mm²/s	13.2	14.54	14.63	24.43	13.97

3.1 DATA ACQUISITION SIGNAL HANDLING

For the data acquisition/signal handling system, adjustments were first made to the gate times used for the measurement of the input and output torque frequency signals. In the data acquisition system, the gate time specifies the duration of time the frequency signal is sampled for a single discrete measurement, and the overall resolution of this measurement is effected by the length of the gate time and number of counts that occur during the specified gate. For example, for the input 1kNm (737.6 lbft) torque flange used on the MTV axle installation, the output signal operates over a nominal frequency range of 120kHz for the full 1kNm measurement range of the torque flange. This results in a signal measurement resolution of approximately 0.61 lbft/count at a nominal gate time of 0.01 seconds. For the same conditions under a longer 0.05 second gate time, overall signal measurement resolution improves to 0.13 lbft/count. This is because at the same input frequency (i.e., torque level), the longer gate time accumulates more counts. In general, resolution for frequency measurement increases with the longer gate times, but as the gate times increase, update rates for the measured parameters slow. Overall gate time is also practically limited by the counting capacity of the data acquisition systems frequency counter/timer chipset. For the original shakedown and repeatability work conducted and reported under IR471, a specified gate time of 0.01 sec was used to provide the quickest data update rate. Through investigation and testing, an updated gate time of 0.05 sec was implemented. This improved the measurement resolution of the input and output torque frequency signals to a level greater than that of the actual measurement accuracy class of the torque flange itself (i.e., the accuracy of the measurement device became the limiting factor, not the signal measurement resolution), while not showing any noticeable impact from the changed update rate. In addition to the change in gate time, the input signals from the axle input/output torque and input/output speed measurements had 0.5 sec digital low-pass filters applied to reduce any signal noise present that might negatively impact the repeatability of the efficiency calculations. Through testing, both of these changes demonstrated an improvement in data repeatability and calculations of axle efficiency.

3.2 DIFFERENTIAL TEMPERATURE CONTROL

The second change investigated to improve run to run repeatability was the design and implementation of a differential/gear oil temperature control system. Temperature of the differential gear oil during operation has substantial influence in overall mechanical efficiency of the axle/differential, thus temperature variation between efficiency runs can impact data repeatability. In stationary type axle efficiency testing, two general schools of thought have been identified regarding temperature control. The first considers that during real-world operation, the axle will naturally stabilize to its own steady state temperature dependent on the loading conditions, the lubricant being used, its resulting efficiency, and the ambient temperature it's being operated in. To replicate this in laboratory testing, a temperature control system would be configured in such a way to provide a fixed cooling rate to the axle for base cooling, while still allowing the gear oil temperature to seek its natural steady state based on loading conditions. The second school of thought is that in order to get a direct comparison between two differing fluids, all variables, including temperature, need to be precisely and repeatability controlled. This requires a control system that can maintain a specified differential oil temperature over a potentially wide range of operating conditions, requiring the ability to heat or cool the axle gear oil, depending on the temperature specification and the specified input/output speed and loading conditions. For this testing a fixed temperature control system was selected. While both of these schools of thought have merit, the fixed temperature recirculation loop was more dictated by laboratory limitations than greater technical merit over the fixed cooling rate approach.

The temperature control loop designed for the axle efficiency stand was based off of a similar control system successfully developed by Anderson et al. during General Motors axle efficiency testing [6]. The external control system is made up of a small fixed displacement gear pump, an appropriately sized recirculation heater, and a liquid to liquid heat exchanger. The gear pump was sized to provide approximately 5 GPM of flow during operation, and the differential temperature control measurement is taken at the drain port of the axle with a closed tip thermocouple protruding approximately 1″ into the differential housing. Figure 2 shows a simplified block diagram of the temperature control loop, while Figure 3, Figure 4, and Figure 5 respectively show the actual installed system, the control loop return port located at the axles original fill port, and the control loop supply port located at the axles original drain port (shown for the originally installed MTV axle). As discussed in further detail below, implementation of the differential gear oil temperature control system provided additional improvement in run to run data repeatability.

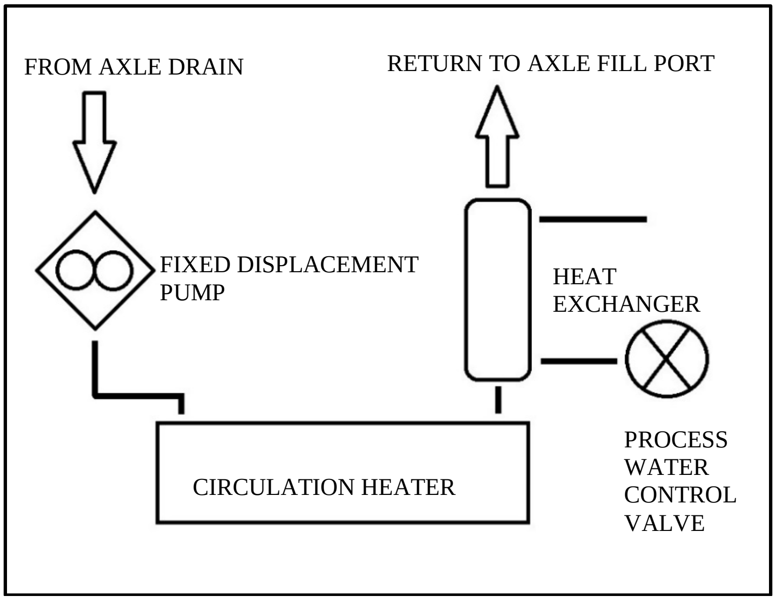

Figure 2. Block Diagram of Temperature Control Loop System

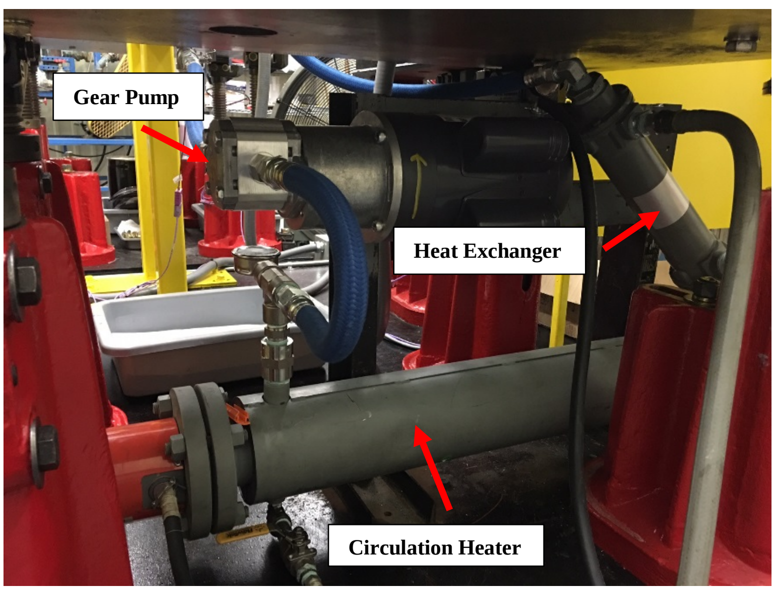

Figure 3. Heater Control Loop Hardware

Figure 4. Heater Control Loop - Return to Axle

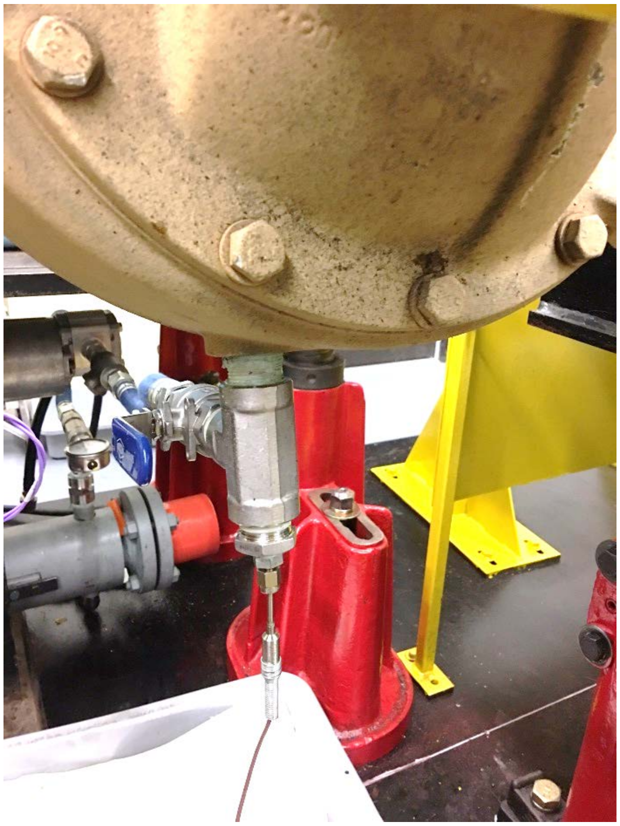

Figure 5. Heater Control Loop – Supply From Axle

4.0 MTV AXLE TEST DEVELOPMENT

With the successful completion of the test stand refinements, development work continued using the MTV axle. The following sections outline SAE J1321 transient driving cycle replication, differential fluid temperature impact investigation, efficiency mapping, and development of the final proposed FTM test cycle for the MTV axle.

4.1 TRANSIENT DRIVING CYCLE REPLICATION (POST STAND REFINEMENTS)

With the implementation of the differential oil temperature control system, continued transient driving cycle replication was conducted using the MTV axle. Table 3 lists the MTV transient driving cycle axle operating conditions (i.e., input speed and load) previously introduced under IR471. In addition, the table now shows initial target differential fluid temperature setpoints used in testing. These temperatures were derived from the average natural stabilization temperatures from the axle efficiency stand test observed during early 80W-90 repeatability testing prior to temperature control. This allowed for a direct comparison of the “post temperature controlled” runs to those conducted before temperature control to identify improvement in run to run repeatability, and they also provided a starting point to control the follow-on developmental oils when introduced into the system to investigate the stands ability to discriminate oils.

Table 3. MTV Replicated Driving Cycle, Input Speed & Load Conditions

Approximate Vehicle Velocity	Pinion Input Speed [rpm]	Pinion Input Load	Approximate Input Power	Differential Temperature
88.5kph (55mph)	3,207	141Nm (104lbft)	48kW (64hp)	107 °C (225 °F)
56kph (35mph)	2,033	91Nm (67lbft)	19kW (26hp)	103 °C (217 °F)
48kph (30mph)	1,723	89Nm (66lbft)	16kW (22hp)	98 °C (208 °F)
40kph (25mph)	1,469	73Nm (54lbft)	11kW (15hp)	93 °C (200 °F)
32kph (20mph)	1,157	61Nm (45lbft)	7kW (10hp)	88 °C (190 °F)
24kph (15mph)	865	61Nm (45lbft)	5kW (7hp)	82 °C (180 °F)
16khp (10mph)	684	88Nm (56lbft)	5kW (7hp)	78 °C (173 °F)
8kph (5mph)	294	108Nm (80lbft)	3kW (4hp)	75 °C (167 °F)

Testing with the implemented temperature control loop was conducted for the baseline 80W-90 and the developmental 75W-90 and 75W-140 oils. Upon completion of each oil, the axle and temperature control system was then double flushed to reduce any oil carryover. Multiple evaluations were conducted with each oil to establish observed run to run repeatability of results. With results plotted, the test stands run to run repeatability and ability to discriminate between different lubricants was established. Figure 6 shows the plotted efficiency results for each of the oils.

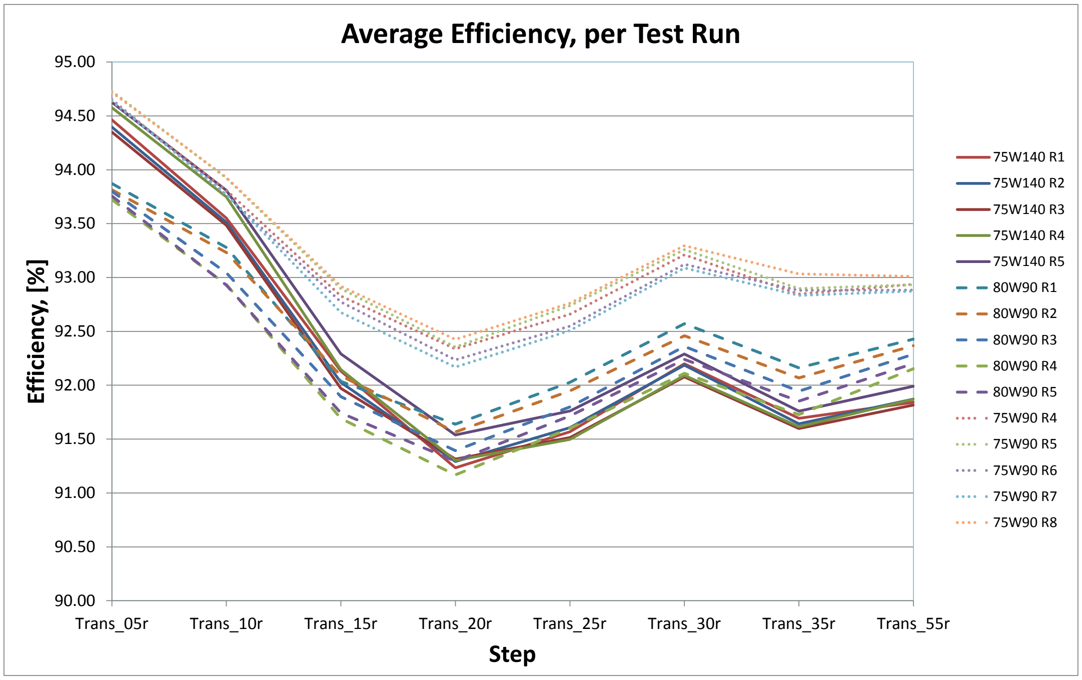

Figure 6. MTV Efficiency Results – SAE J1321 Driving Cycle Replication

The 75W-90 oil produced higher efficiency than the baseline 80W-90 for all tested operating points of the replicated driving cycle. This was consistent with trends observed in the previous full scale vehicle tests. A more varied response was observed for the 75W-140. At the low load and high speed conditions, the 75W-140 yielded similar or worse efficiency than the baseline 80W-90 oil, while at the low speed high load points providing improvement. This range of performance highlights the importance of selecting the most real-world applicable operating conditions for conducting stationary axle efficiency testing.

4.1.1 Temperature Investigation

With discrete temperature setpoints for each step of the driving cycle, time to reach temperature stabilization at each step during testing was longer than desired. This resulted in long test durations and increased the time required to complete multiple runs for each oil. To determine if the test length could be improved, a brief investigation was conducted using a simplified temperature profile to determine if similar results could be achieved. This allowed the stands temperature control system to control multiple steps at the same temperature, reducing the stabilization time required at each speed/load condition. Table 4 shows the driving cycle conditions with the simplified temperature setpoints.

Table 4. MTV Replicated Driving Cycle, Input Speed & Load Conditions (Modified)

Approximate Vehicle Velocity	Pinion Input Speed [rpm]	Pinion Input Load	Approximate Input Power	Differential Temperature
88.5kph (55mph)	3,207	141Nm (104lbft)	48kW (64hp)	104 °C (220 °F)
56kph (35mph)	2,033	91Nm (67lbft)	19kW (26hp)	
48kph (30mph)	1,723	89Nm (66lbft)	16kW (22hp)	93 °C (200 °F)
40kph (25mph)	1,469	73Nm (54lbft)	11kW (15hp)	
32kph (20mph)	1,157	61Nm (45lbft)	7kW (10hp)	
24kph (15mph)	865	61Nm (45lbft)	5kW (7hp)	78 °C (173 °F)
16khp (10mph)	684	88Nm (56lbft)	5kW (7hp)	
8kph (5mph)	294	108Nm (80lbft)	3kW (4hp)	

Testing was conducted using the 75W-90 oil that the axle and heater control system was already charged with. Figure 7 shows the plotted results comparing the original 5 runs with the full detailed temperature profile, and the 2 follow-on runs completed following the simplified temperature profile. What was observed was that for most of the operating conditions, very little shift in the resulting efficiency was seen, with only 2 of the 8 points showing a noticeable shift in efficiency response.

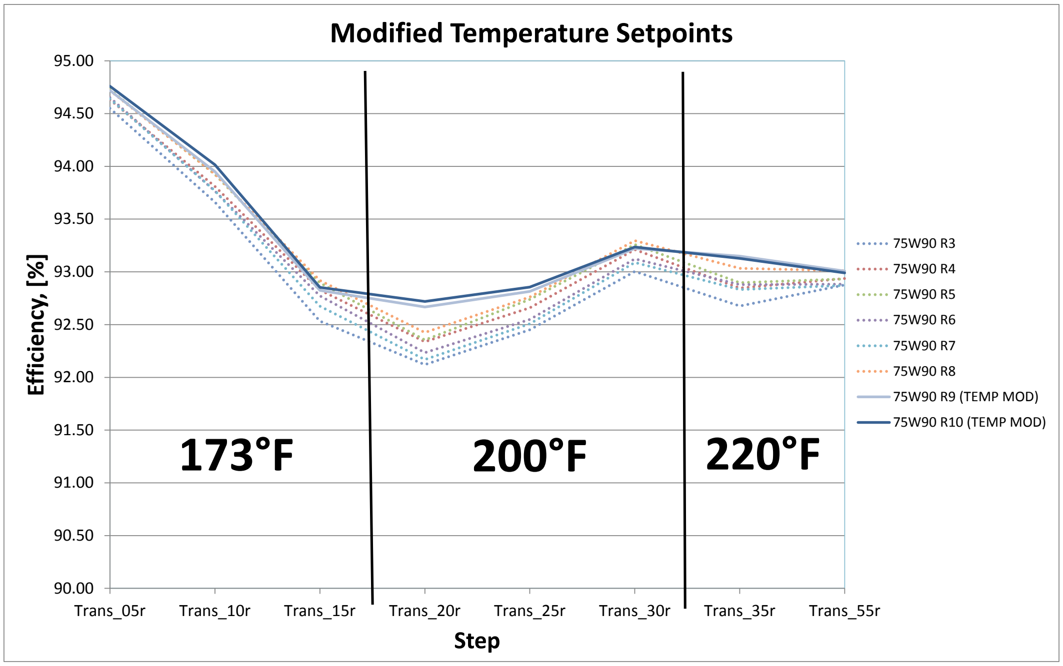

Figure 7. Efficiency Response, Replicated Driving Cycle, Simplified Temperature Profile

Since the original temperature setpoints used for the replicated driving cycle testing were initially based off the natural stabilization temperature of the 80W-90 under the typical laboratory operating conditions as opposed to actual measured vehicle temps, a study of collected vehicle data was then conducted for the MTV to investigate real world operating temperatures. Since two different iterations of full scale MTV testing had been conducted, one during winter months and the second during summer months, a wide range of differential oil temperatures were identified. Recorded temperatures ranged from lows of 50 °C (125 °F) to highs of over 121 °C (250 °F) depending on driving cycle, ambient temperature, and axle location (i.e., front, intermediate, or rear). In addition, with the exception of some of the longer highways cycle segments at 25mph and 55mph, nearly all of the operating conditions showed continued transient temperature responses, either heating or cooling based on current speed and load conditions versus the previous, while never achieving a steady state temp. Based on this varied response, no set temperature matrix was identified to use during future replicated driving cycle testing. Since data varied over such a wide range of operation and ambient temperatures, a temperature of approximately 79.4 °C (175 °F) was identified as an average representative temperature for typical MTV operation. This temperature was a common approximate median temperature across the wide range of recorded conditions, as well as specific axle location. As such it was selected as a good test temperature for use in efficiency comparisons.

Figure 8 shows a representative plot of axle temperature response for the MTV under the transient driving cycle during ambient air temperatures of nominally 29.4 °C (85 °F) to 35 °C (95 °F). For nearly all testing, the front and rearmost axle of the MTV tended to show similar temperatures, while the intermediate axle, which is also a power pass through to the rear axle, tended to run at a higher temperature.

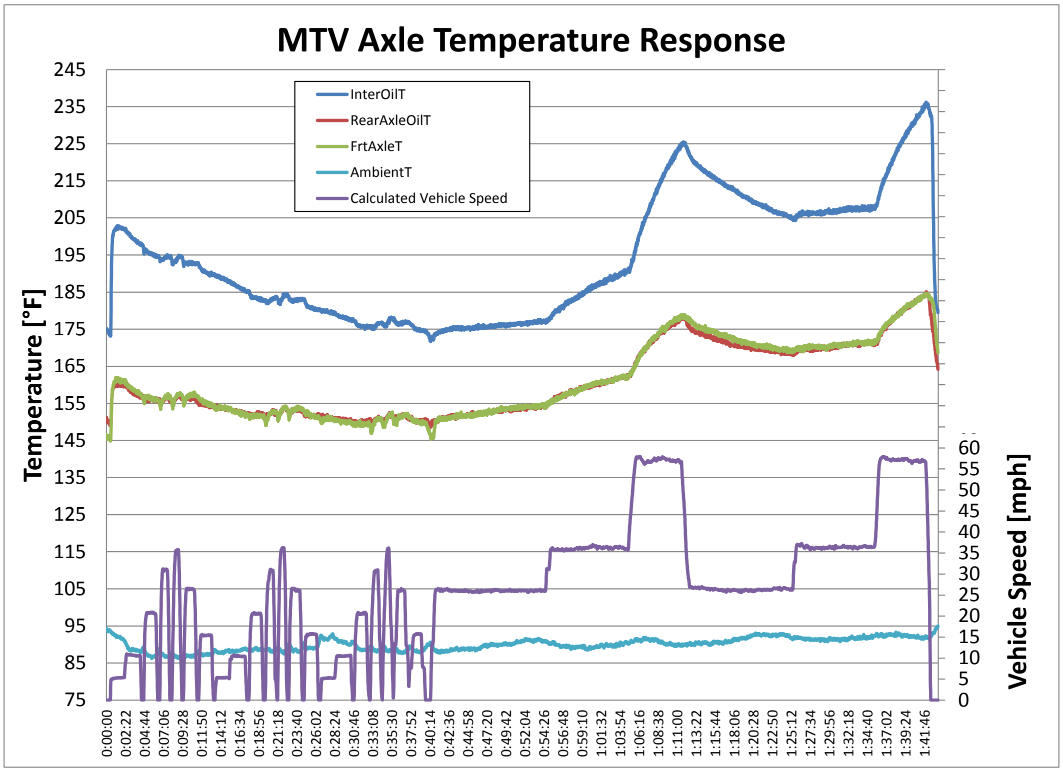

Figure 8. Typical MTV Axle Temperature Response

4.2 Efficiency Mapping

After initial driving cycle replication results were reviewed, consideration was given as to what direction the development path should then take. If the primary goal was to create a laboratory based test that mimicked the exact results of the SAE J1321 city and highway driving cycles, weighted averages of each of the replicated driving cycles operating points based on the duration of time that the vehicle operated in them could be easily calculated, and the preliminary results suggested that the test would likely predict realistic vehicle results. However for the results to be applicable to real world field use, the driving cycle being replicated should be representative of real world operation. Confidence in this was less clear. All of the operating points derived from the MTV driving cycle consisted of relatively low input loads, with all of the points being essentially less than 135Nm (100lbft) of input pinion torque. As the MTV's engine peaks at around 8 times that level of torque (without considering torque multiplication of the torque convertor and transmission gear ratios), a test cycle with that low of input torque levels was not expected to have the ability to accurately predict a more varied real world operational cycle. As a result, it was determined that additional investigation into how the axle reacted over a wider range of input loading conditions would be beneficial, and that a final efficiency test cycle should include higher load operating conditions. This would ensure a greater confidence that predicted efficiency results from the test stand could be realized during real world operation.

To determine what other speed and load points should be used in a final efficiency test cycle, an efficiency mapping exercise was devised to investigate and document the MTV axle's response over a wide range of conditions. In order to ensure that the efficiency test did not turn into a hardware durability test, it was decided that the maximum pinion input load would be limited to 677Nm (500lbft). This was based on what was expected to be approximately 50% of the maximum torque the powertrain package could deliver to the a single rear axle under peak operating conditions (This value was estimated based on the engines maximum peak torque output, multiplied by the transmissions typical 2nd gear starting ratio, and then factored by the advertised torque split front to rear of the vehicle). This was expected to be within the capabilities of the axle where durability would not be effected, and efficiency response would remain stable.

Prior to the mapping exercise, a secondary break-in cycle was conducted to run-in the axle up to the new maximum input load, as additional break-in of the axle was expected during higher load operation. After completion, efficiency mapping was conducted for each of the three developmental oils. Maps were created for several axle gear oil temperatures to establish the consistency of temperature impact. Figure 9, Figure 10, and Figure 11 show the resulting efficiency maps at a gear oil temperature of 79.4 °C (175 °F) (Note, the dotted line overlay at the bottom of the map represents the original operating points of the vehicle driving cycle).

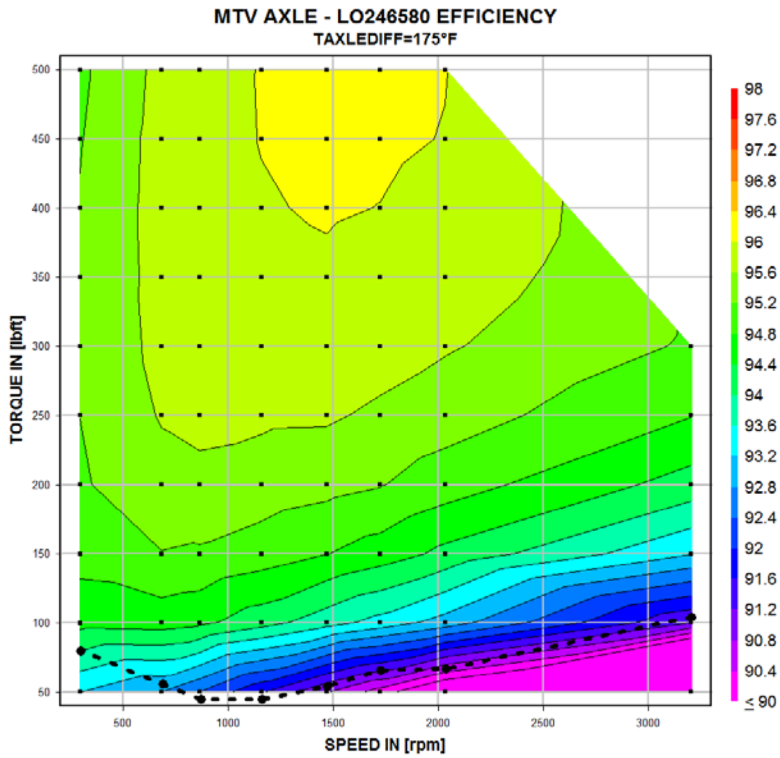

Figure 9. MTV Efficiency Map – 80W-90

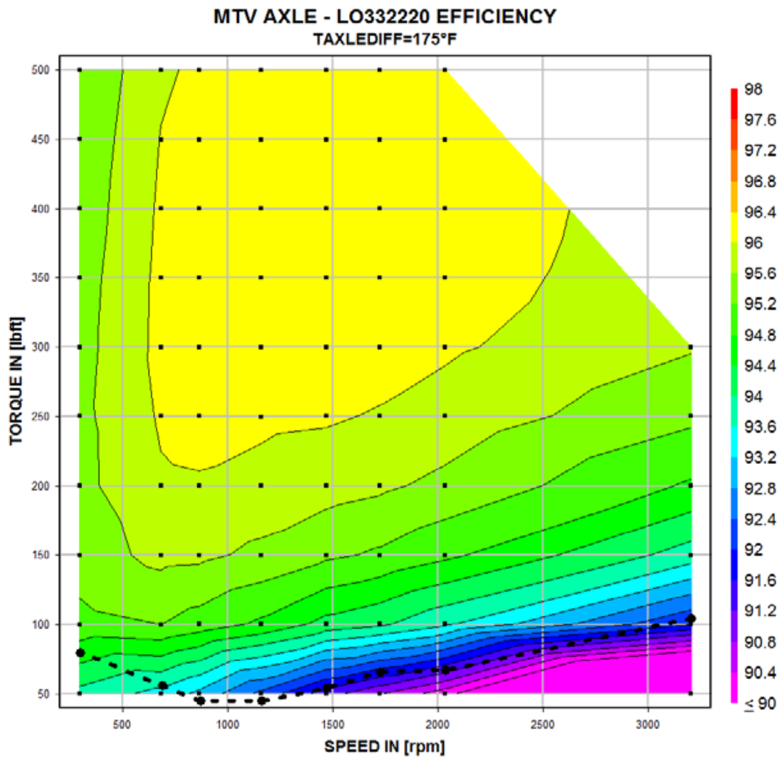

Figure 10. MTV Efficiency Map – 75W-90

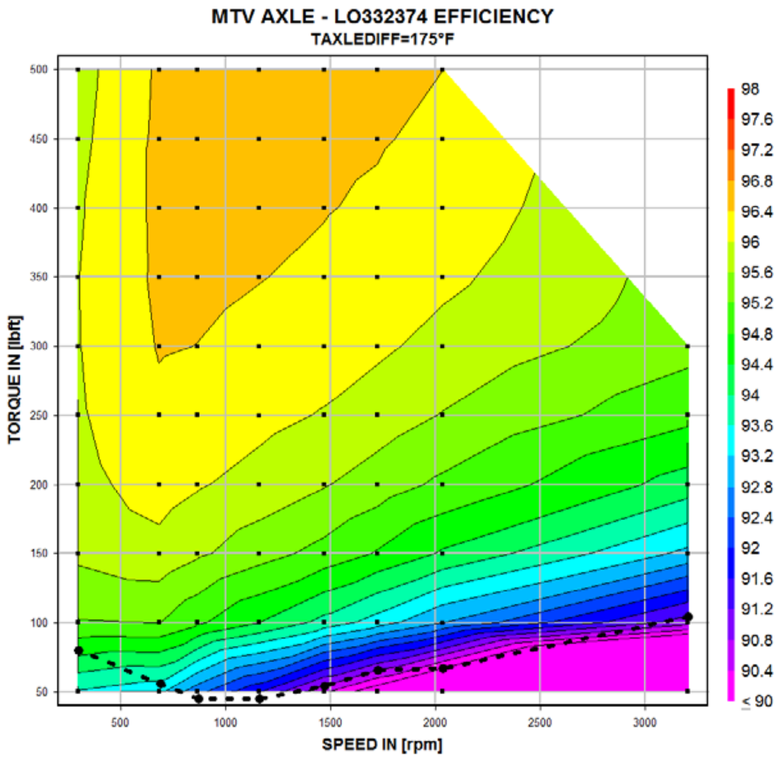

Figure 11. MTV Efficiency Map – 75W-140

From these maps it is apparent how the resulting efficiencies differ based on the oil being evaluated. The 75W-90 fluid shows improved efficiencies over the full range of operating conditions compared to the baseline 80W-90 fluid. This is consistent with the earlier stationary axle test stand results and the full scale vehicle testing. For the 75W-140, the map revealed greater detail into how its efficiency either improved or reduced based on specific operating conditions. For a large portion of the low to mid speed and high load conditions, the 75W-140 shows improved efficiency over both the baseline 80W-90 and the 75W-90. However at the low loads and especially high speeds, the 75W-140 suffers showing efficiencies below both other oils. This response from the 75W-140 is attributed to its viscosity profile. At the higher loads and low speeds when the gear mesh would be expected to be mostly effected by mixed or boundary lubrication, the higher viscosity of the 75W-140 results in an increased film thickness that aids in reducing gear mesh friction and improved efficiency. However as the load decreases and speed increases, churning losses in the differential become a large driver and the 75W-140's higher viscosity becomes a detriment. This shows how dependent on operating conditions, the ranking of these oils in terms of efficiency could vary.

Additional efficiency maps were conducted at 65.5 °C (150 °F), 93.3 °C (200 °F), and 107.2 °C (225 °F) to further understand the temperature impact. These plots are included in Appendix A for reference.

4.3 PROPOSED FEDERAL TEST METHOD CYCLE (MTV)

Based on the findings from the efficiency maps, new test points were identified for inclusion into the final efficiency test cycle for the MTV axle. To limit the growth of the overall test cycle, the existing drive cycle replication points were also reviewed to determine their necessity in the final test cycle. It was desired that the resulting test cycle would be able to capture the full spectrum of efficiency response that the MTV axle exhibited, so points were identified and selected between the original driving cycle and efficiency map results to coincide with the major efficiency islands present in the axle operation. Based on these criteria, the following points shown in Table 5 were proposed for the FTM cycle for the MTV axle. They are also shown graphically in Figure 12, overlaid on the baseline 80W-90 efficiency map. For the proposed or draft FTM cycle, the points were arranged in an order of decreasing power. Based on the previous temperature investigation and vehicle data, it was decided that the target differential oil temperature would continue to be 79.4 °C (175 °F).

Table 5. Proposed Federal Test Method Conditions for MTV Axle

Step	Approximate Vehicle Velocity	Pinion Input Speed [rpm]	Pinion Input Load	Approximate Input Power	Differential Temperature
1	40kph (25mph)	1,469	610Nm (450lbft)	94kW (126hp)	79.4 °C (175 °F)
2	56kph (35mph)	2,033	338Nm (250lbft)	72kW (97hp)	
3	40kph (25mph)	1,469	440Nm (325lbft)	68kW (91hp)	
4	72kph (45mph)	2,600	237Nm (175lbft)	65kW (87hp)	
5	24kph (15mph)	865	542Nm (400lbft)	49kW (66hp)	
6	88kph (55mph)	3,207	141Nm (104lbft)	48kW (64hp)	
7	56kph (35mph)	2,033	91Nm (67lbft)	19kW (26hp)	
8	40kph (25mph)	1,469	73Nm (54lbft)	11kW (15hp)	
9	24kph (15mph)	865	61Nm (45lbft)	5kW (7hp)	
10	8kph (5mph)	294	108Nm (80lbft)	4kW (5hp)	

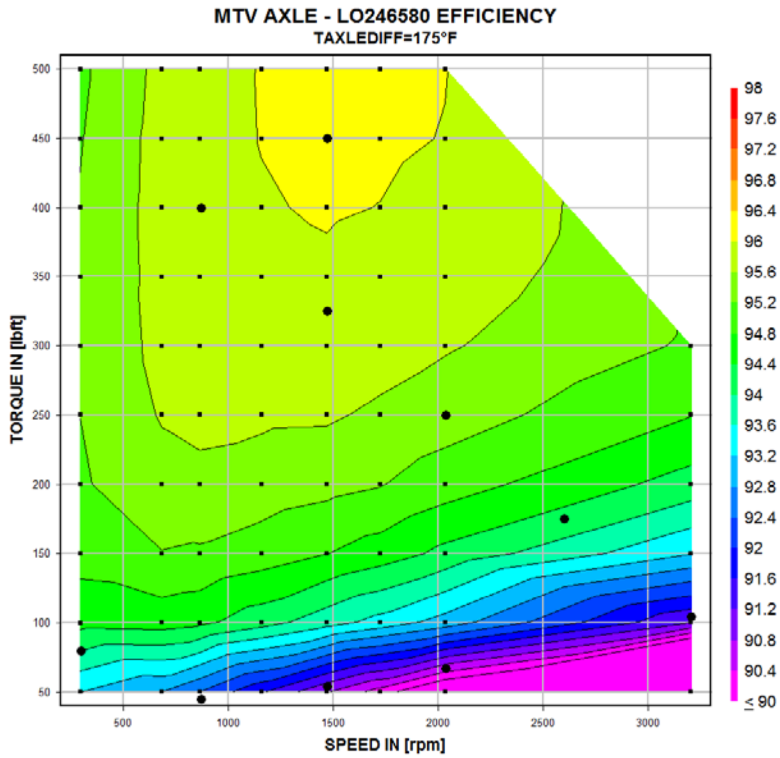

Figure 12. MTV Efficiency Map, 80W-90, Proposed FTM Point Overlay

With the proposed test points identified, evaluations were conducted for each of the three oils to measure efficiency response. Figure 13 and Figure 14 show the plotted results for the 75W-90 and 75W-140 versus the baseline 80W-90.

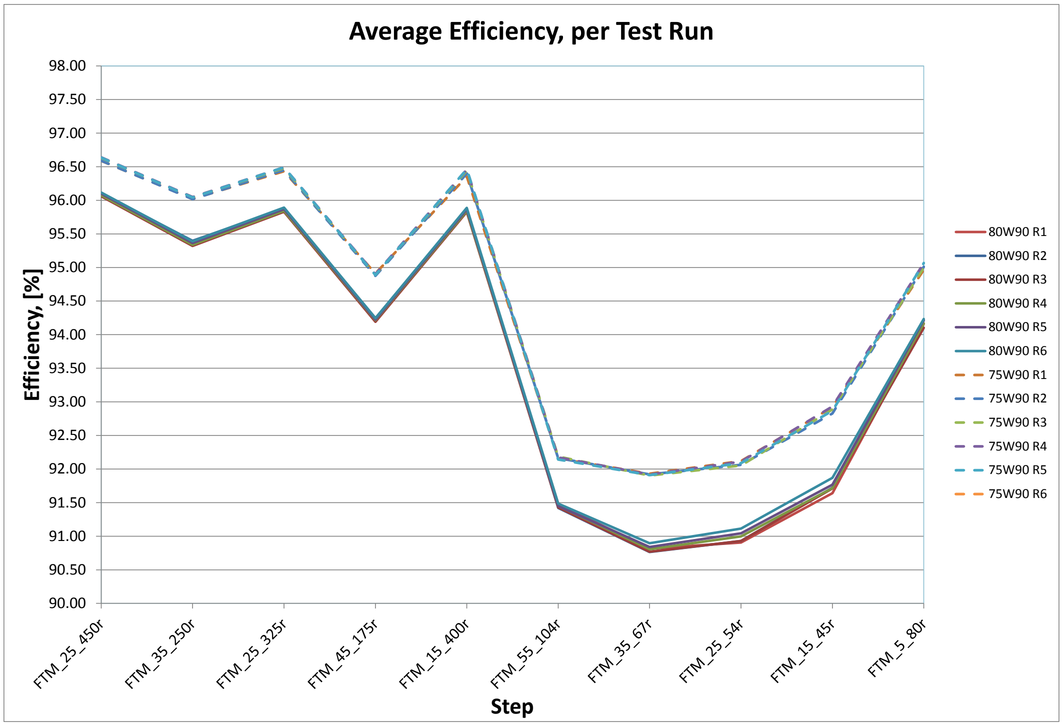

Figure 13. MTV Efficiency Results – Proposed FTM – 75W-90

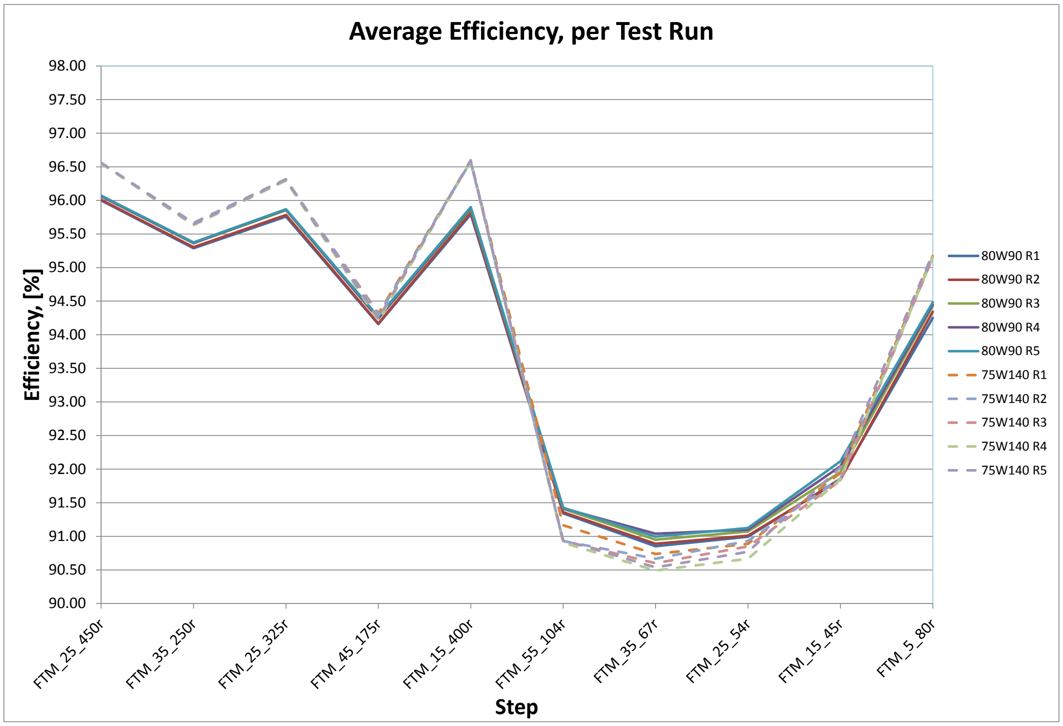

Figure 14. MTV Efficiency Results – Proposed FTM – 75W-140

The 75W-90 continued to show improved efficiency over the 80W-90 at all operating conditions using the new FTM operating points. However the 75W-140 now showed its propensity to improve, decrease, or match the 80W-90 efficiency based on the particular operating conditions. With this greater diversity in the test cycle, a more applicable weighting system could be developed to predict resulting real world efficiency changes. It is also worth noting that the visual grouping of the data for each oil appeared to be tighter and more repeatable than what was seen in the earlier lighter load vehicle cycle replication runs. This is a result of the initial stand improvement efforts, and improved control consistency with the higher load operation.

Statistical analysis was then conducted to establish the statistical significance in the changes between each oil with regards to the stands repeatability. The statistical approach was as follows. First, the variance for each oil's data set was calculated. This variance was then used in a statistical F-test model to determine if the variances between the two compared data sets could be considered equal. Based on that result, two different T-test models (one for variances equal, and one for unequal) were used to calculate the differences in means between the two compared oils, and establish upper and lower 95% confidence interval bounds. These values were calculated for each operating condition of the FTM cycle. Figure 15 and Figure 16 show the plotted improvement of each of the oils along with the confidence intervals.

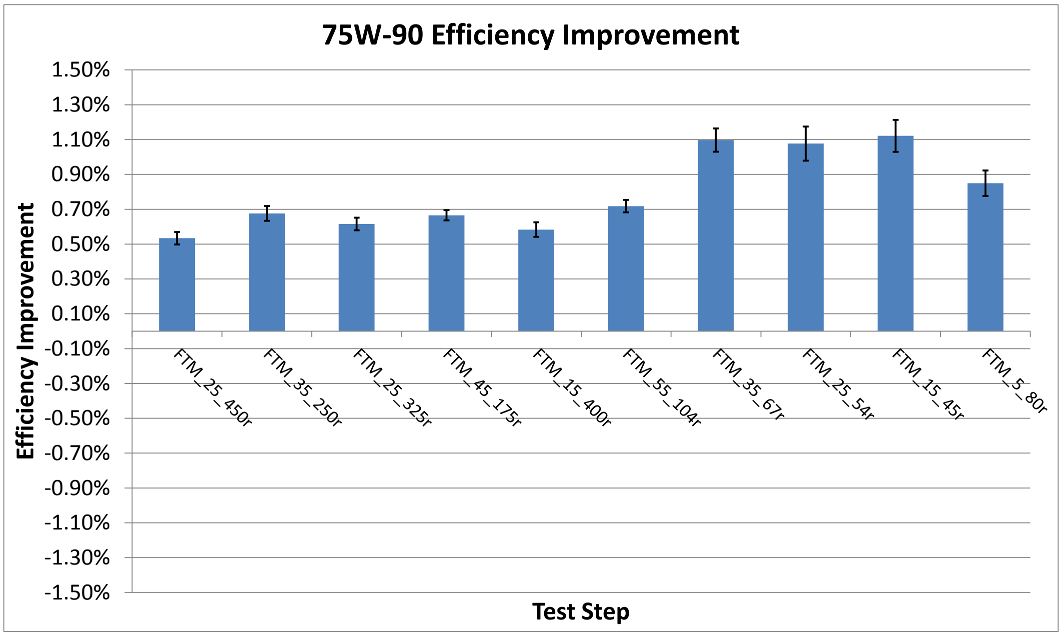

Figure 15. MTV Axle Statistical Efficiency Improvement – Proposed FTM – 75W-90

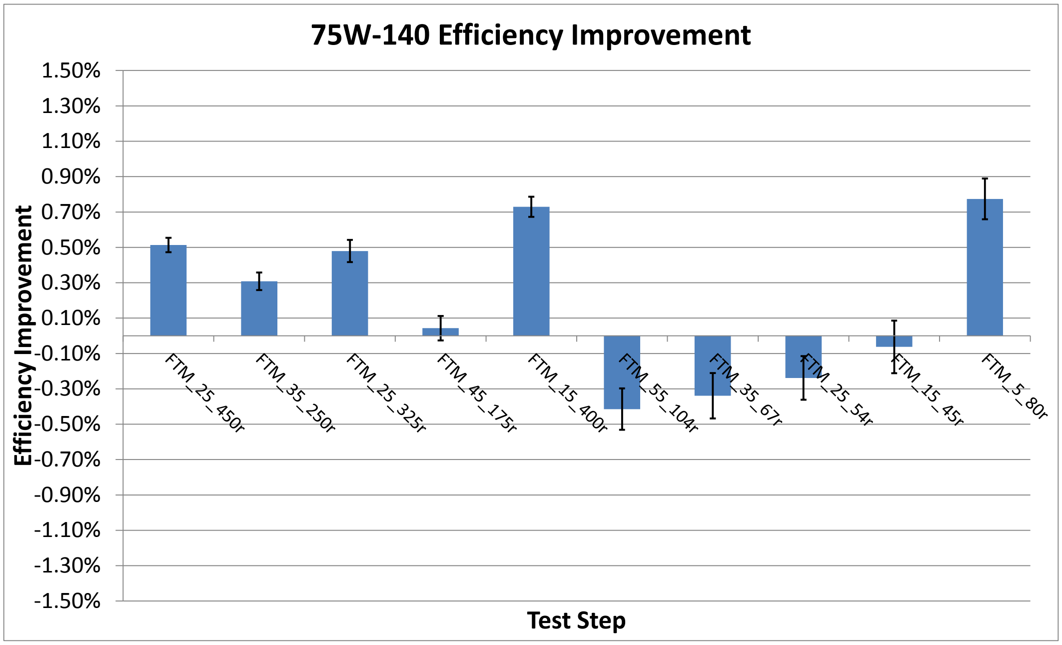

Figure 16. MTV Axle Statistical Efficiency Improvement – Proposed FTM – 75W-140

The efficiency response of the 75W-90 ranged from +0.5% to just over +1.1% improvement at all operating points. Results are clearly statistically significant, with the resulting confidence intervals being +/- 0.1% or less for all conditions. For the 75W-140, improvement ranged from +0.3% to just over +0.7% for the more highly loaded or extreme low speed points, and detriments ranged from approximately -0.2% to -0.4% where low loads or high speeds were prevalent. Although measured efficiency response was slightly more varied in the 75W-140, results for all but two of the operating points showed statistically significant difference in efficiency from the baseline 80W-90. At the completion of these tests the MTV hardware was removed from the test stand and the HMMWV hardware was installed to investigate light duty hardware performance.

5.0 HMMWV AXLE TEST DEVELOPMENT

Similar to the work conducted on the MTV hardware, the HMMWV rear differential was used to determine efficiency response of light-duty hardware used by the U.S. Army. The following sections outline the overall development process using the HMMWV hardware, starting with a description of the hardware and specifics of its installation, differential oil temperature investigation, efficiency mapping, and proposed FTM operating conditions for the light duty hardware.

(NOTE: at the completion of the MTV development work, a new batch of 80W-90 baseline oil was introduced to the stand as LO272251. As confirmed by later checks with the MTV axle reinstalled, no changes in performance were identified between the new baseline batch and the previous LO246580 batch. For all developmental testing reported for the HMMWV axle, the baseline 80W-90 was the LO272251 batch).

5.1 HMMWV Axle Installation Details

For the HMMWV, the complete rear axle consists of a separate center differential housing, two constant velocity (CV) shafts, and left and right wheel end reduction hubs. This general configuration is the same at both the front and rear of the HMMWV. To set the axle arrangement up on the stationary axle test stand, a structural frame was built to locate and support all components in their correct relative locations. Figure 17 shows an overhead shot of the structural frame constructed. The frame was built in such a way as to facilitate the removal and replacement of each component as required, specifically pertaining to the differential housing, so that components could be easily replaced to support a wide range of potential testing.

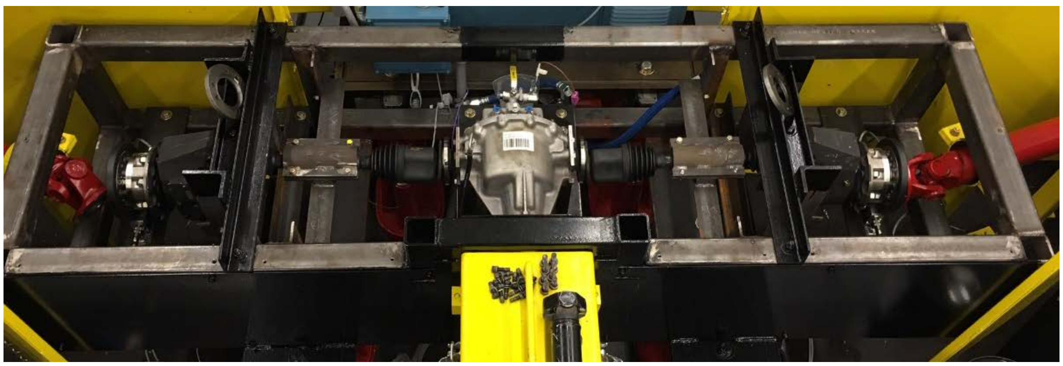

Figure 17. HMMWV Axle Installation

For differential temperature control, the center differential housing was plumbed into the same heater control loop constructed for the MTV axle. The suction/supply side of the loop was plumbed to the lower differential housing drain port, and the return side of the loop was plumbed to the differential housings fill port consistent with the MTV axle plumbing. No other changes were made to the control loops hardware or configuration for this installation. For the M1151A1 version of the HMMWV tested in this program, the rearmost differential included a factory rear differential cover that incorporated a small liquid heat exchanger internal to the differential housing. In the HMMWV, this heat exchanger is then plumbed to the coolant system and is used to control the differential gear oil temperate during operation. Although the heat exchanger was present in the tested differential housing, no cooling medium was supplied, and all temperature control was provided with the test stands heater control loop. (Note: the front differential of the HMMWV, as well as the rear differentials for earlier model HMMWV's do not have integrated cooling. They rely solely on forced convection from air cooling)

Since the wheel reduction hubs and center differential are not housed in a common system, each wheel end hub contained its own oil sump for lubrication. For all of the HMMWV testing the wheel end hubs were filled with the baseline 80W-90 gear oil, thus all changes in measured efficiency during testing were specific to the differential assembly only. In addition, the temperature of the wheel end hubs were not directly controlled during testing, apart from two small cooling fans positioned underneath the stand to provide a nominal level of cooling.

Similar to those constructed for the MTV, special output hubs where fabricated to mount the output torque flanges to wheel end reduction hub's wheel mounting flange. In addition, the output torque flanges were replaced from the MTV's 3kNm range down to a lower 2kNm range to help support better measurement resolution for the lower operating loads of the HMMWV hardware. For the input torque flange, the same 1kNm input torque flange used on the MTV axle was used. However for the HMMWV, it was relocated in between the input motor drive flange and input driveshaft as opposed to being mounted directly at the differential. This was done so that the input driveshaft could directly couple to the differential pinions factory universal joint input yoke, which could not be modified in a satisfactory manner to allow the direct mounting of the input torque meter. Apart from input and output guard changes adapted to the smaller HMMWV axle, the remainder of the stand used the same configuration as the MTV axle. Figure 18 shows the completed installation of the HMMWV axle on the stationary axle efficiency test stand.

Figure 18. Completed HMMWV Axle Installation

5.2 TEMPERATURE INVESTIGATION

Since the temperature control loop from the MTV installation was already implemented to the HMMWV differential, HMMWV vehicle data was reviewed from the SAE J1321 test cycles to determine typical operating temperatures. The full scale vehicle testing of the HMMWV's was conducted during late winter/early spring timeframe, and ambient air temperatures ranged from 1 °C (34 °F) to 38 °C (100 °F) during testing. As a result, differential temperatures observed also varied widely for the font differential of the HMMWV, which is cooled only by forced conduction. For the rear differential of the tested M1151A1, the integrated rear cooler system effected temperatures considerably. Since the rear differential is tied to the engine coolant system, it provides a heat supply to the differential helping to warm the gear oil when ambient temperatures are low and loading conditions are not severe, and provides a heat rejection source when ambient temperatures are high and operating conditions are severe. This resulted in is a much tighter range of observed operating temperatures in the rear differential. For the front differential, temperatures during operation ranged from 38 °C (100 °F) to just over 93 °C (200 °F), while for the rear differential, temperatures only ranged from 66 °C (150 °F) to 92 °C (198 °F), with an average temperature of 79.4 °C (175 °F). Based on this data, it was decided to continue with the same target differential temperature set point of 79.4 °C (175 °F) for the HMMWV axle testing.

5.3 BREAK-IN

Prior to efficiency testing the HMMWV differential was operated on a break-in cycle to ensure that differential efficiency response was stabilized prior to testing. The break-in cycle was developed to operate the HMMWV over its full range of input speed correlating with 5mph to 55mph vehicle speed. Similar to the MTV mapping exercise where an upper input torque limit was defined, a reduced maximum HMMWV input torque was established to ensure its durability was maintained. 339Nm (250lbft) was identified as approximately 50% of the maximum possible sustained load that could be supplied to the single axle by the HMMWV's powertrain, and thus was established as the maximum limit for input pinion torque for the light duty hardware (This value was estimated based on the engines maximum peak torque output, multiplied by the transmissions 1st gear ratio, high range transfer case ratio, and then factored by the advertised torque split front to rear of the vehicle). The end of the run-in was determined by plotting the resulting efficiency response versus time for the axle. Once the efficiency stabilized, the break-in was terminated. Table 6 shows the operating conditions developed for the break-in cycle. One complete pass through all 11 steps completed a single cycle. A total of 87 cycles were completed before efficiency was observed to stabilize. This was equivalent to approximately 43hrs of continuous operation, or a total of just over 1,600 accumulated miles. (Note, in general the axle is expected to experience additional break-in with continued operation over a large portion of its life. The run-in conducted for this testing just ensures that gross initial break-in effects have stabilized prior to efficiency testing.)

Table 6. HMMWV Axle Break-In Conditions

	Pinion Speed	Input Load	Duration	Approximate Power
	[RPM]	[lbft]	[min]	[hp]
warmup	2417.00	*150*	Condition Based	69
55	2954.79	200	2	113
50	2686.17	100	4	51
45	2417.56	250	2	115
40	2148.94	50	4	20
35	1880.32	150	2	54
30	1611.70	75	4	23
25	1343.09	250	2	64
20	1074.47	50	4	10
15	805.85	200	2	31
10	537.23	100	4	10
5	268.62	150	2	8

5.4 EFFICIENCY MAPPING

After break-in, development moved directly into efficiency mapping efforts. This was because loading conditions for replicating the SAE J1321 drive cycle were not available. At the time of the SAE J1321 testing, direct measurement of input pinion speed and load was outside of the scope and budget for the project, and since the HMMWV has a mechanically controlled powertrain, CAN data did not exist to use in estimating the loading conditions. For the HMMWV efficiency mapping, the differential was operated from 5mph to 55mph over an input load of 34 Nm (25lbft) to the established maximum of 339 Nm (250lbft) maximum to map efficiency response. Figure 19, Figure 20, and Figure 21 show the results of the efficiency mapping for the 80W-90, 75W-90, and 75W-140 oils respectively. All mapping was conducted at the controlled differential fluid temperature of 79.4 °C (175 °F).

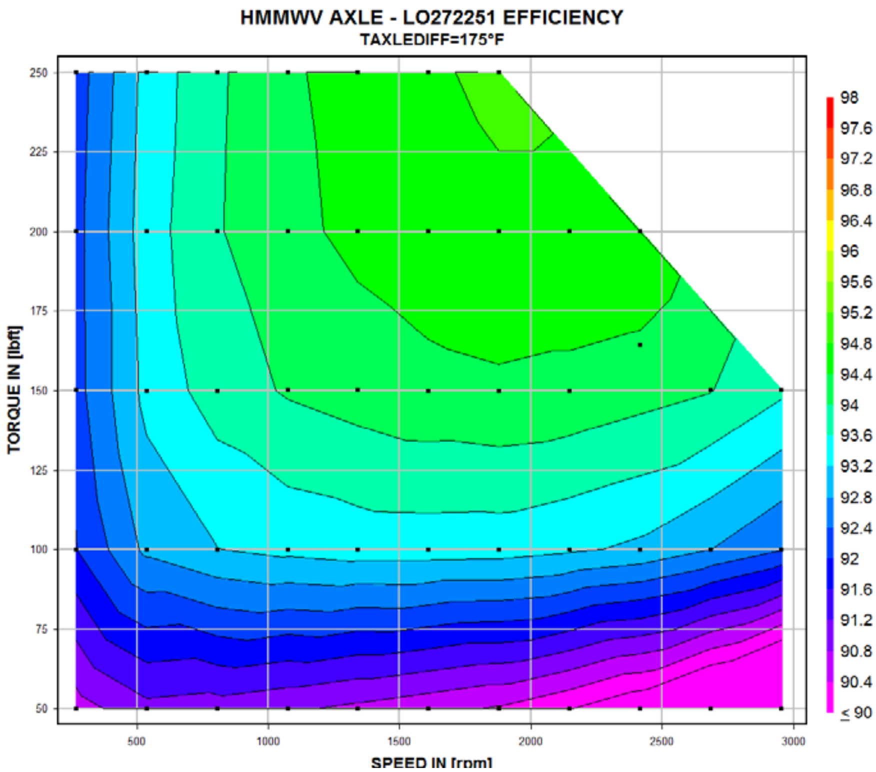

Figure 19. HMMWV Efficiency Map – 80W-90

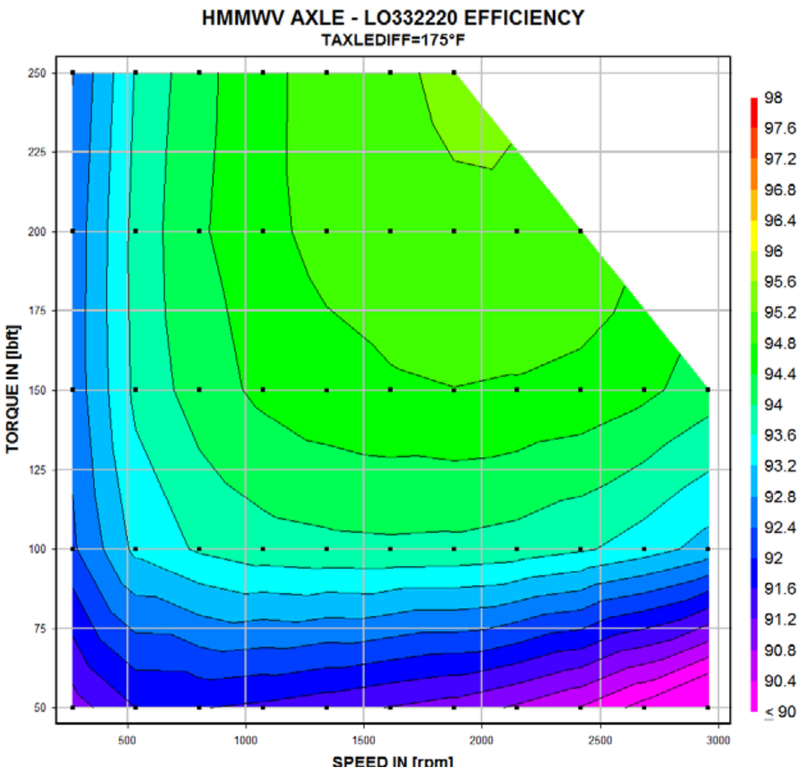

Figure 20. HMMWV Efficiency Map – 75W-90

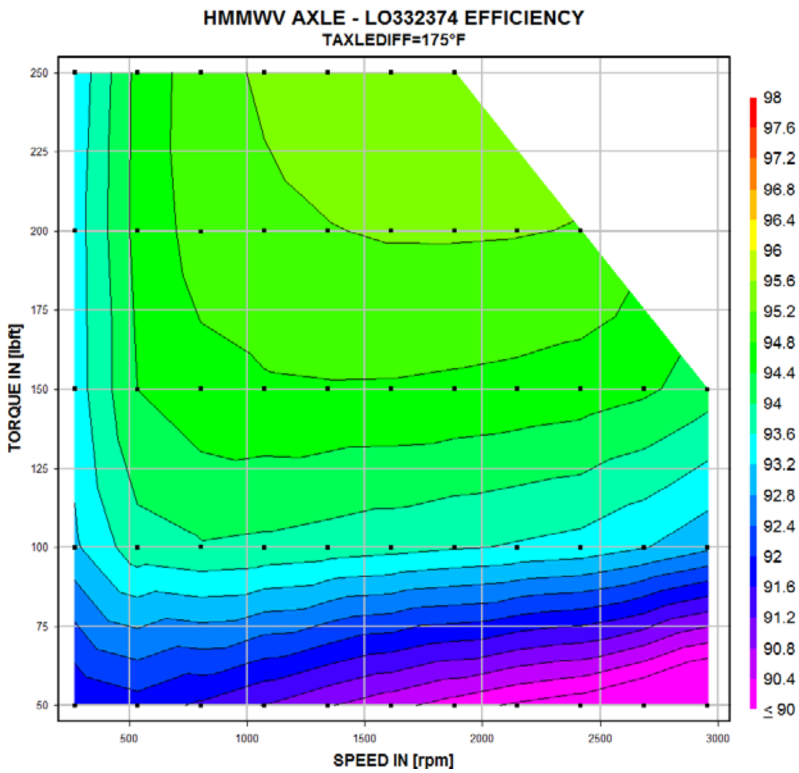

Figure 21. HMMWV Efficiency Map – 75W-140

When scaled the same as the MTV maps, it was immediately observed that the overall efficiency level of the HMMWV differential was much lower than the MTV axle. However, much of the general efficiency trends between the oils observed in the MTV axle persisted in the HMMWV axle. Overall the 75W-90 showed an improved efficiency response across the entire map compared to the 80W-90, and the 75W-140 showed even greater gains than both the baseline 80W-90 and 75W-90 in loads greater than 100lbft. One distinct difference in response between the HMMWV and MTV maps was the observed lack of efficiency loss at higher speeds and low loads with the 75W-140. Unlike the losses that appeared for the MTV axle in this area, churning losses in the HMMWV differential as a result of increased viscosity didn't appear as prominent. This was attributed to overall differential oil capacity differences between the two axles. For the HMMWV, oil capacity is approximately 1.9L (2qts), while the MTV has a capacity of approximately 13.2L (3.5gal).

5.5 PROPOSED FEDERAL TEST METHOD CYCLE (HMMWV)

With the efficiency mapping data collected, investigation into proposed test points for an efficiency test cycle began. Since driving cycle data from the SAE J1321 tests did not exist, other sources of vehicle operating data was investigated for applicability. In previously identified work supported by the U.S. Army TARDEC and Southwest Research Institute (SwRI), investigation into HMMWV differential efficiency was conducted to determine effects of super-finished hypoid gear sets for the HMMWV over a Peacetime – Operational Mode Summary/Mission Profile (OMS/MP) [7]. In this work, detailed axle pinion loads and speeds for the HMMWV were identified through use of vehicle simulation under a peacetime type operational duty cycle. As this operational cycle was considered representative of typical military HMMWV use, this same data set was revisited to determine applicability in defining points for an efficiency test cycle.

Figure 22 shows the plotted results for the differential input torque versus vehicle speed for the Peace Time OMS/MP. The full set of operating points were trimmed to the core usable area for the efficiency test, eliminating any vehicle speeds lower than 5mph, and any torque values higher than 338Nm (250lbft) or less than zero (the simulation included possible downhill gradients where engine braking occurred, resulting in negative pinion input torque). With the remaining data, the input torque conditions were binned based on discrete vehicle speed and torque ranges to determine the frequency of operation in a particular area. This identified the most common occurring input loads and speeds. Table 7 shows the resulting input torque versus vehicle speed frequency bins.

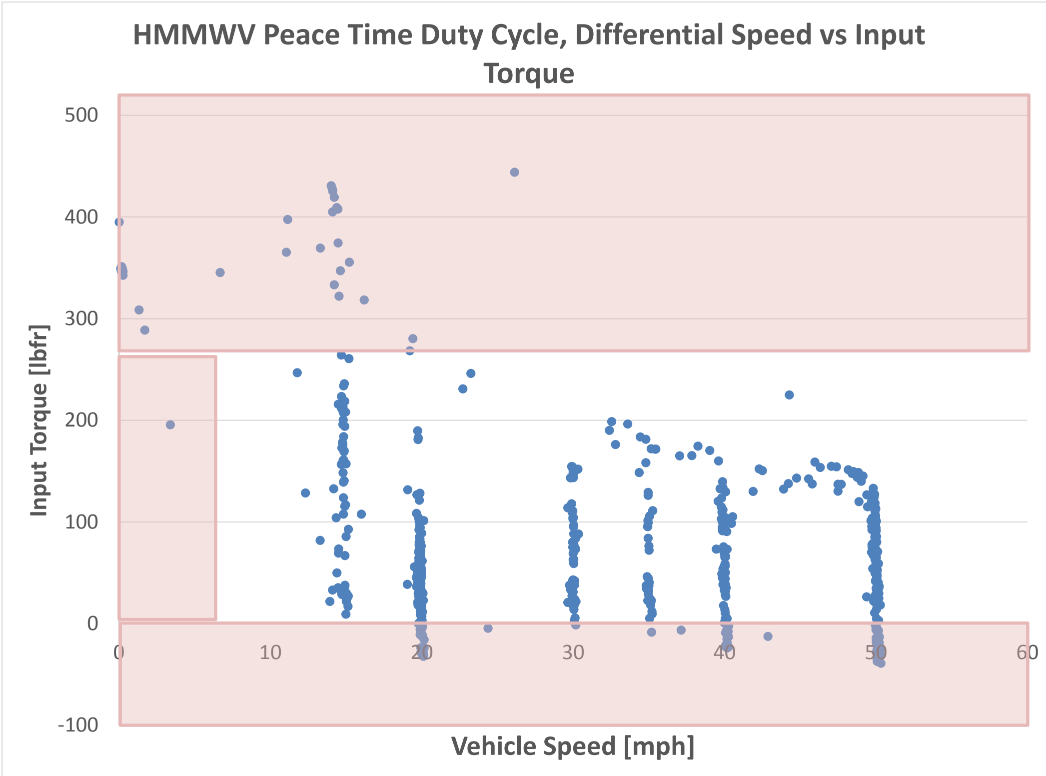

Figure 22. HMMWV Peace Time Duty Cycle Differential Input Conditions

Table 7. HMMWV Peace Time Duty Cycle Torque/Speed Bins

Pinion Input Torque Bins [lbft]	Vehicle Speed Bins [mph] 15	20	30	35	40	45	50
25	57	116	13	17	15	0	24
50	2	129	7	4	16	0	21
75	5	24	11	3	8	0	32
100	4	14	9	6	18	0	34
125	5	5	2	2	7	5	16
150	8	0	10	2	4	7	11
175	6	2	0	7	3	0	0
200	6	1	2	1	0	0	0
225	6	1	0	0	0	1	0
250	1	1	0	0	0	0	0

From this data and the previous efficiency mapping data, 10 discrete speed and load points were identified and proposed for the HMMWV FTM test cycle (see Table 8).

Table 8. HMMWV Proposed FTM Operating Conditions

Approximate Vehicle Velocity	Pinion Input Speed [rpm]	Pinion Input Load	Approximate Input Power	Differential Oil Temperature
80kph (50mph)	2,686	136Nm (100lbft)	38kW (51hp)	79.4 °C (175 °F)
48kph (30mph)	1,611	203Nm (150lbft)	34kW (46hp)	
64kph (40mph)	2,149	135Nm (100lbft)	31kW (41hp)	
80kph (50mph)	2,686	102Nm (75lbft)	28kW (38hp)	
24kph (15mph)	806	271Nm (200lbft)	23kW (31hp)	
80kph (50mph)	2,686	68Nm (50lbft)	19kW (26hp)	
80kph (50mph)	2,686	47Nm (35lbft)	13kW (18hp)	
32kph (20mph)	1,074	102Nm (75lbft)	11kW (15hp)	
32kph (20mph)	1,074	68Nm (50lbft)	7kW (10hp)	
32kph (20mph)	1,074	47Nm (35lbft)	5kW (7hp)	

The HMMWV axle was then operated over the proposed FTM cycle for all three of the oils. As with the MTV, the operational order was conducted in the order of decreasing power, and multiple runs were conducted to establish a basis to determine statistical significance. The plotted results are shown in Figure 23 and Figure 24.

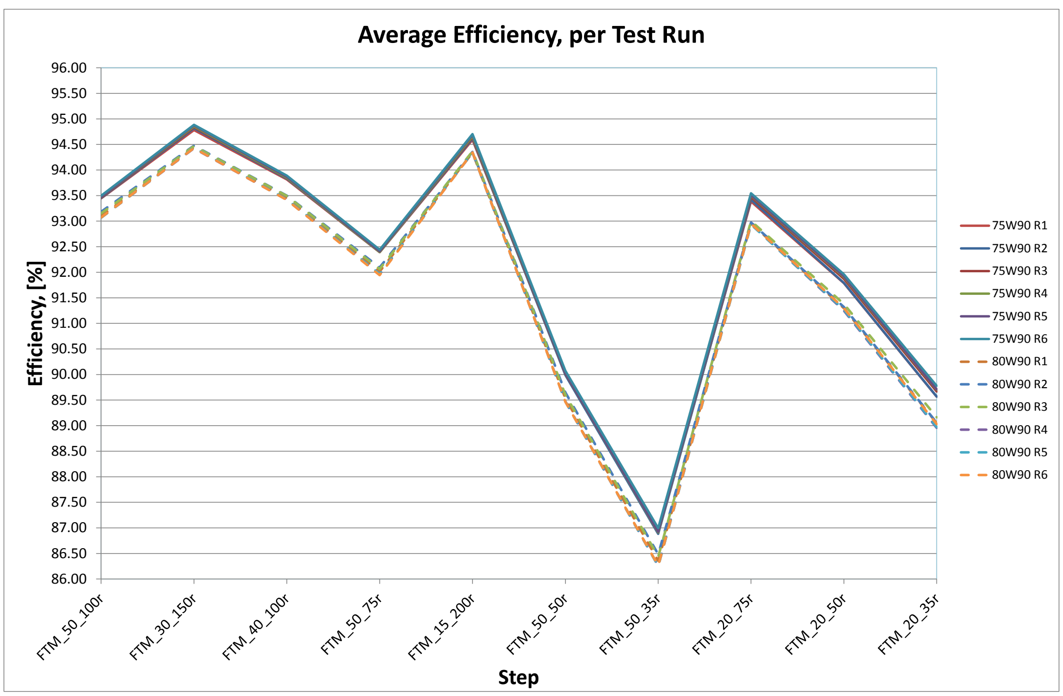

Figure 23. HMMWV Efficiency Results – Proposed FTM – 75W-90

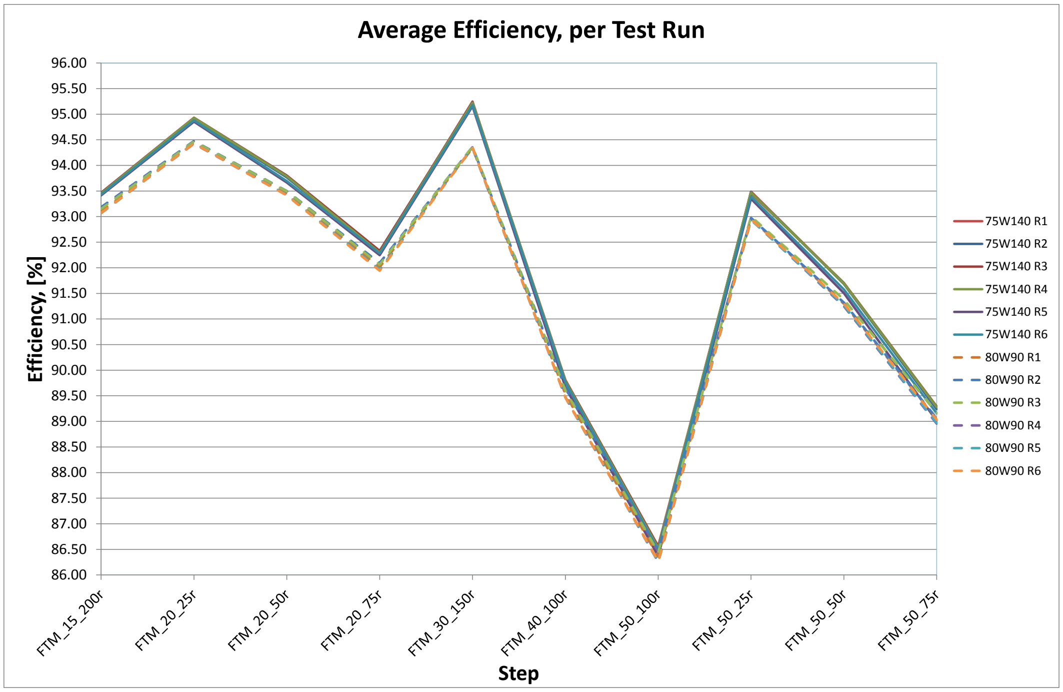

Figure 24. HMMWV Proposed Efficiency Results – Proposed FTM – 75W-140

Statistical analysis was conducted on the HMMWV data to determine significance in results. The plotted results showing efficiency improvement and resulting confidence interval at each point can be seen in Figure 25 and Figure 26.

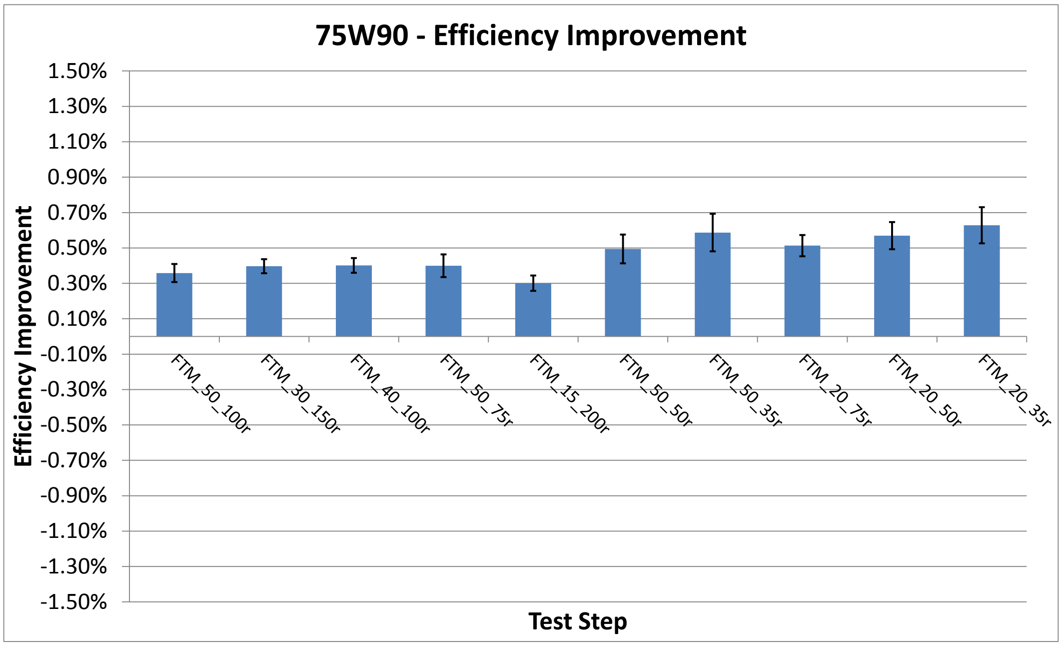

Figure 25. HMMWV Axle Statistical Efficiency Improvement – Proposed FTM – 75W-90

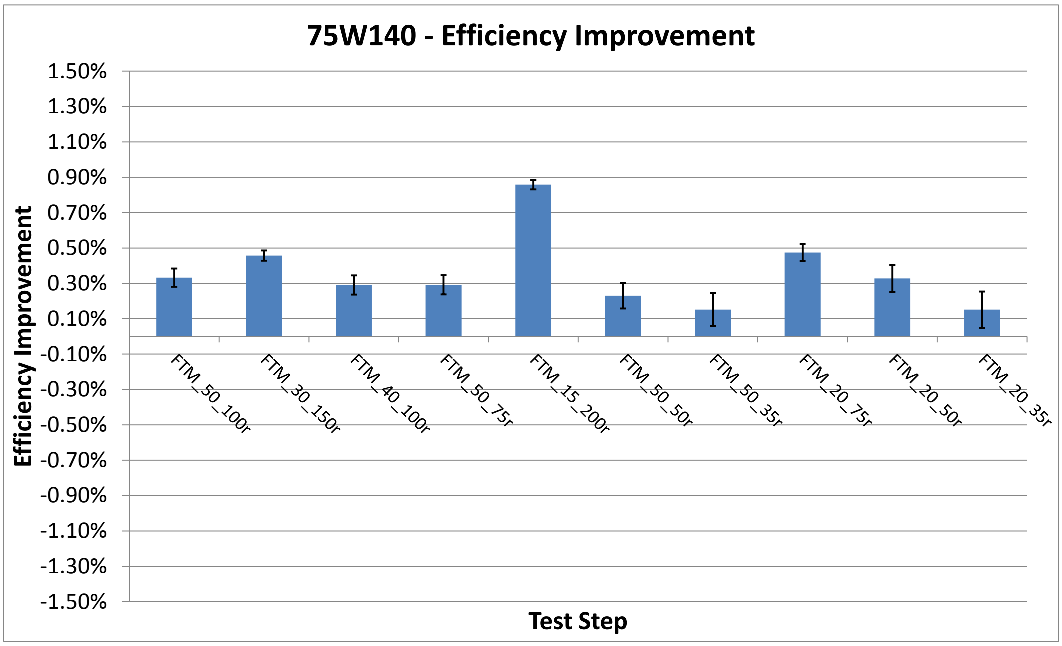

Figure 26. HMMWV Axle Statistical Efficiency Improvement – Proposed FTM – 75W-140

The 75W-90 showed gains ranging from +0.3% to +0.6% improvement over the 80W-90 for all operating conditions. Similar to the MTV testing, repeatability in the results was excellent, with resulting confidence intervals of +/- 0.1% or less for each condition. For the 75W-140, results ranged from approximately +0.15% to about +0.85% improvement, with confidence intervals again being +/- 0.1% or less. This trended correctly with the data derived from the SAE J1321 testing. Also clearly evident is the impact of the 75W-140 on efficiency related to load. For the highest 200lbft input pinion condition, the resulting efficiency improvement was the greatest compared to all other points for both the 75W-90 and 80W-90.

6.0 Final Federal Test Method Development

With development completed for the MTV and HMMWV, focus shifted to defining the final draft FTM. The following sections cover the down select rationale for the hardware selected for the FTM, documentation of the desired test procedure, re-testing of the baseline and developmental oils, and testing a selection of commercially available candidates to bolster the efficiency result data base.

(NOTE: at the completion of the HMMWV development work, a new batch of 80W-90 baseline oil was introduced to the stand as LO330868. With this batch change, some minor shift in baseline performance was identified between the new baseline batch and the previous LO272251 and LO246580 batches. Changes in performance were noted primarily at the low load operating points in the MTV axle, yielding a slightly higher resulting efficiency at those point versus the previous baseline data collected. For all testing reported from here out, the baseline 80W-90 is the latest LO330868 batch).

6.1 HARDWARE DOWN-SELECT

The MTV axle was selected for the proposed final FTM based on the results from the developmental process, and consideration of the test stand installation and representation in the current military fleet. The rationale for this selection is as follows:

- The MTV axle utilizes a common oil sump for the differential and wheel end hub reductions as opposed to the HMMWV's separate wheel end reduction hubs. This provides greater consistency, and ensures the entire axle system responds to changes in the lubricant composition and/or operating conditions.
- The HMMWV, although currently numerous in the fleet, is an aging light tactical platform with a replacement vehicle in development. HMMWV utilization and numbers in the fleet are expected to see a marked reduction in the future.
- The MTV being the representative "medium" sized axle provides a good middle ground approach for representing the wide range of military hardware currently fielded.
- Current and future "light" tactical vehicle hardware is approaching the same overall vehicle size and weight (thus driveline hardware size) as the current medium tactical vehicle range, thus the MTV axle should have good relevancy to future light tactical vehicles.

6.2 TEST PROCEDURE DOCUMENTATION

A draft FTM procedure was created to document the final testing procedure specific to the MTV axle (See Appendix B). There were no significant changes made to the scope or procedure from that followed during the earlier development process, apart from some minor adjustment to one of the input operating speeds to attenuate an undesirable dynamic instability in the driveline experienced during operation (35mph point changed from 2033rpm to 2100rpm). This change in input pinion speed was referenced against the efficiency map prior to implementation, and was noted to not represent any significant shift in the operating efficiency island that the point was aimed to capture. Table 9 outlines the final operating conditions for the FTM.

Table 9. Final MTV Axle FTM Input Speed and Load Conditions

Step	Approximate Vehicle Velocity	Pinion Input Speed [rpm]	Pinion Input Load	Approximate Input Power	Differential Temperature
1	40kph (25mph)	1,469	610Nm (450lbft)	94kW (126hp)	79.4 °C (175 °F)
2	56kph (35mph)	2,100	338Nm (250lbft)	75kW (100hp)	
3	40kph (25mph)	1,469	440Nm (325lbft)	68kW (91hp)	
4	72kph (45mph)	2,600	237Nm (175lbft)	65kW (87hp)	
5	24kph (15mph)	865	542Nm (400lbft)	49kW (66hp)	
6	88kph (55mph)	3,207	141Nm (104lbft)	48kW (64hp)	
7	56kph (35mph)	2,100	91Nm (67lbft)	20kW (27hp)	
8	40kph (25mph)	1,469	73Nm (54lbft)	11kW (15hp)	
9	24kph (15mph)	865	61Nm (45lbft)	5kW (7hp)	
10	8kph (5mph)	294	108Nm (80lbft)	4kW (5hp)	

The following sections outline details regarding the double flush procedure used in changing between tested fluids in the axle, the general efficiency test procedure, and calculations used in data analysis.

6.2.1 Double Flush Fluid Change

A double flush procedure is used to ensure that a thorough changeover occurs between tested lubricants. Samples pulled during the development process have demonstrated that changeover efficiencies of the double flush procedure are in the high 90% range. The following steps pulled from the proposed FTM outline the general procedure for a double flush:

1. If starting with the axle already drained, proceed to step 3. If starting with the axle full, start the test stand and operate the axle at approximately 3200 rpm and 200 lbft until the differential fluid temperature is ≥ 175 °F.

2. Next 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.

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. 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 rear of the axle).

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

5. Turn off the circulation pump and reposition the three way valve at the rear fill port of the axle to the vent position. Add fluid to the axle housing through the upper vent port until the fluid level is topped off to the rear housing fill port level (this is noted by a trickle of fluid from the vented three way valve on the rear of the axle).

6. Reposition the three way valve at the rear fill port of the axle back to the recirculation position for testing.

7. Repeat steps 1 through 6 to complete the second flush.

6.2.2 General Efficiency Test Procedure

At the start of the testing 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 back to the reference lubricant, and an additional single baseline run is conducted using the reference oil to determine test validity. The overall test is considered valid if the post-candidate reference run returns data 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. The general procedure for conducting a single run on the stationary axle efficiency test stand is as follows:

1. Start the test stand and ramp the axle to step 1 test conditions (see Table 9) and hold until the differential oil temperature reaches 175 °F +/- 1 °F.

2. Once the differential oil reaches temperature, progress the axle through the speed and load points outlined in Table 9 while logging (at a minimum) input torque, left and right output torque, input speed, output speed, and axle differential fluid temperature.

3. Operation at each test condition of the FTM 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 data recording sub-step.

4. During the stabilization sub-step, the axle should be operated at the specified test condition in Table 9 for a minimum of 5 minutes, and the moving average of the axle differential fluid temperature should be 175 +/- 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 a minimum of 0.2 Hz (5 sec).

5. 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 test condition for stabilization.

6. 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.

6.2.3 Calculations

All calculations are completed using the data from the data recording sub-step captured after the stabilization step at each speed and load condition. To determine overall efficiency for a reference or candidate run, efficiency for each step of all 10 cycles is calculated as follows:

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

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

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

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

From these calculations, a matrix of efficiency is compiled for a baseline or candidate run. An example is shown below in Table 10, where "xx" denotes the calculated efficiency for cycles 2 through 10 of a 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).

Table 10. Example Single Run Results Table

	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

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, a composite result table for a single run is shown in Table 11.

Table 11. Example Composite Single Run Result Table

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

A minimum of 5 composite runs must be conducted for each baseline or candidate test. After all 5 composite runs are completed, a baseline or candidate composite result table can be formed. An example is shown Table 12.

Table 12. Example Baseline/Candidate Composite Result Table

	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

Once a composite result table for the baseline and candidate oil has been established, statistical analysis can be conducted to determine overall efficiency change and confidence interval for each operating condition. For both the baseline and candidate test composite result table, calculate the mean, standard deviation, and variance for each individual operating condition.

Table 13. Statistical Analysis Table

	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

For each step, conduct an F-Test to determine if the baseline and candidate tests have equal variances. Based on the results of F-Test, conduct an appropriate T-Test for each step between the baseline and candidate test to establish the statistical significance (95% confidence interval) of the difference in means. Final results should be complied in a single table as shown below.

Table 14. Example Final Results Table

	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

6.3 FINAL TEST RESULTS

Using the proposed final FTM procedure, a full matrix of efficiency tests were initiated. This included baseline segments between each individual FEGO candidate, and the FEGO candidates included the developmental 75W-90 and 75W-140, as well as second 75W-90 from an alternate supplier, a 75W-85, and a 75W-110 product. The following sections outline the chemical and physical properties for each oil, and the final efficiency results for each.

6.3.1 Baseline and FEGO Chemical & Physical Analysis

Table 15 contains the basic chemical and physical properties of the baseline and candidate gear oils tested in the final matrix. Shown is the elemental analysis which gives some indication of the additive pack differences between oils, as well as measured viscosity at 40 °C (104 °F) and 100 °C (212 °F), and calculated viscosity at the operating temperature of 79.4 °C (175 °F). Based on the chemical and physical properties and the actual efficiency results that follow, it is identified that the efficiency of the MTV axle is not only a singular viscosity response, and that additive chemistry also plays an important role in resulting efficiency (Reference 6.3.2 and 6.3.4 which tested two different formulations of a 75W-90 product with different resulting efficiencies).

Table 15. Baseline and Candidate FEGO Chemical and Physical Properties

Test	ASTM Method	Units	LO330868 Baseline 80W-90	LO332374 Developmental 75W-140	LO332220 Developmental 75W-90	LO310411 Candidate 75W-90	LO338028 Candidate 75W-85	LO351656 Candidate 75W-110
Elements	D5185							
Aluminum		ppm	<1	<1	<1	<1	<1	<1
Antimony		ppm	<1	<1	<1	4	<1	<1
Barium		ppm	<1	<1	<1	<1	<1	<1
Boron		ppm	233	224	151	150	283	238
Calcium		ppm	7	<1	3	10	<1	<1
Chromium		ppm	<1	<1	<1	<1	<1	<1
Copper		ppm	<1	<1	<1	<1	<1	<1
Iron		ppm	<1	<1	<1	<1	<1	<1
Lead		ppm	<1	<1	<1	<1	<1	<1
Magnesium		ppm	<1	<1	10	2	<1	<1
Manganese		ppm	<1	<1	<1	<1	<1	<1
Molybdenum		ppm	<1	<1	<1	<1	<1	<1
Nickel		ppm	<1	<1	<1	<1	<1	<1
Phosphorus		ppm	942	1331	1812	980	1289	1351
Silicon		ppm	<1	<1	<1	<1	<1	<1
Silver		ppm	<1	<1	<1	<1	<1	<1
Sodium		ppm	<5	<5	<5	<5	<5	<5
Tin		ppm	<1	<1	<1	<1	<1	<1
Zinc		ppm	5	<1	2	2	<1	1
Potassium		ppm	<5	<5	<5	<5	<5	<5
Strontium		ppm	<1	<1	<1	<1	<1	<1
Vanadium		ppm	<1	<1	<1	<1	<1	<1
Titanium		ppm	<1	<1	<1	<1	<1	<1
Cadmium		ppm	<1	<1	<1	<1	<1	<1
Kinematic Viscosity	D445							
Test Temperature		°C	40	40	40	40	40	40
Viscosity		mm²/s	138.81	178.28	87.27	100.55	65.08	151.9
Kinematic Viscosity	D445							
Test Temperature		°C	100	100	100	100	100	100
Viscosity		mm²/s	14.63	24.43	13.97	16.11	11.25	22.57
Kinematic Viscosity (Calculated)	D341							
Test Temperature		°C	79.4	79.4	79.4	79.4	79.4	79.4
Viscosity		mm²/s	26.62	42.29	23.09	26.69	18.2	38.28

6.3.2 Developmental 75W-90

Figure 27 and Table 16 and Figure 28 show the final efficiency improvement measured from the developmental 75W-90 candidate LO332220. The overall average improvement in efficiency over the baseline 80W-90 was +0.615% (max of 0.793%, min of 0.487%).

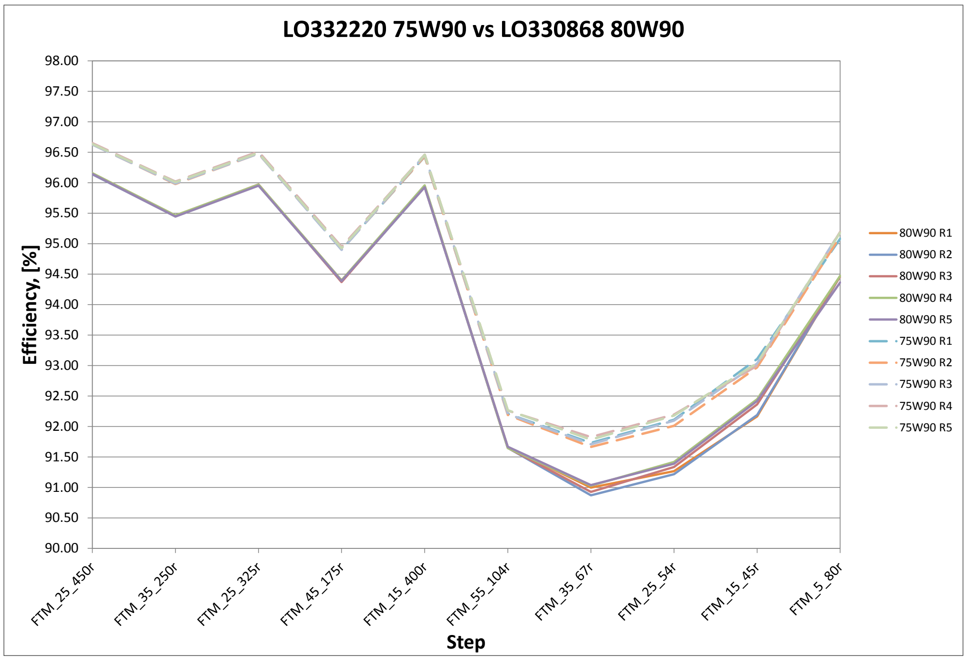

Figure 27. MTV Axle LO332270 75W-90 vs LO330868 80W-90 (Plotted)

Table 16. MTV Axle LO332270 75W-90 vs LO330868 80W-90 (Statistical Tabular)

LO332220	Candidate Improvement Over Baseline	Step #	Statistical Difference Between Oils	Estimated Efficiency Change	95% Confidence Interval	
		FTM_25_450r	Yes	0.487%	±	0.013%
		FTM_35_250r	Yes	0.541%	±	0.021%
		FTM_25_325r	Yes	0.526%	±	0.017%
		FTM_45_175r	Yes	0.531%	±	0.024%
		FTM_15_400r	Yes	0.508%	±	0.020%
		FTM_55_104r	Yes	0.570%	±	0.043%
		FTM_35_67r	Yes	0.770%	±	0.099%
		FTM_25_54r	Yes	0.793%	±	0.115%
		FTM_15_45r	Yes	0.713%	±	0.146%
		FTM_5_80r	Yes	0.709%	±	0.072%

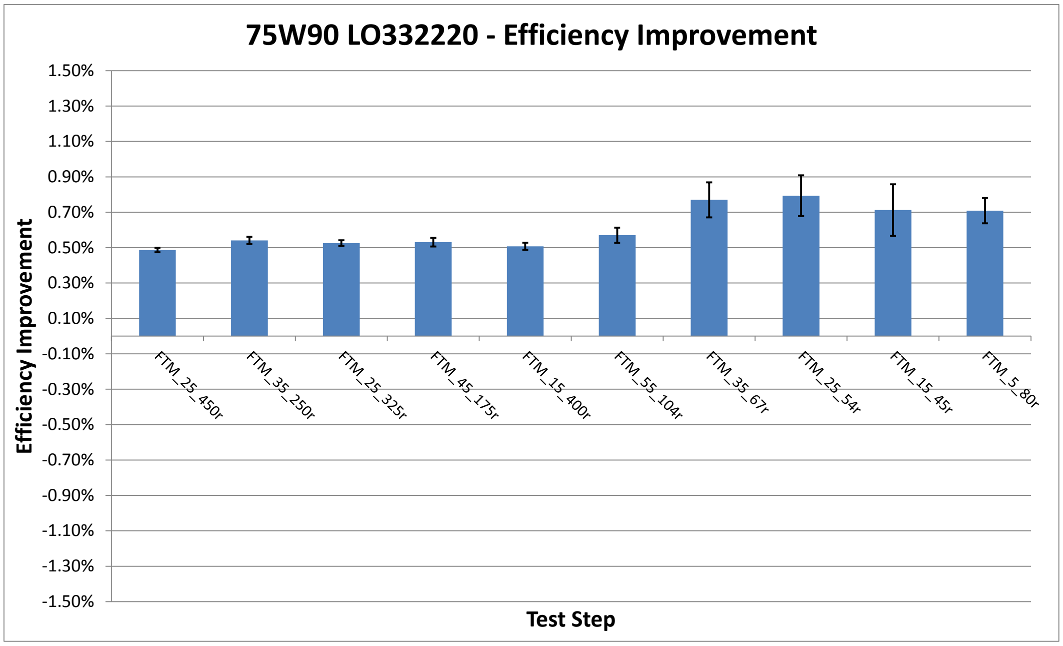

Figure 28. MTV Axle LO332270 75W-90 vs LO330868 80W-90 (Statistical Plotted)

6.3.3 Developmental 75W-140

Figure 29, Table 17 and Figure 30 show the final efficiency improvement measured from the developmental 75W-140 candidate LO332374. The overall average improvement in efficiency over the baseline 80W-90 was +0.033% (max of 0.641%, min of -0.544%).

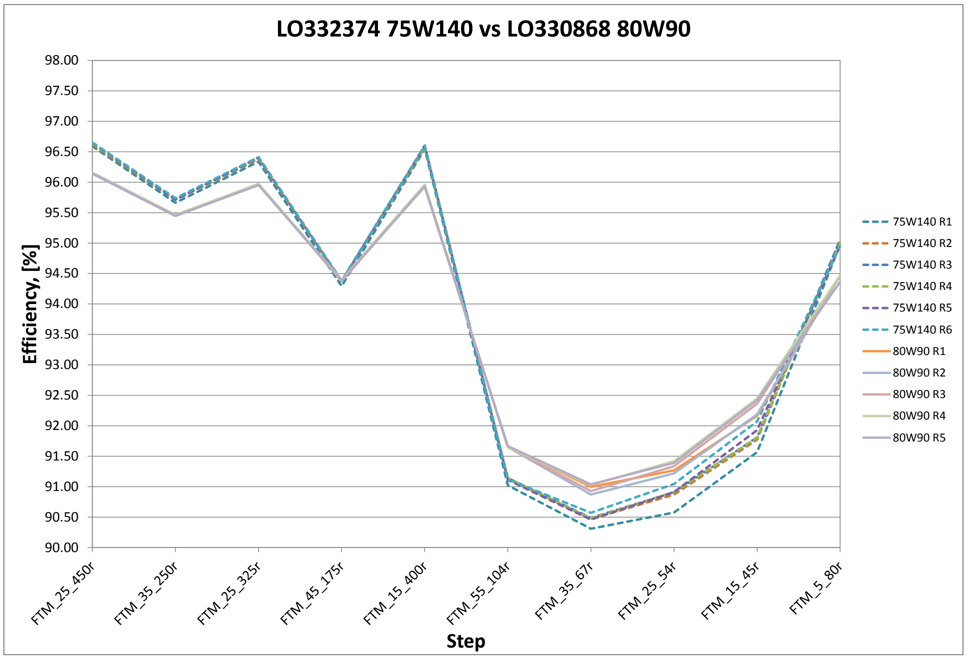

Figure 29. MTV Axle LO332374 75W-140 vs LO330868 80W-90 (Plotted)

Table 17. MTV Axle LO332374 75W-140 vs LO330868 80W-90 (Statistical Tabular)

		Step #	Statistical Difference Between Oils	Estimated Efficiency Change	95% Confidence Interval	
LO332374	Candidate Improvement Over Baseline	FTM_25_450r	Yes	0.480%	±	0.025%
		FTM_35_250r	Yes	0.255%	±	0.027%
		FTM_25_325r	Yes	0.424%	±	0.029%
		FTM_45_175r	No	N/A	±	0.037%
		FTM_15_400r	Yes	0.641%	±	0.026%
		FTM_55_104r	Yes	-0.544%	±	0.048%
		FTM_35_67r	Yes	-0.510%	±	0.109%
		FTM_25_54r	Yes	-0.456%	±	0.177%
		FTM_15_45r	Yes	-0.491%	±	0.210%
		FTM_5_80r	Yes	0.555%	±	0.064%

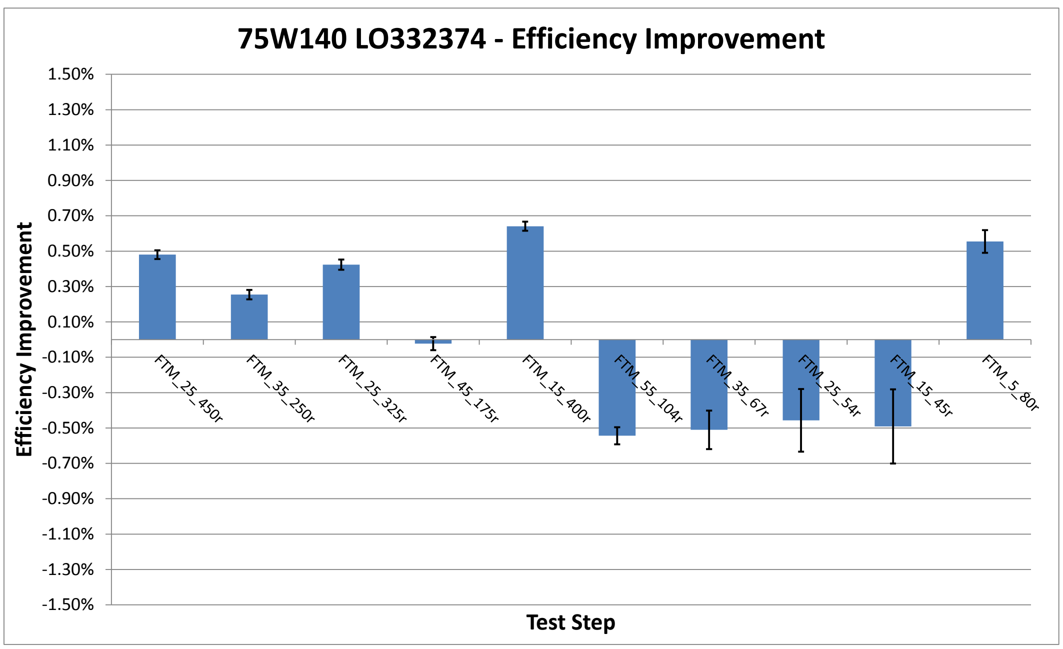

Figure 30. MTV Axle LO332374 75W-140 vs LO330868 80W-90 (Statistical Plotted)

6.3.4 Commercial 75W-90

Figure 31, Table 18 and Figure 32 show the efficiency improvement measured from the alternate supplier 75W-90 candidate LO310411. The overall average improvement in efficiency over the baseline 80W-90 was +0.709% (max of 1.029%, min of 0.531%).

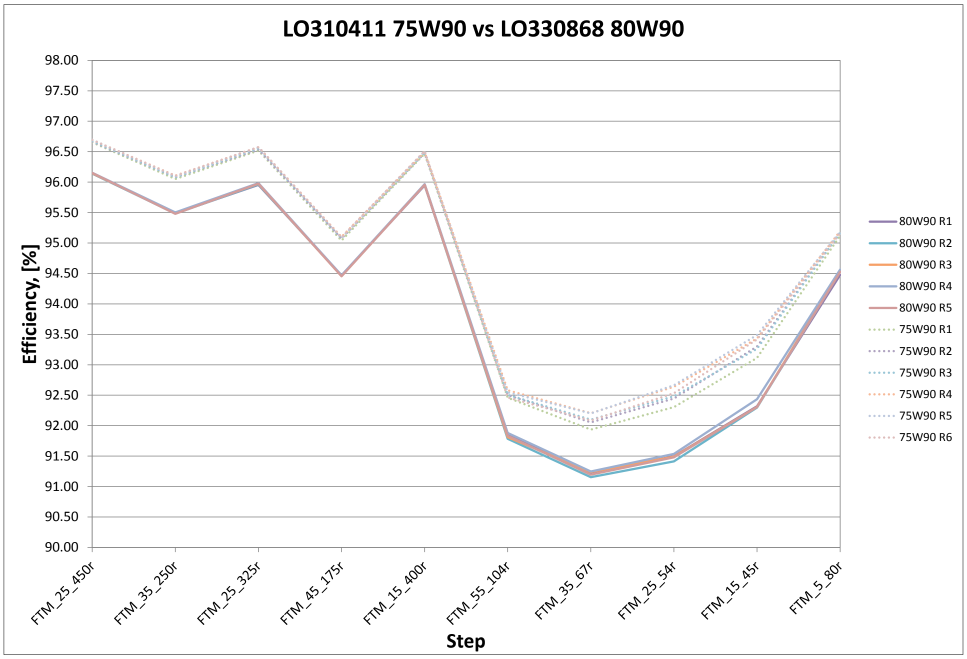

Figure 31. MTV Axle LO310411 75W-90 vs LO330868 80W-90 (Plotted)

Table 18. MTV Axle LO310411 75W-90 vs LO330868 80W-90 (Statistical Tabular)

LO310411	Candidate Improvement Over Baseline	Step #	Statistical Difference Between Oils	Estimated Efficiency Change	95% Confidence Interval	
		FTM_25_450r	Yes	0.531%	±	0.019%
		FTM_35_250r	Yes	0.596%	±	0.022%
		FTM_25_325r	Yes	0.584%	±	0.026%
		FTM_45_175r	Yes	0.617%	±	0.023%
		FTM_15_400r	Yes	0.532%	±	0.019%
		FTM_55_104r	Yes	0.679%	±	0.058%
		FTM_35_67r	Yes	0.883%	±	0.109%
		FTM_25_54r	Yes	1.029%	±	0.141%
		FTM_15_45r	Yes	1.002%	±	0.151%
		FTM_5_80r	Yes	0.634%	±	0.040%

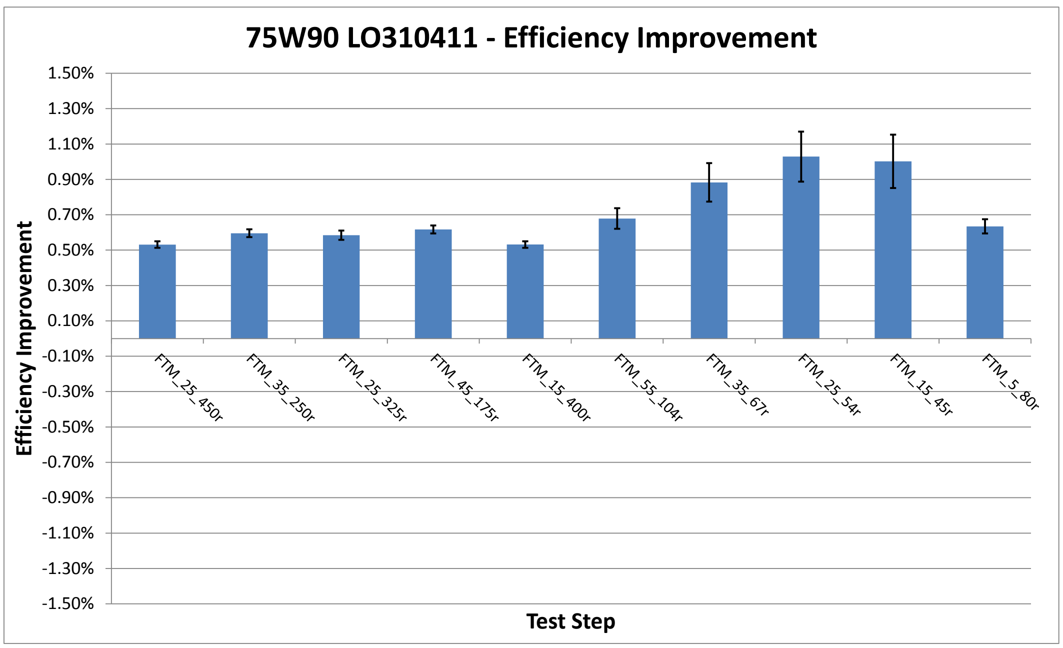

Figure 32. MTV Axle LO310411 75W-90 vs LO330868 80W-90 (Statistical Plotted)

6.3.5 Commercial 75W-85

Figure 33, Table 19 and Figure 34 show the efficiency improvement measured from the 75W-85 candidate LO338028. The overall average improvement in efficiency over the baseline 80W-90 was +1.007% (max of 1.689%, min of 0.484%).

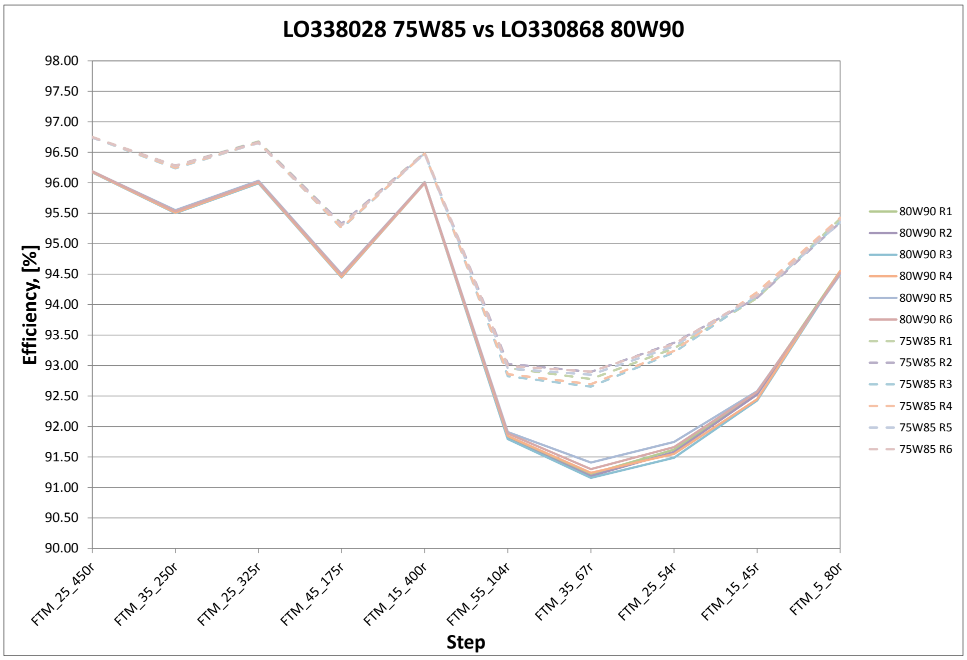

Figure 33. MTV Axle LO338028 75W-85 vs LO330868 80W-90 (Plotted)

Table 19. MTV Axle LO338028 75W-85 vs LO330868 80W-90 (Statistical Tabular)

		Step #	Statistical Difference Between Oils	Estimated Efficiency Change	95% Confidence Interval	
LO338028	Candidate Improvement Over Baseline	FTM_25_450r	Yes	0.564%	±	0.007%
		FTM_35_250r	Yes	0.745%	±	0.023%
		FTM_25_325r	Yes	0.650%	±	0.015%
		FTM_45_175r	Yes	0.824%	±	0.034%
		FTM_15_400r	Yes	0.484%	±	0.010%
		FTM_55_104r	Yes	1.094%	±	0.084%
		FTM_35_67r	Yes	1.543%	±	0.126%
		FTM_25_54r	Yes	1.689%	±	0.101%
		FTM_15_45r	Yes	1.630%	±	0.066%
		FTM_5_80r	Yes	0.850%	±	0.037%

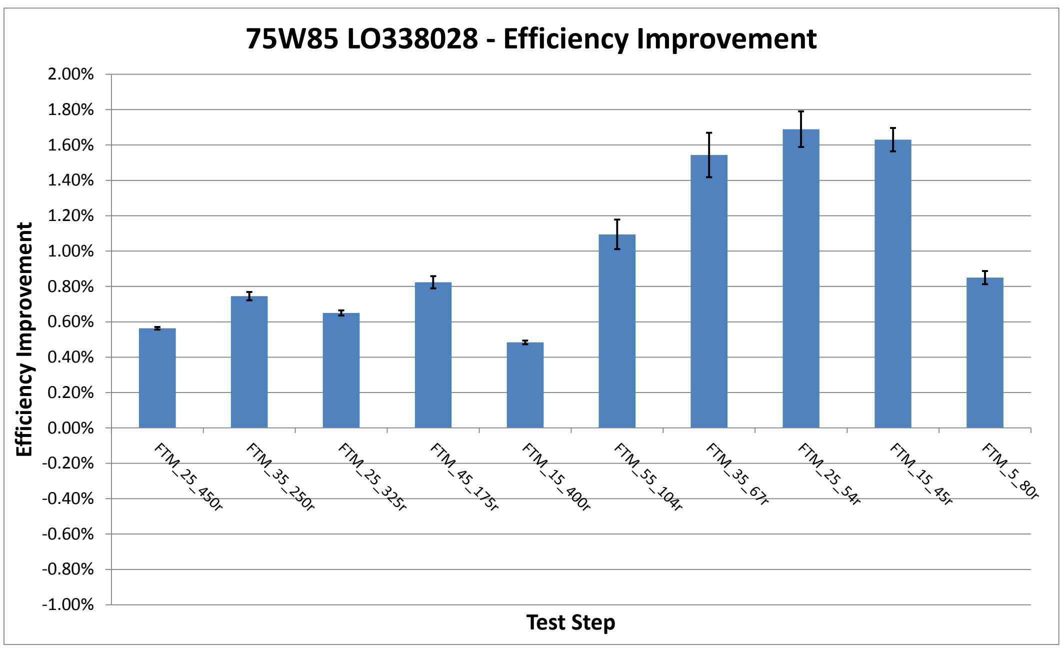

Figure 34. MTV Axle LO338028 75W-85 vs LO330868 80W-90 (Statistical Plotted)

6.3.6 Commercial 75W-110

Figure 35, Table 20 and Figure 36 show the efficiency improvement measured from the 75W-110 candidate LO351656. The overall average improvement in efficiency over the baseline 80W-90 was +0.349% (max of 0.757%, min of -0.033%).

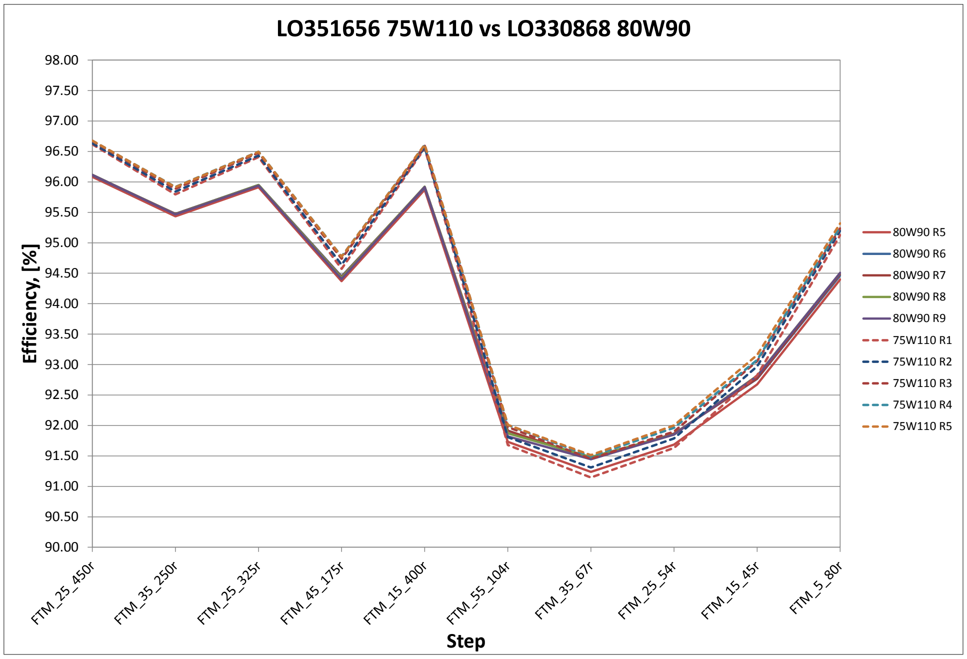

Figure 35. MTV Axle LO351656 75W-110 vs LO330868 80W-90 (Plotted)

Table 20. MTV Axle LO351656 75W-110 vs LO330868 80W-90 (Statistical Tabular)

		Step #	Statistical Difference Between Oils	Estimated Efficiency Change	95% Confidence Interval	
LO351656	Candidate Improvement Over Baseline	FTM_25_450r	Yes	0.547%	±	0.032%
		FTM_35_250r	Yes	0.406%	±	0.057%
		FTM_25_325r	Yes	0.522%	±	0.044%
		FTM_45_175r	Yes	0.282%	±	0.098%
		FTM_15_400r	Yes	0.680%	±	0.034%
		FTM_55_104r	No	N/A	±	N/A
		FTM_35_67r	No	N/A	±	N/A
		FTM_25_54r	No	N/A	±	N/A
		FTM_15_45r	Yes	0.249%	±	0.144%
		FTM_5_80r	Yes	0.757%	±	0.088%

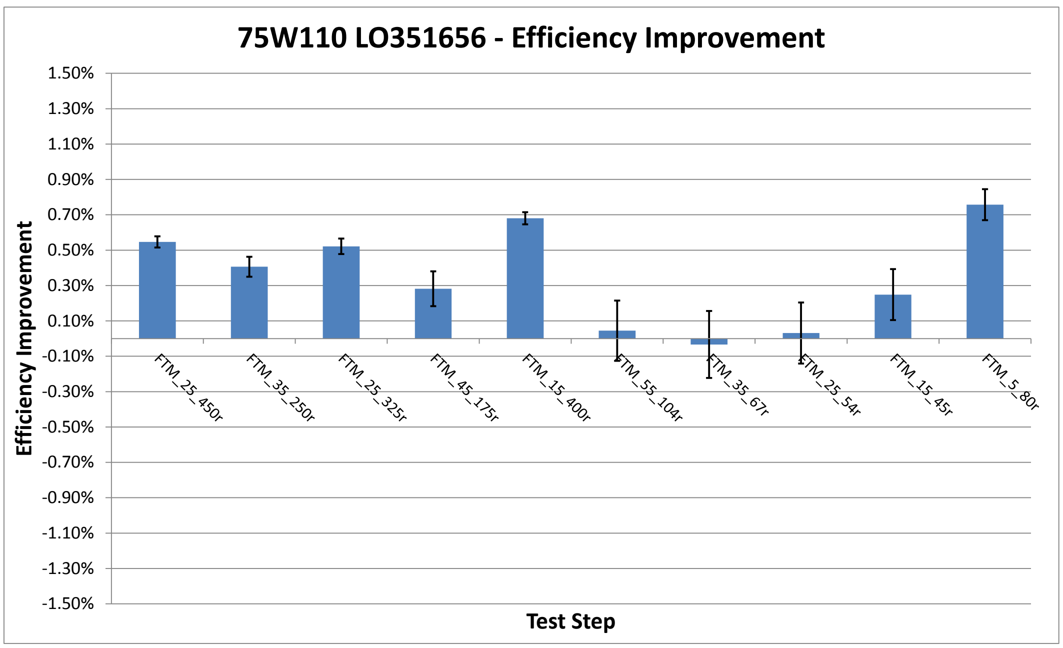

Figure 36. MTV Axle LO351656 75W-110 vs LO330868 80W-90 (Statistical Plotted)

6.3.7 Compiled Results

Table 21 and Figure 37 show the compiled final results for efficiency improvement over the baseline 80W-90 for each of the tested oils. As shown, the largest differentiator in efficiency response for each oil was in the low power/low load operating points, which ranged from a detriment in efficiency by approximately -0.5%, to an increase in efficiency at just over 1.6%. For the higher load/high power steps, efficiency response for all oil was group much tighter, but the results still tended to align the oils by viscosity with the 15mph 400lbft operating point as the only exception.

Table 21. Compiled FEGO Candidate Results (Tabular)

	Step #	LO332220 75W-90	LO332374 75W-140	LO310411 75W-90	LO338028 75W-85	LO351656 75W-110
Candidate Improvement Over Baseline	FTM_25_450r	0.487%	0.480%	0.531%	0.564%	0.547%
	FTM_35_250r	0.541%	0.255%	0.596%	0.745%	0.406%
	FTM_25_325r	0.526%	0.424%	0.584%	0.650%	0.522%
	FTM_45_175r	0.531%	N/A	0.617%	0.824%	0.282%
	FTM_15_400r	0.508%	0.641%	0.532%	0.484%	0.680%
	FTM_55_104r	0.570%	-0.544%	0.679%	1.094%	N/A
	FTM_35_67r	0.770%	-0.510%	0.883%	1.543%	N/A
	FTM_25_54r	0.793%	-0.456%	1.029%	1.689%	N/A
	FTM_15_45r	0.713%	-0.491%	1.002%	1.630%	0.249%
	FTM_5_80r	0.709%	0.555%	0.634%	0.850%	0.757%

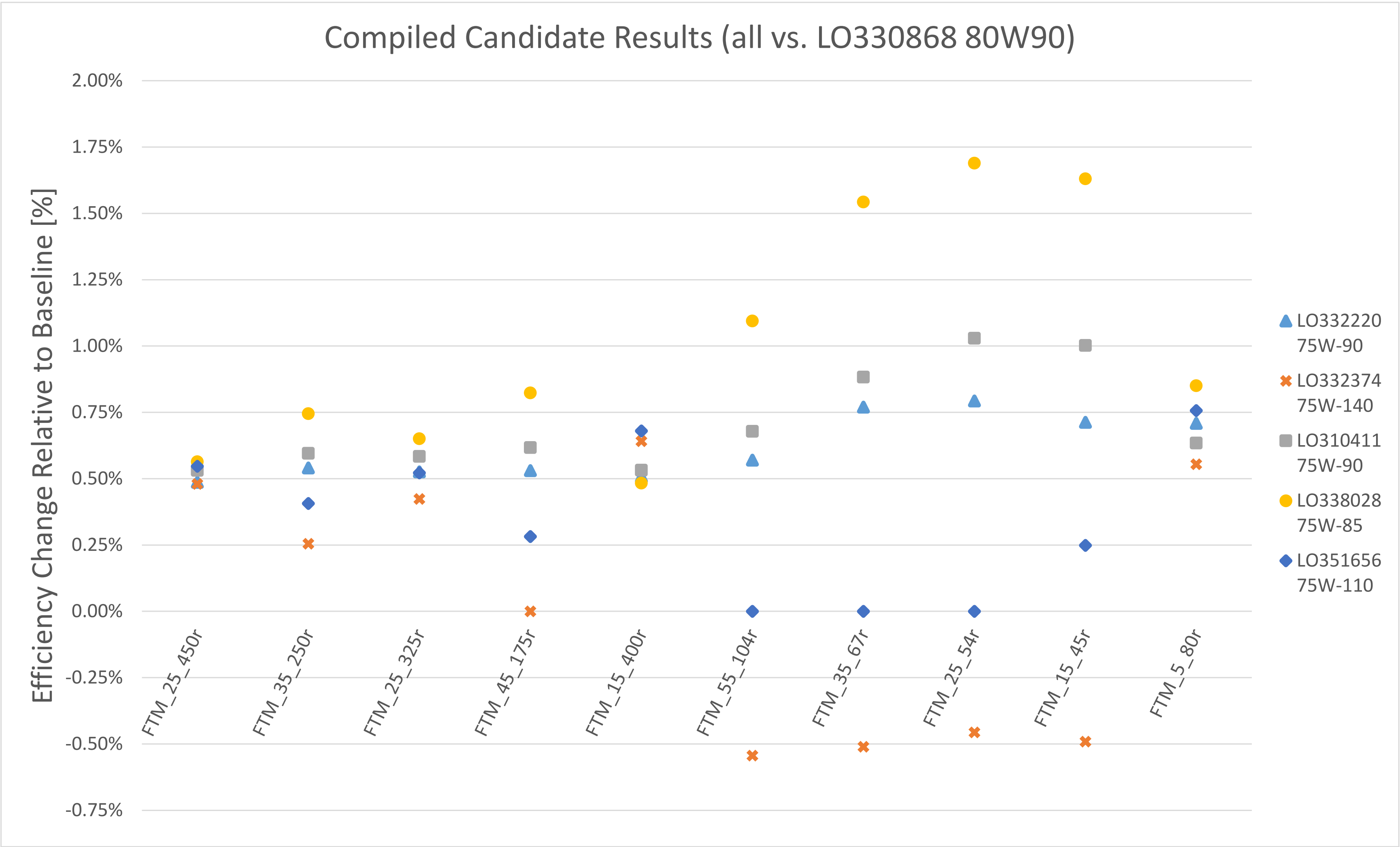

Figure 37. Compiled FEGO Candidate Results (Plotted)

7.0 GENERAL OBSERVATIONS

Over the course of the development process, other trends in collected data were identified, but have not been fully investigated at this time. This section includes documentation of these areas for future consideration.

7.1 LONG TERM BREAK-IN/BASELINE SHIFT

Low level changes in efficiency versus usage have been noticed for the MTV axle over the development process. These were identified through the repeated 80W-90 baseline runs completed on the axle between each candidate test. At the completion of the project the MTV axle had accumulated approximately 72k miles, and despite this, trends in increasing efficiency were still being observed in the low power/light load operating conditions of the FTM cycle. Figure 38 shows the average baseline results for each of the baseline segments completed since the MTV axle was reinstalled for the final FTM testing. (Note: Disregard shifts shown between BL1 and BL2, and BL6 and BL7. Each of these were a results of other extenuating circumstances not attributed to break-in).

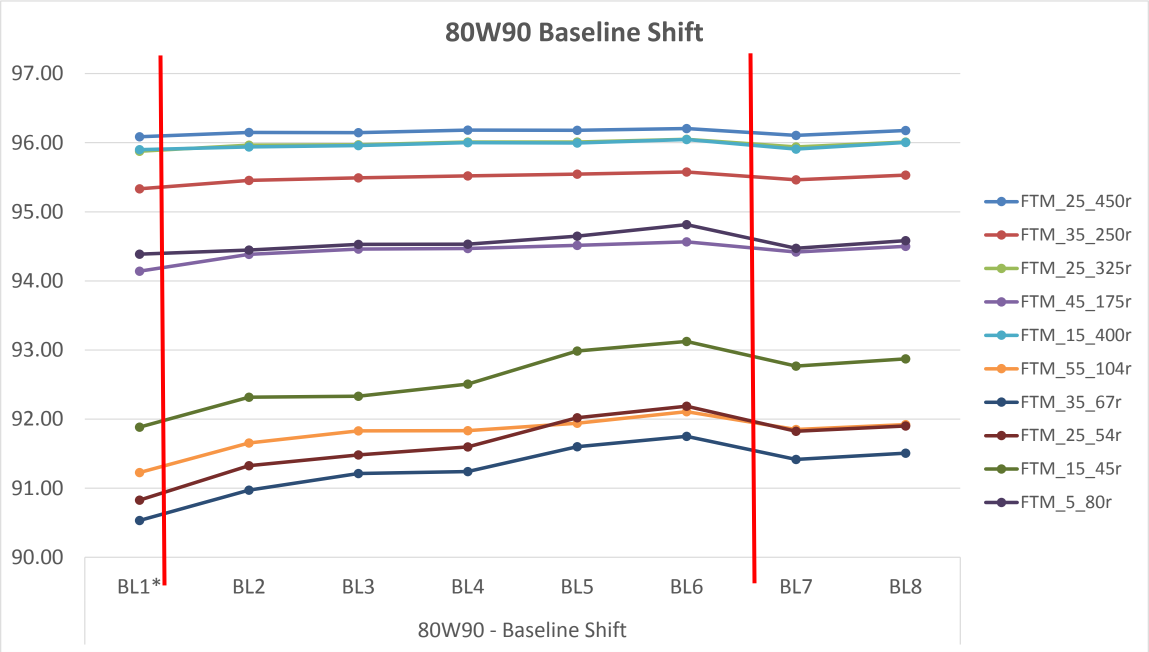

Figure 38. MTV Axle Baseline Shift

As shown, for the low power/light load operating condition, efficiency has increased by approximately 0.75% from BL2 to BL6. This highlights the importance of requiring continued baseline testing before each candidate, as each candidate is being compared against baseline data on the axles current condition. It is currently undetermined how the results from re-running any of the previous run candidates would compare to their earlier evaluations as a result of continued break-in. It is expected that the results would continue to trend the same, but overall magnitude of efficiency improvement predicted by the test might vary depending on when it was conducted.

7.2 ADDITIVE PACK TRIBO-FILM CHANGE BETWEEN TESTED CANDIDATES

During candidate testing some oils tended to show a progressively improving response in efficiency between their first and second runs in the axle versus their later runs when conducting the minimum 5 runs for the proposed FTM cycle. This potentially suggests that some oils additive packs require an extended amount of time to deplete/change the chemical tribofilm created on the gear surface when changing from one oil chemistry to the next. Although not seen with every oil change, several of the oils showed this effect (review previous plots). An extended flush procedure which includes some specified axle operation time/loading conditions could be implemented between oil changes to help reduce this effect, and would potentially further tighten the statistical data analysis for the candidate oils.

8.0 RESULTS AND CONCLUSIONS

- Development work for the MTV and HMMWV axles on the stationary axle efficiency test stand yield results that align with full scale SAE J1321 vehicle tests. This suggests that the design and operation of the stationary axle stand is realistic, and given that a specified stationary axle test cycle is an accurate representation of real world vehicle operation, results derived from the stationary axle stand can be expected to be translated to real world performance changes.

- The draft FTM developed using the MTV axle provides a good measure of axle efficiency as a function of the lubricant. Run to run results are consistent, and statistical analysis demonstrates good differentiation in efficiency as a function of the lubricant.

- Final prove out testing following the draft FTM shows that the largest differentiation in axle efficiency is shown in the MTV axle in the lower power and lightly loaded operating conditions. For the high power/high load conditions, overall grouping of the results between oils tightened significantly, but still appeared to rank primarily against the oils viscosity (lowest viscosity equating to highest efficiency).

- Based on the results attained in the efficiency testing, and given sufficient information regarding no-harm impact to durability, the lowest viscosity candidate (75W-85) shows the most potential for improvement in axle efficiency, and would be expected to provide the highest level of fuel consumption improvement in a full scale vehicle.

- Continued operation of the MTV axle does document the axle’s propensity to continually shift with usage. This was primarily noted in the lower power and lightly loaded operating points, which tended to show a trend of increasing efficiency over the course of the entire development process, despite the accumulated mileage of the MTV axle exceeding 70k miles.

9.0 RECOMMENDATIONS

- The current draft FTM yields changes in efficiency and confidence interval for each of the 10 defined operating conditions. Future work should investigate real world operating data to determine a weighting system to apply to the current FTM cycle results.

- Fixed cooling rate versus a fixed temperature control system should be investigated to determine impact on results ranking. Efficiency of each oil is expected to impact actual observed operating temperatures during real world operation, and as a result could have the potential to change the results of each oil relative to one another.

- Additional candidate testing should be conducted to further investigate differences in oil chemistry, and to better understand the effect on efficiency from viscosity versus additive pack.

- Future revisions of the FTM procedure should consider an extended run-in/flush procedure with each new oil, as data collected suggests that changes in axle efficiency for a new oil can take time to stabilize as the chemical/tribofilm present on the gear surfaces changes from one oil to the next.

10.0 REFERENCES

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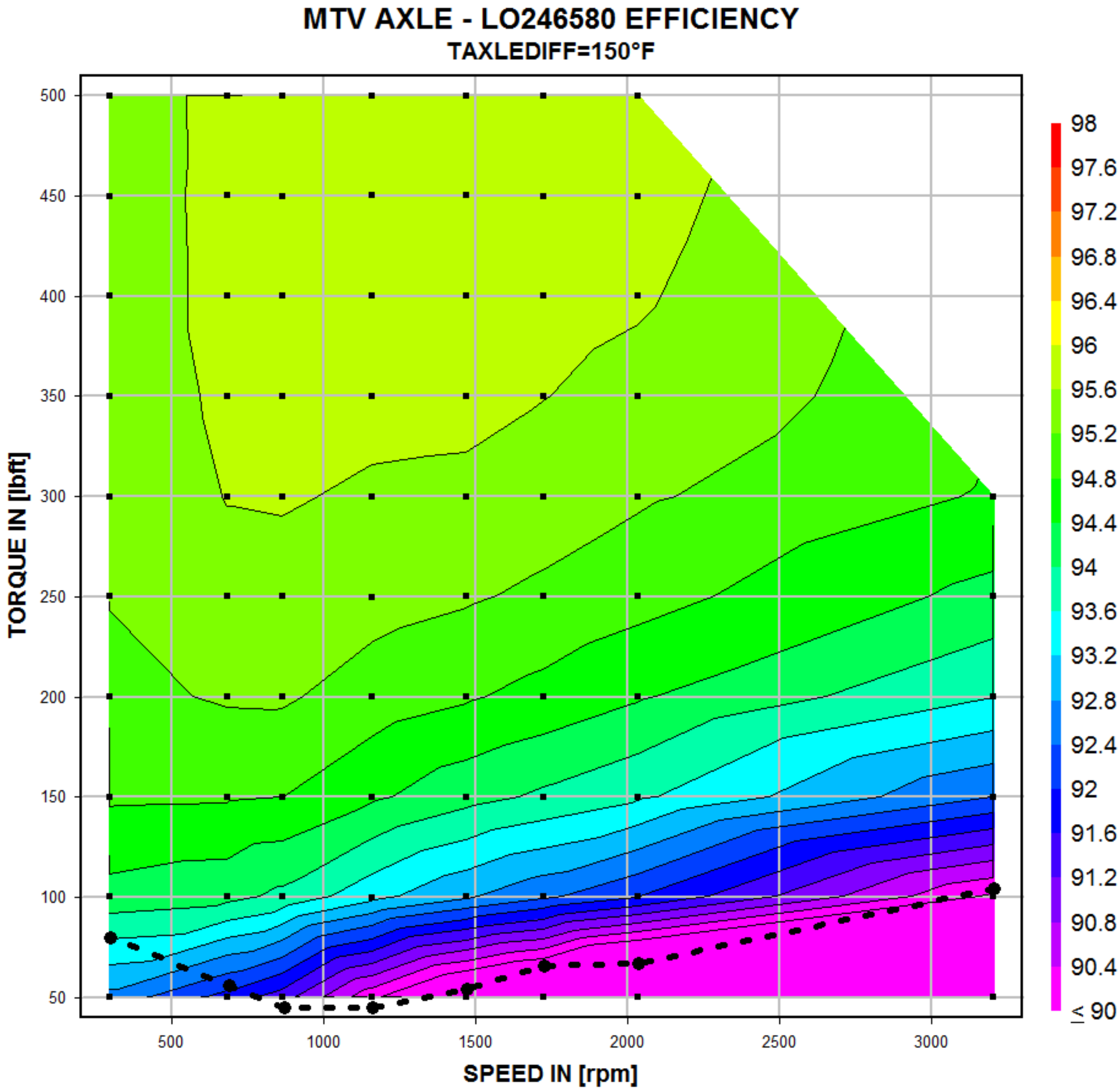
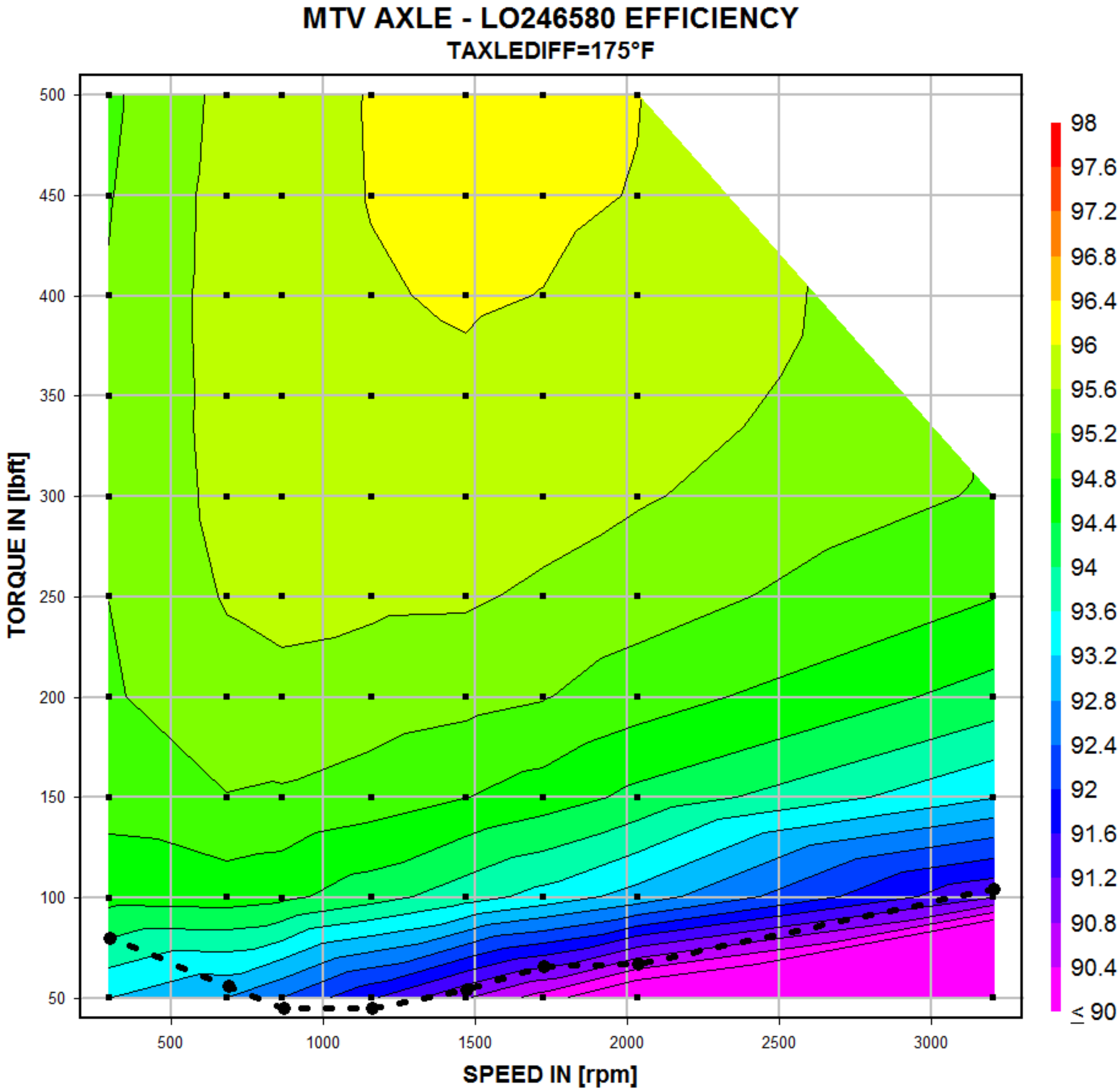
7. Dykas, B., Rizzo, D., Fussner, D., McDonnell, R. et al., "HMMWV Axle Testing Methodology to Determine Efficiency Improvements with Superfinished Hypoids," SAE Int. J. Passeng. Cars - Mech. Syst. 6(2):665-673, 2013

APPENDIX A. MTV Axle Efficiency Maps



(LO246580 80W-90 Baseline)



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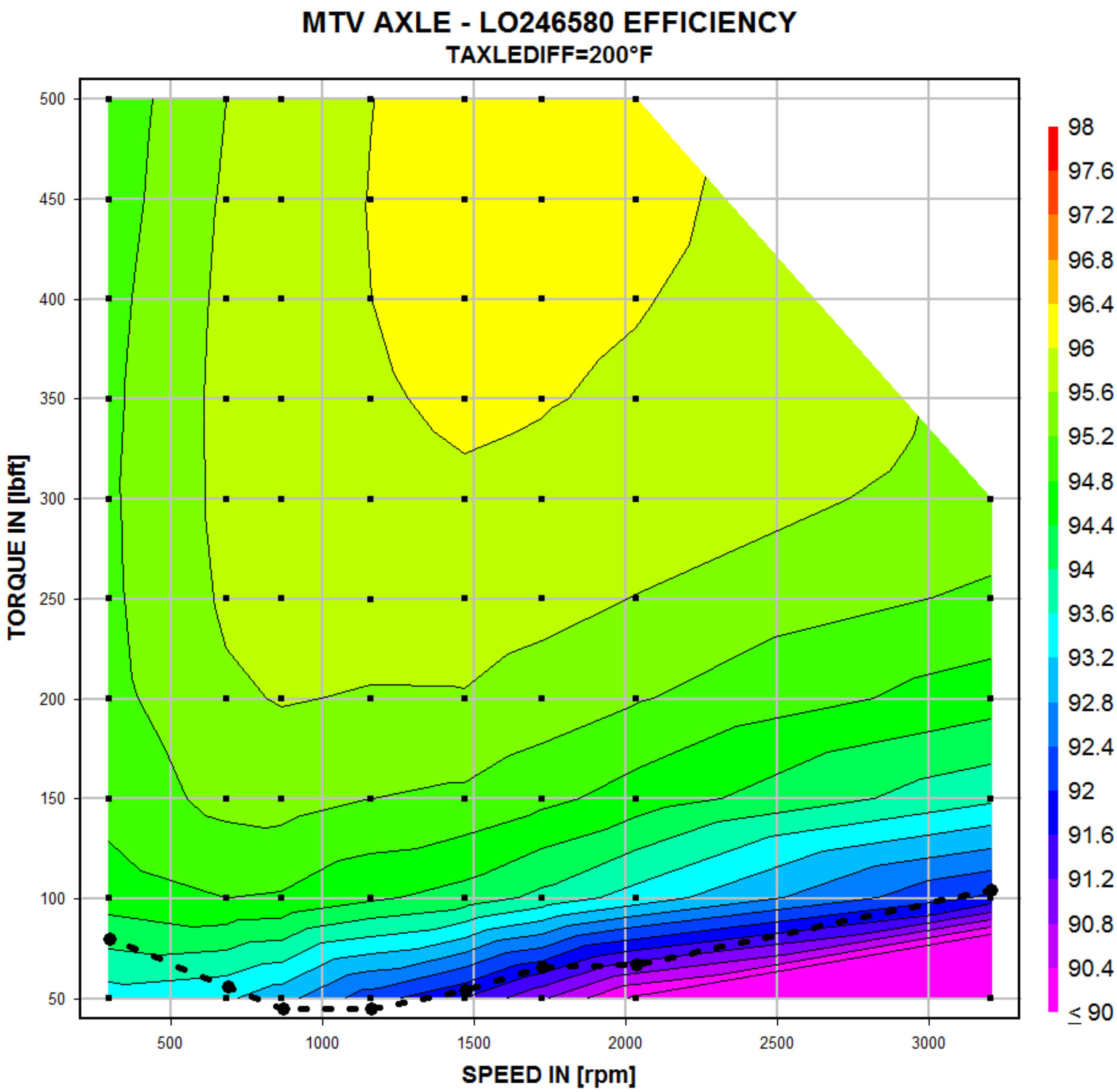

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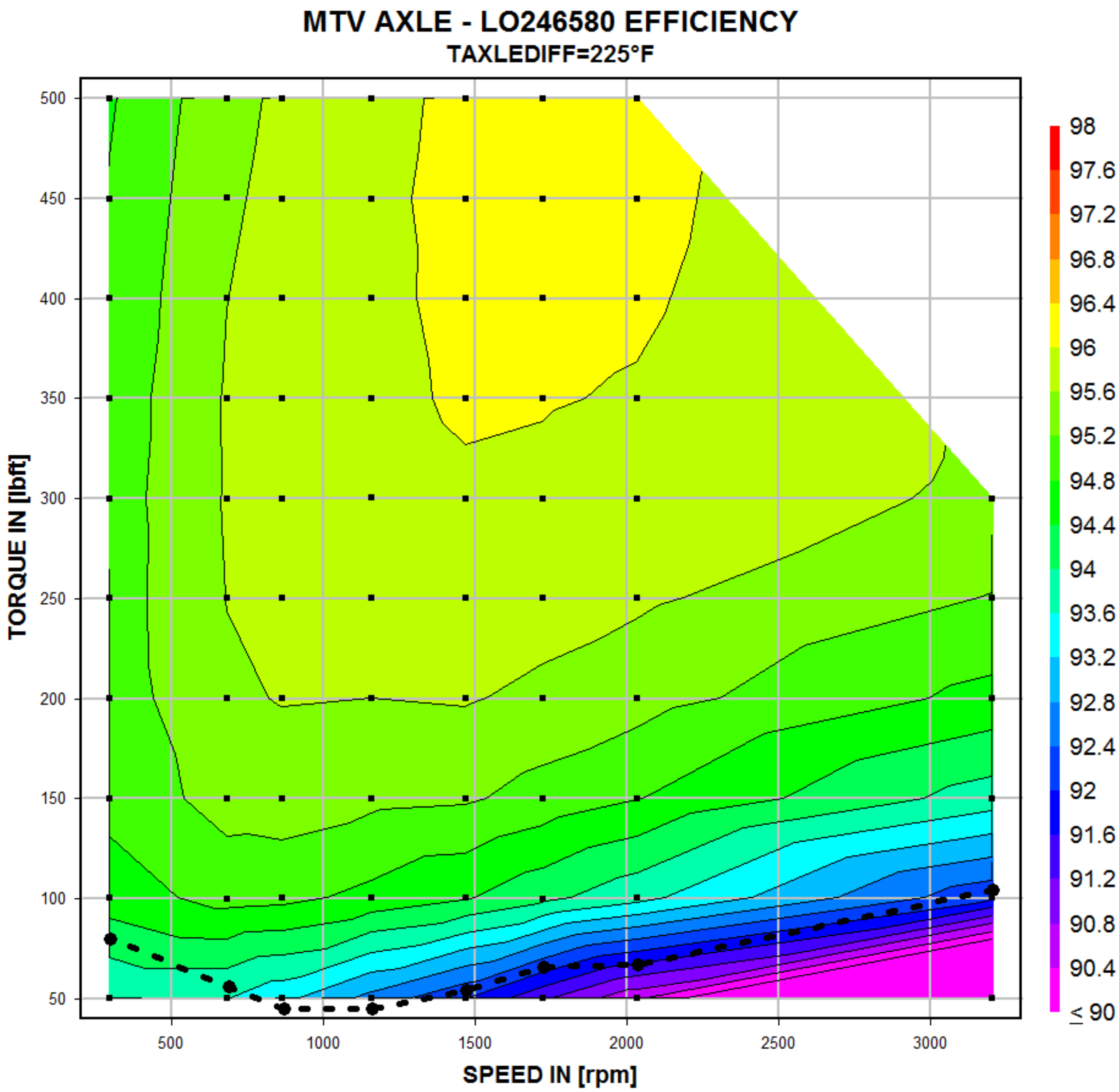

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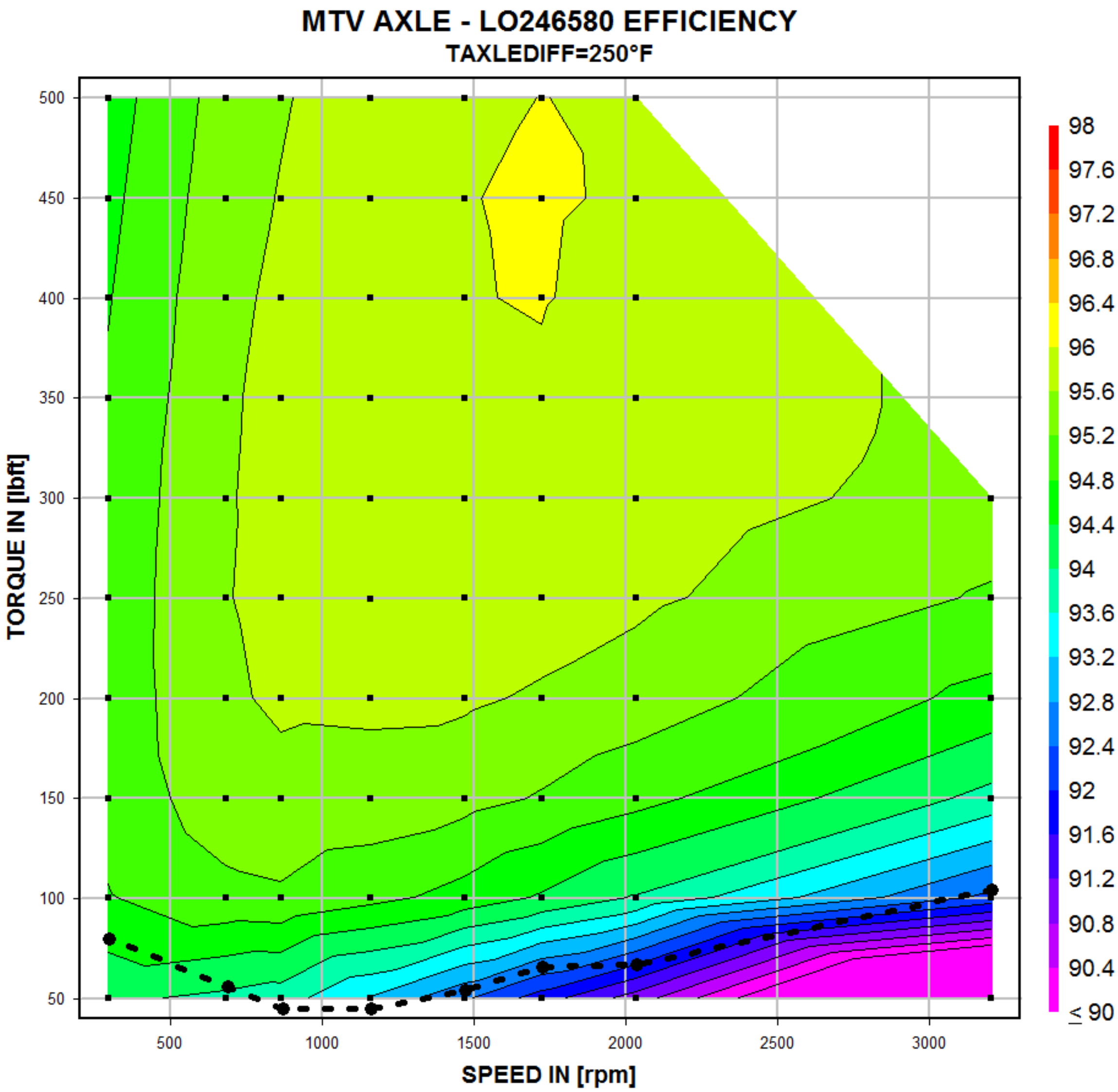

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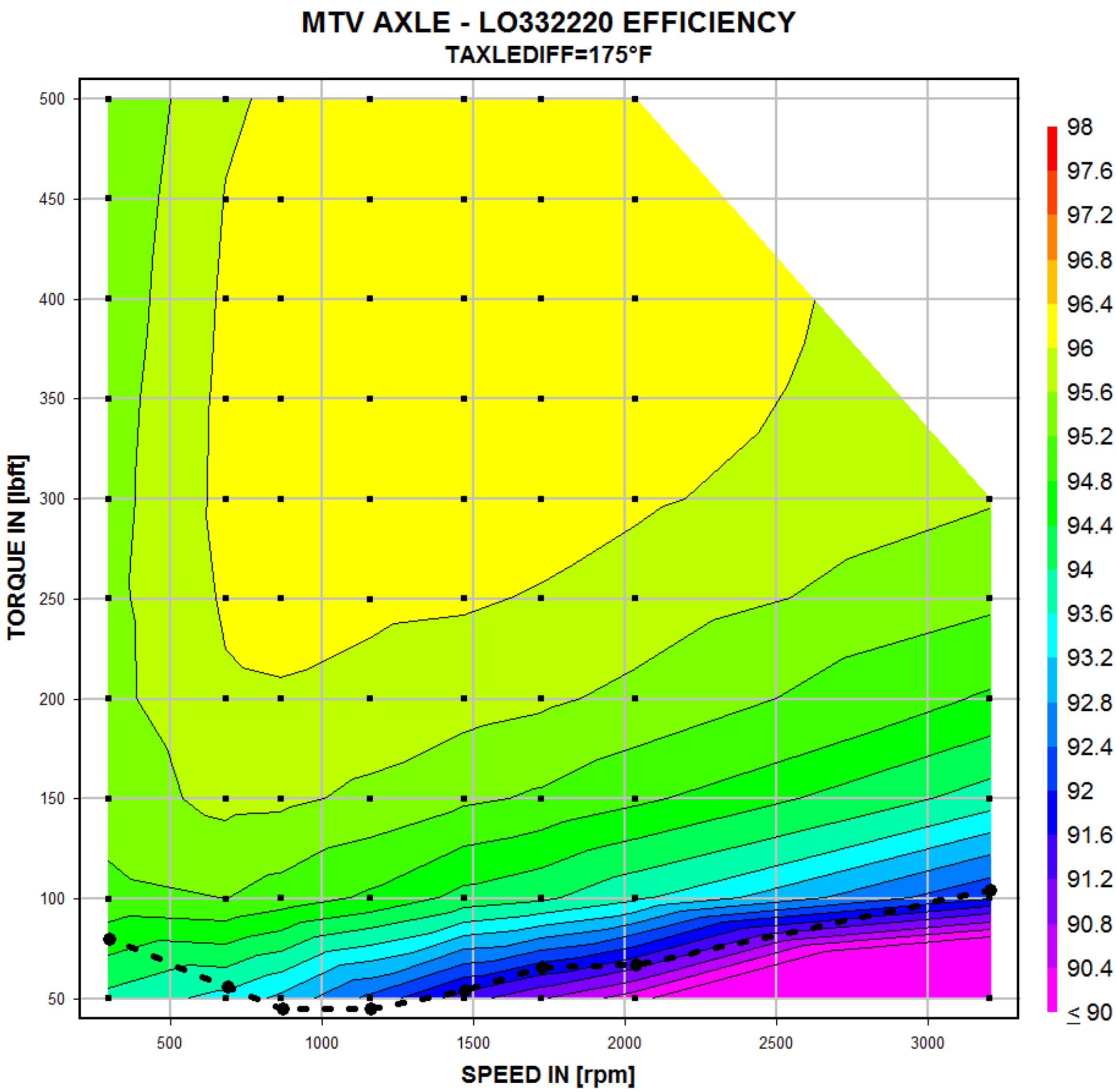
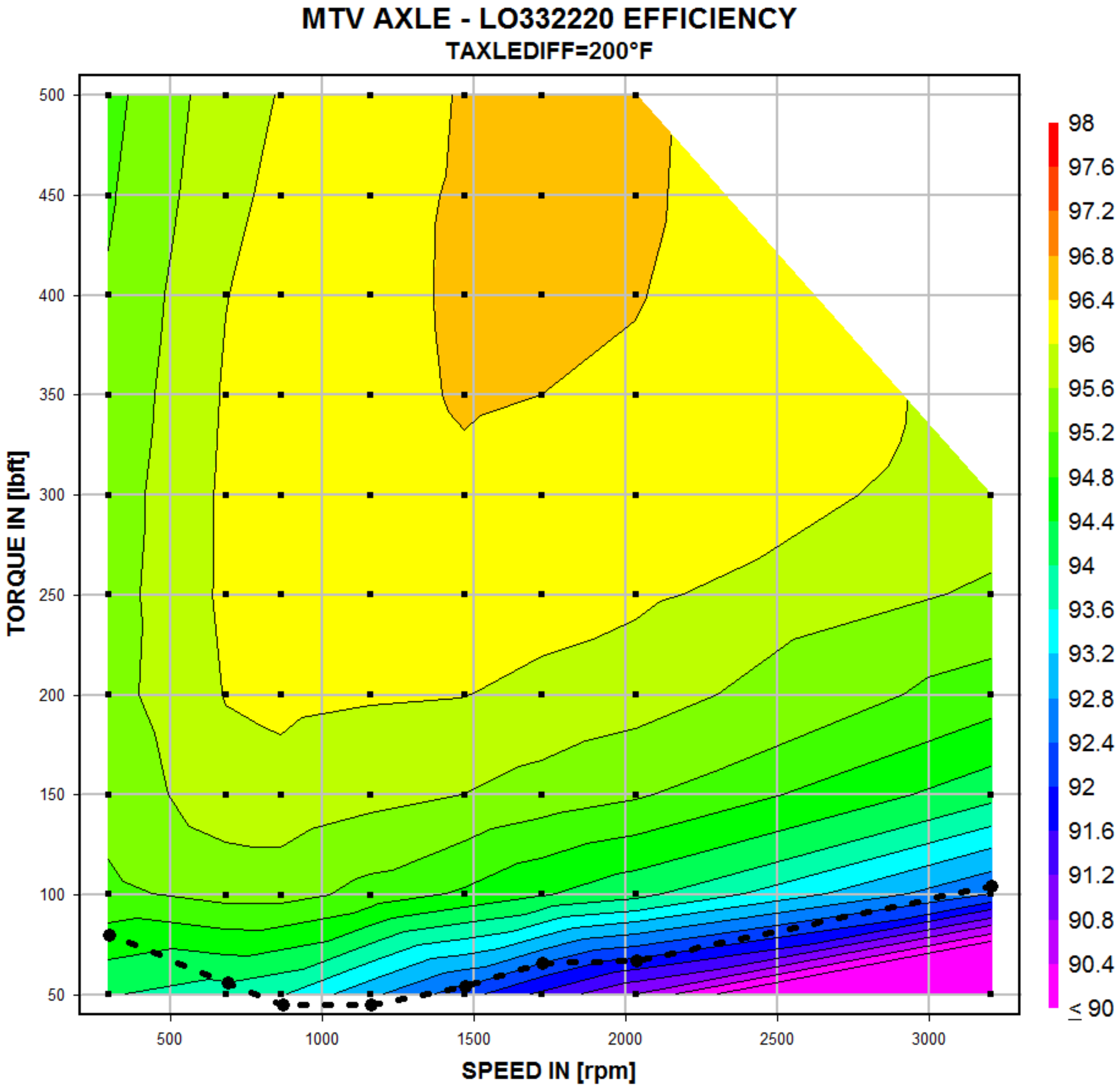


(LO332220 75W-90 Developmental)



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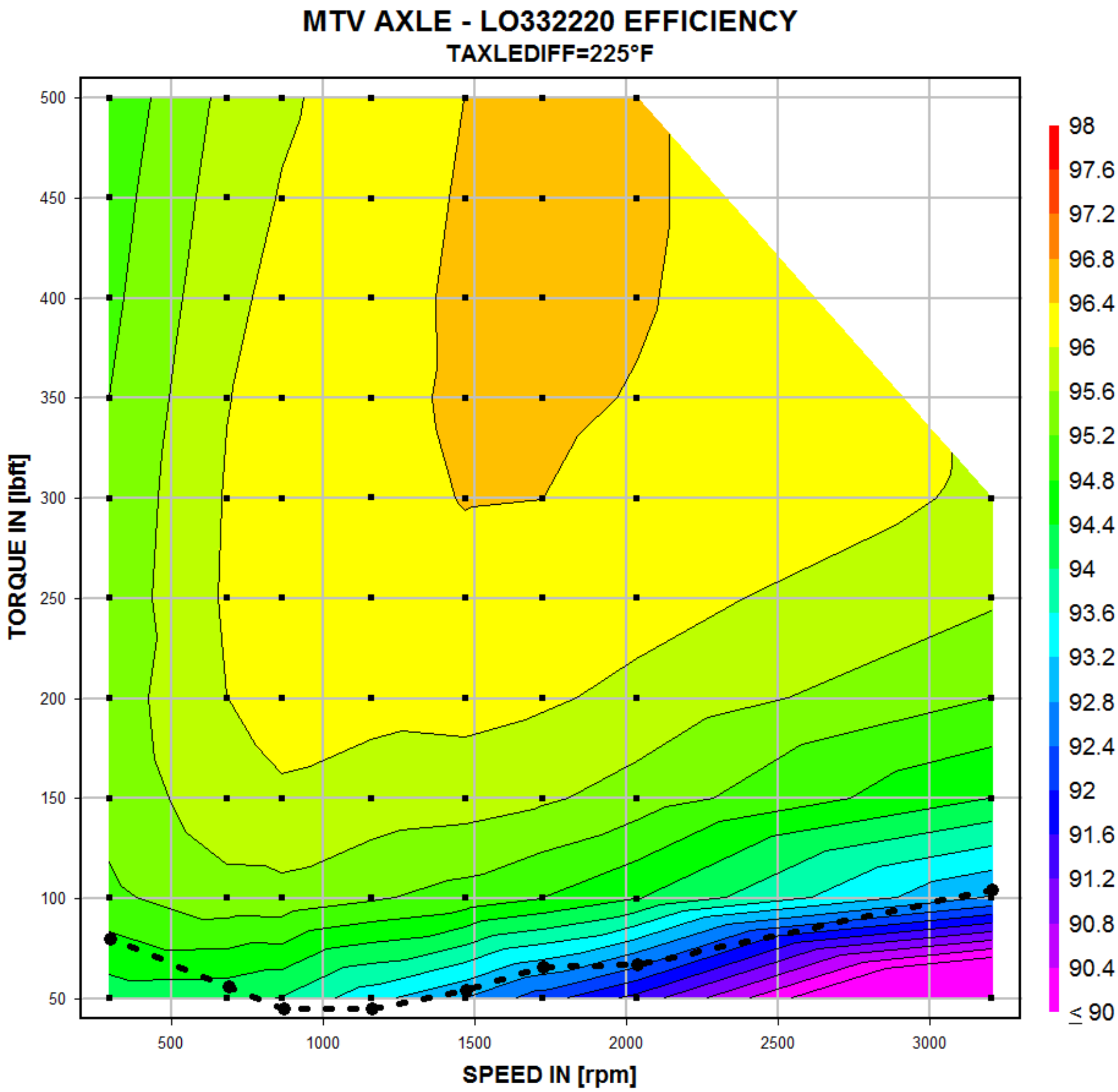

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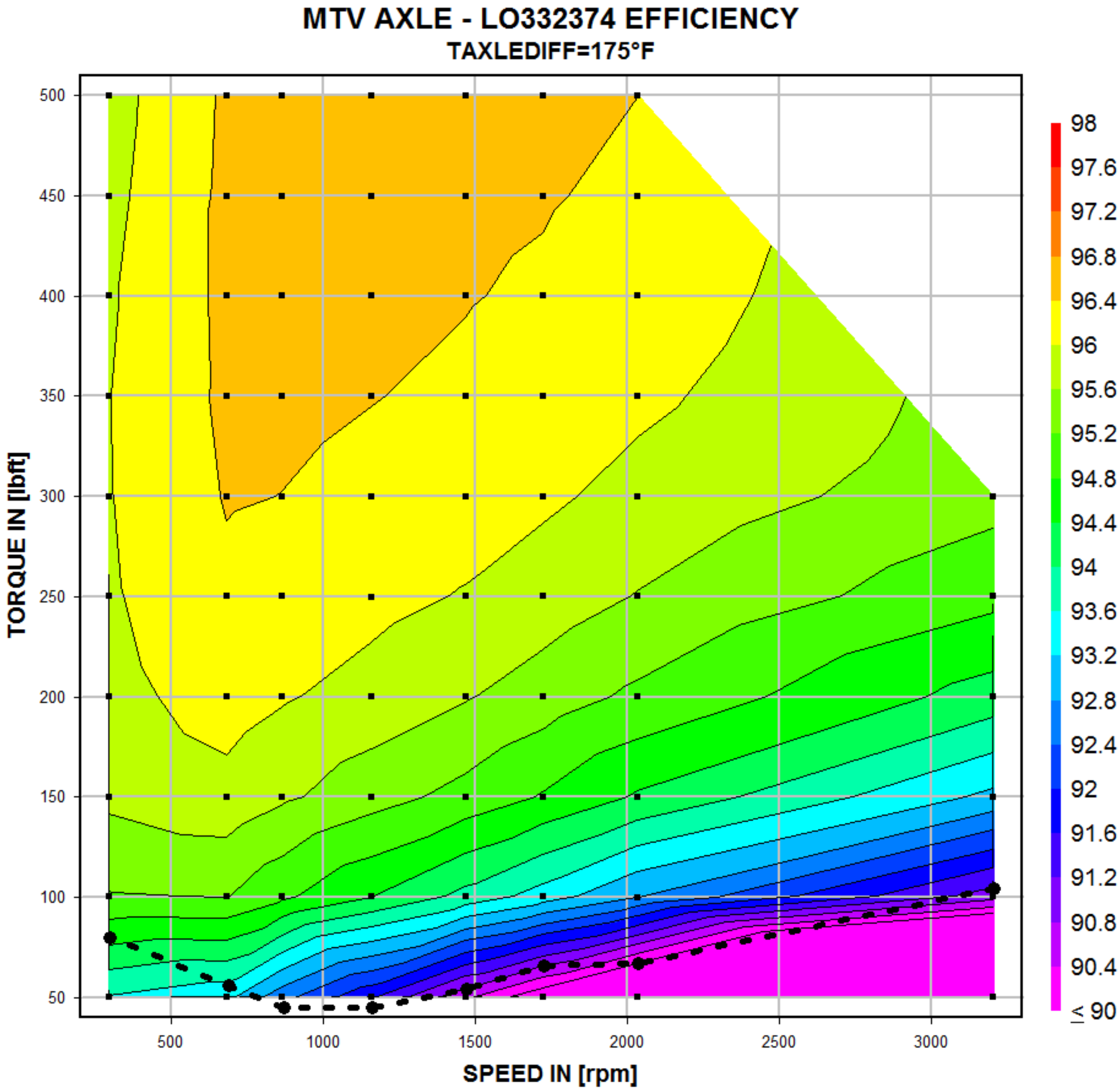
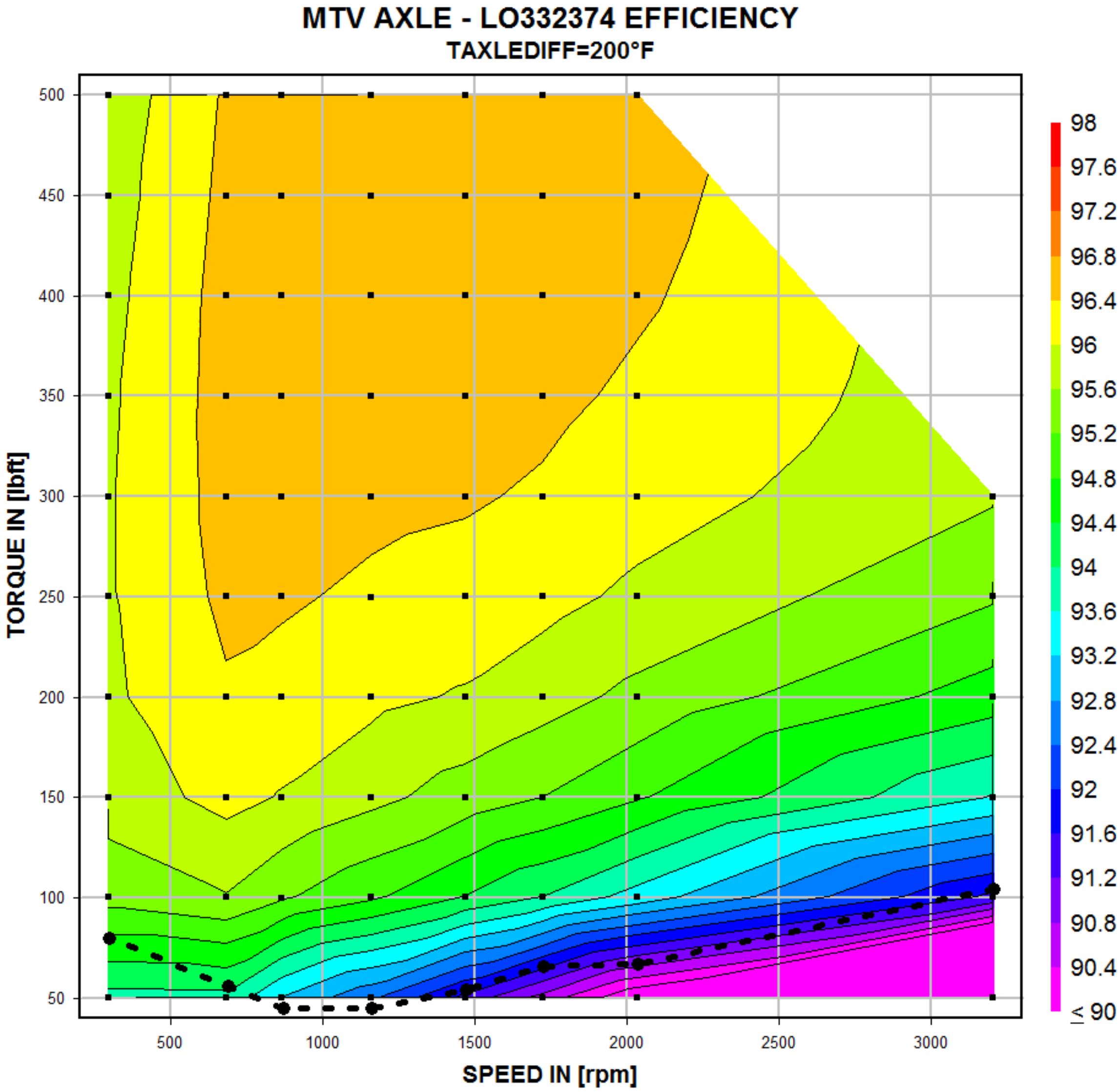


(LO332374 75W-140 Developmental)



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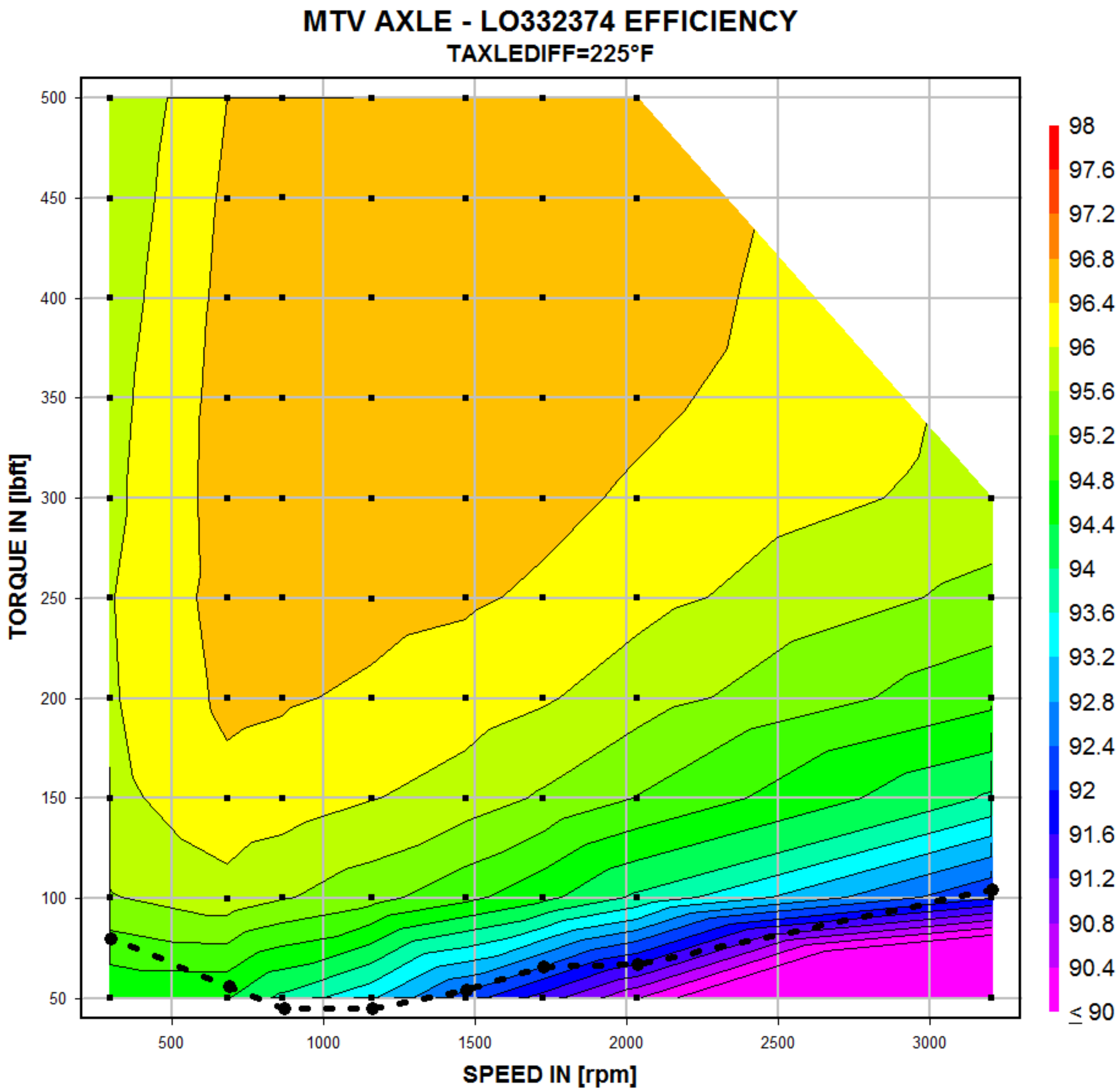


(LO332374 75W-140 Developmental)

APPENDIX B. Draft FTM

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.

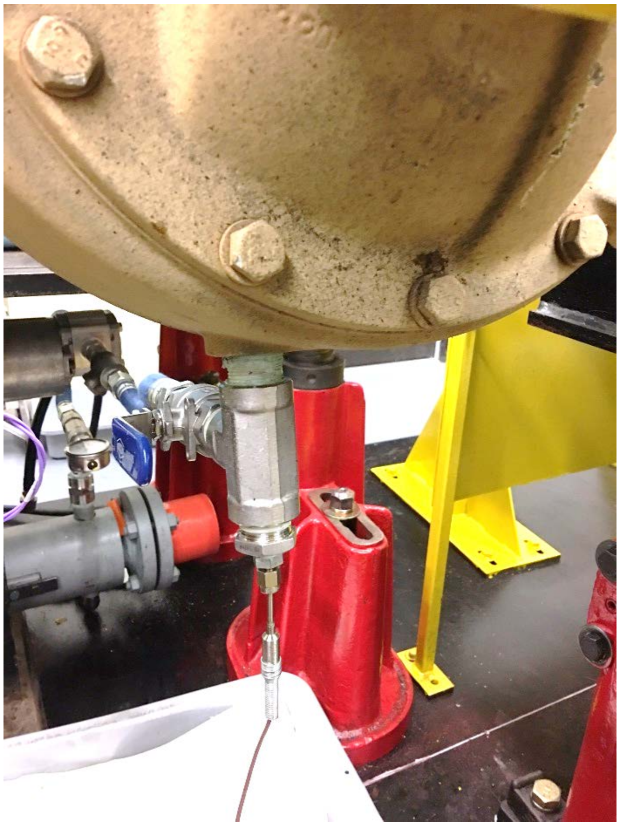
4.4.3. Input torque is measured using a 1 kNm digital torque flange with a minimum 0.05 accuracy class.

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).

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).



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 3200 rpm and 200 lbft 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.

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. 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, 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 and load 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. 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.

6.2.4. 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 175° +/- 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).

6.2.5. 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.

Step	Nominal Speed [mph]	Pinion Speed [rpm]	Pinion Load [lbft]
1	25	1469	450
2	35	2100	250
3	25	1469	325
4	45	2600	175
5	15	865	400
6	55	3207	104
7	35	2100	67
8	25	1469	54
9	15	865	45
10	5	294	80

Table 1. Federal Test Method Speed & Load Points

6.2.6. 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. A 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 0, the candidate improvement table calculated in step 7.2.4, and the post-candidate reference run result to document test validity.

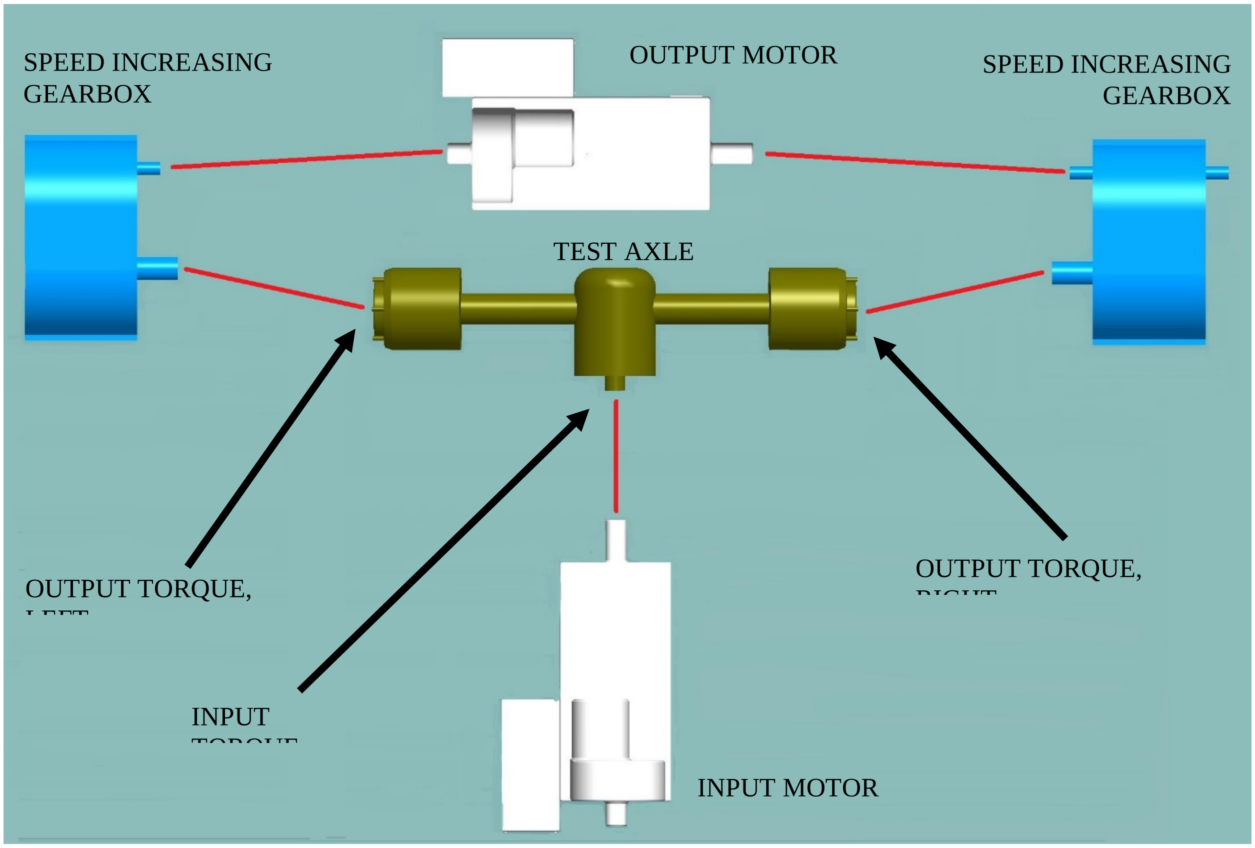
9. PRECISION

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 – 2016

APPENDIX A

1. Axle test stand block diagram:



2. Heater recirculation loop block diagram: