ADA

AXLE LUBRICANT EFFICIENCY

INTERIM REPORT
TFLRF No. 444

by
Robert W. Warden
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 Technologies
Warren, Michigan

Contract No. W56HZV-09-C-0100 (WD17)

May 2014

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Gary Bessee

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U.S. Army TARDEC Fuels and Lubricants
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EXECUTIVE SUMMARY

An evaluation of fuel consumption using three FMTVs showed the potential for significant improvement using advanced lubricants. For the engine and transmission, the baseline OE/HDO-15/40 oil was replaced with a candidate Single Common Powertrain Lubricant (SCPL). The GO-80/90 baseline for the axles was replaced with synthetic SAE 75W-90 oil selected by TARDEC. Over a two-speed highway cycle, an average improvement of 6.1% was observed. When operated on a cycle which included stationary idle and transients, the average fuel consumption improvement increased to 7.8%.

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 October 2011 through May 2014 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 S. Comfort of TARDEC served as project technical monitor.

The authors would like to acknowledge the contribution of the TFLRF technical and administrative support staff.

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ACRONYMS AND ABBREVIATIONS

%	Percent
˚C	Degrees centigrade
˚F	Degrees Fahrenheit
ARL	Army Research Lab
ASTM	American Society for Testing and Materials
Baseline Segment	A segment in which the control and test vehicle have identical fluids
CAN	Controller Area Network
CAT	Caterpillar
C.I.	Confidence Interval
cSt	CentiStoke
CTIS	Central Tire Inflation System
ECM	Engine Control Module
FMTV	Family of Medium Tactical Vehicles
GO	Gear Oil
GPS	Global Positioning System
GVW	Gross Vehicle Weight
HDO	Heavy Duty Oil
HET	Heavy Equipment Transporter
HMMWV	High-Mobility Multipurpose Wheeled Vehicle
lbs	Pounds
mph	Miles Per Hour
OE	Oil Engine
OEA	Oil Engine Arctic
PLS	Palletized Load System
SAE	Society of Automotive Engineers
SCPL	Single Common Powertrain Lubricant
SPN	Suspect Parameter Number
T/C Ratio	The ratio of fuel consumed in the test vehicle to fuel consumed in the control vehicle
TARDEC	Tank Automotive Research, Development and Engineering Center
Test Run	Combination of one driving cycle of a test vehicle and the baseline vehicle
Test/Baseline Segment	Three Test Runs which have T/C Ratios within a 2% band
TM	Technical Manual
TMC	Technology and Maintenance Council of American Trucking Association
ULSD	Ultra Low Sulfur Diesel

1.0 BACKGROUND AND OBJECTIVE

The U.S. Army desires to increase the fuel efficiency of its ground vehicle fleet. One potential area for fuel consumption improvement is the lubricating fluids located throughout the driveline. By improving the lubricating fluids used, a reduction in mechanical losses can be achieved [1]. These mechanical losses can occur in many forms including frictional, pumping, and churning losses, and are dependent on the fluid's chemical/physical properties and equipment design. A relatively small increase in driveline efficiency could have a significant impact financially when multiplied over the entire U.S. Army vehicle fleet. One aspect of this investigation looked at the fuel consumption effects of engine, transmission, and axle gear lubricants as used in the Family of Medium Tactical Vehicles (FMTV). Fuel consumption changes were determined based on the SAE J1321 Fuel Consumption In-Service Test Procedure – Type II [2] using the FMTV vehicles shown in Figure 1.

Figure 1. Test FMTVs

2.0 IN-VEHICLE TEST APPROACH

2.1 SAE J1321 TEST METHOD

The SAE J1321 procedure is used to evaluate fuel consumption impacts from a variety of sources ranging from component changes to aerodynamic modifications. During the course of the program, the SAE J1321 procedure was updated for the first time in 25 years. Where possible, accommodations were made to follow the guidelines of the new standard. However, there were some instances in which this conflicted with the project goals and the work that had already been initiated. In these cases, the deviation from the revised standard has been noted in the applicable section of this report. Multiple vehicles were operated in the test to account for weather and environmental effects.

A SAE J1321 test consists of a baseline segment and test segment. Each of these segments requires a minimum of three test runs. From each run, the total fuel consumed for the control and test truck were measured and used to form a Test-to-Control, T/C, ratio for the test run. To create a segment (baseline or test), three of these T/C ratios must fall within a 2% band. This means that the smallest T/C ratio must be no more than 2% below the largest ratio. Test runs were repeated until appropriate values were obtained for each segment. Once three T/C ratios were within the appropriate range, they were averaged to obtain a Segment T/C Ratio. The average ratios for the Baseline Segments and Test Segment were then used to determine the improvement in fuel consumption for the test. This process is shown in Table 1. To increase the sample size of data obtained, a second test truck was run which used the same control truck for comparison. This allowed for multiple test results to be formed at once.

Table 1. SAE J1321 Testing Steps

Baseline Segment: Both Trucks Filled with Same Oil	Control Truck Fuel Consumed B1	Baseline Run 1 T/C Ratio	Baseline Segment Average T/C ratio (all T/C ratios within 2% band)	Completed SAE J1321 Test for Candidate Fluid - Percent Fuel Saved or Fuel Consumption Improvement Based Upon Change in Segments T/C Ratios
	Test Truck Fuel Consumed B1			
	Control Truck Fuel Consumed B2	Baseline Run 2 T/C Ratio		
	Test Truck Fuel Consumed B2			
	Control Truck Fuel Consumed B3	Baseline Run 3 T/C Ratio		
	Test Truck Fuel Consumed B3			
Test Segment: Test Truck Filled with Candidate Oil, Control Truck Remains Filled with Baseline Oil	Control Truck Fuel Consumed T1	Test Run 1 T/C Ratio	Test Segment Average T/C ratio (all T/C ratios within 2% band)	
	Test Truck Fuel Consumed T1			
	Control Truck Fuel Consumed T2	Test Run 2 T/C Ratio		
	Test Truck Fuel Consumed T2			
	Control Truck Fuel Consumed T3	Test Run 2 T/C Ratio		
	Test Truck Fuel Consumed T3			

$$\%\ \mathbf{Improvement} = \frac{\mathbf{Ave.\,Baseline\,T/C\,Ratio - Ave.\,Test\,T/C\ \ Ratio}}{\mathbf{Ave.\,Test\,T/C\ \ Ratio}} \times \mathbf{100}$$

2.2 PROGRAM VEHICLES

Two 5-Ton Cargo M1083A1P2 FMTVs and one Load Handling System M1148A1P2 FMTV were supplied by the U.S. Army for fuel consumption testing [3]. While the current revision of the SAE J1321 standard indicates that vehicles selected should be consistent from an aerodynamic, mileage, and tire condition standpoint, the shipping of these vehicles was underway prior to the release of the updated standard. It was decided that the use of military vehicles, even two different variants, outweighed the differences between them because the driveline components of the two vehicles are nearly identical. The components in the vehicle which were subjected to test oils included: engine, transmission, front axle wheel hubs, front axle differential, intermediate axle, and rear axle. Basic vehicle information is provided in Table 2 in accordance with SAE J1321 requirements, the vehicles themselves are shown in Figure 2.

Figure 2. FMTV Vehicles at Test Site

Table 2. Program Vehicles

	Control Vehicle 1	Test Vehicle 2	Test Vehicle 3
Model	M1148A1P2	M1083A1P2	M1083A1P2
Manufacturer	Oshkosh Defense		
Serial Number Ending	125009	124996	124997
Manufacture Year	2010	2010	2010
Designation	OLHAP	OMB	OMA
Test Start Mileage	2232 miles	22176 miles	24133 miles
Test Weight – Steer	14480 lbs	14500 lbs	14560 lbs
Test Weight - Tandem	16080 lbs	16060 lbs	16000 lbs
Test Weight -Net	30560 lbs	30560 lbs	30560 lbs
Engine Information	Caterpillar Inc. C7 ACERT – 330 hp @ 2400 RPM, 860 ft-lbs @ 1440 RPM, Meets 2006 EPA Emissions Standards under National Security Exemption (No DPF/Exhaust Aftertreatment)		
Transmission	Allison MD3070PT, 7 Speed Automatic, 30% Torque Front Axle, 70% Torque Rear Tandem, Ratios: 6.93, 4.184, 2.237, 1.691, 1.2, 0.899, 0.783:1, 2nd Gear Start		
Front Axle	Meritor RF-19-611		
Rear Axle	Meritor RT-15-611		
Differential Ratio	3.9:1		
Wheel End Reduction	2:1		
Tires	395/85 R20 XML		
Cold Tire Pressure	85 psi		
Wheel Base	209 in. (5300 mm)	161 in. (4100 mm)	161 in. (4100 mm)
Length	370 in (9396 mm)	273 in. (6935 mm)	273 in. (6935 mm)
Width	96 in. (2438 mm)	96 in. (2438 mm)	96 in. (2438 mm)
Height	112 in. (2845 mm)	112 in. (2845 mm)	112 in. (2845 mm)

Upon receipt, all vehicles underwent a thorough inspection. Tires were relocated in an effort to match wear for each axle. All test component fluids were thoroughly flushed to the baseline lubricants for testing and checked for leaks. A secondary fuel tank was also added for the purpose of consumption measurement during testing. This was installed in such a way that vehicle operation could be conducted from either the main vehicle tank or the secondary tank depending upon driver selection.

2.3 PROGRAM FLUIDS

Test lubricants were selected to showcase the fuel consumption improvement of SCPL and fuel efficient axle lubricants compared to the military standard oils. The axle baseline lubricant was a commercially available, petroleum based, SAE 80W-90 product meeting SAE J2360 standard while the candidate was a SAE 75W-90 oil selected by TARDEC [4]. This candidate oil, within the viscosity grades currently approved for military use, was a fully synthetic product featuring an advanced additive package for improved load handling and friction reduction. The engine and transmission utilized a MIL-PRF-2104H 15W-40 oil as the baseline lubricant [5]. Candidate lubricant for these components was a SAE 0W-20 developmental oil from the Single Common Powertrain Lubricant program that had shown beneficial effects in previous laboratory testing for fuel economy and engine durability [6]. For all oil changes a double flush method was used. The axle oil was drained and refilled with test oil and the vehicle was driven for approximately 20 minutes on the track. This procedure was repeated a second time, and then the axle oil was drained and the axle was charged with fresh axle oil. All fuel for the program was from a single bulk source of commercially available ULSD.

2.4 TEST FACILITY

Testing was conducted at The Southwest Center for Transportation Research and Testing, a closed course track located outside of Pecos, TX during the months of May and June 2012. A view of the track from an elevated observation area is shown in Figure 3.

Figure 3. Test Track View

The track is a 9-mile, three lane circle with approximately 46 feet of elevation change. An estimation of this based upon GPS data is shown in Figure 4.

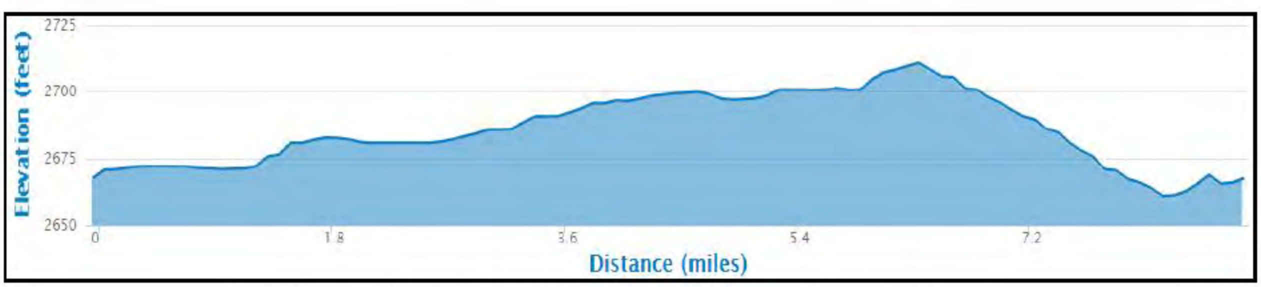

Figure 4. Test Track Approximate Elevation Profile

2.5 TEST ROUTES

Two routes were developed for the evaluation of fuel consumption changes due to powertrain lubricants. The first was a slight modification of a route used in previous testing with FMTV vehicles. Two vehicle speeds were run for a set distance to simulate highway or convoy operation. The original cycle was based upon the track length of another facility and was modified to improve consistency with the 9-mile circular track where the current program was performed. Table 3 provides the operating speeds and distances for the highway cycle and a comparison between the current and previous programs. The distance of the current highway cycle was 1.5 miles longer.

Table 3. Highway Test Route

Operating Condition	Vehicle Speed	Distance (Current Highway Cycle)	Distance (Old Highway Cycle)
1	25 mph (40.2 kph)	22.5 miles (36.2 km)	21 miles (33.8 km)
2	50 mph (80.5 kph)	22.5 miles (36.2 km)	21 miles (33.8 km)

A second test route was designed to simulate a combination of stop-and-go driving along with limited duration medium and high speed operation. This route was based upon two cycles from SAE J1376, the "Local Test Cycle" and "Short Haul Test Cycle", modified to suit the 9-mile track [7]. These cycles were each repeated multiple times to develop a route with sufficient total distance to meet the 1986 revision SAE J1321 standard, but falls 5 miles short of the 2012 revision minimum of 50 miles. In instances where two "Idle" steps occurred in the series, one was eliminated from the overall route. The conditions for this cycle are provided in Table 4 and graphically in Figure 5.

Table 4. Transient Style Test Route

Step	Maneuver	Total Distance (miles)	Cycle Type
0	Start Engine	0.00	SAE J1376 Local Test Cycle #1
1	30 Second Idle	0.00	
2	Accelerate to and hold 5 mph	0.15	
3	Accelerate to and hold 10 mph	0.48	
4	Decelerate to 0 mph	0.49	
5	20 Second Idle	-	
6	Accelerate to and hold 20 mph	0.97	
7	Decelerate to 0 mph	1.00	
8	20 Second Idle	-	
9	Accelerate to and hold 30 mph	1.44	
10	Decelerate to 0 mph	1.50	
11	20 Second Idle	-	
12	Accelerate to and hold 35 mph	1.92	
13	Decelerate to 0 mph	2.00	
14	20 Second Idle	-	
15	Accelerate to and hold 25 mph	2.56	
16	Decelerate to 0 mph	2.60	
17	20 Second Idle	-	
18	Accelerate to and hold 15 mph	2.98	
19	Decelerate to 0 mph	3.00	
20	20 Second Idle	-	
21	Repeat Steps 2-20	6.00	SAE J1376 Local Cycle #2
22	Repeat Steps 2-19	9.00	SAE J1376 Local Cycle #3
23	60 Second Idle	-	SAE J1376 Short Haul Cycle #1
24	Accelerate to and hold 25 mph	15.00	
25	Accelerate to and hold 35 mph	21.00	
26	Accelerate to and hold 55 mph	27.00	
27	Decelerate to and hold 25 mph	33.00	SAE J1376 Short Haul Cycle #2
28	Accelerate to and hold 35 mph	39.00	
29	Accelerate to and hold 55 mph	44.80	
30	Decelerate to 0 mph	45.00	
31	60 Second Idle	-	
32	Shut off Engine	-	

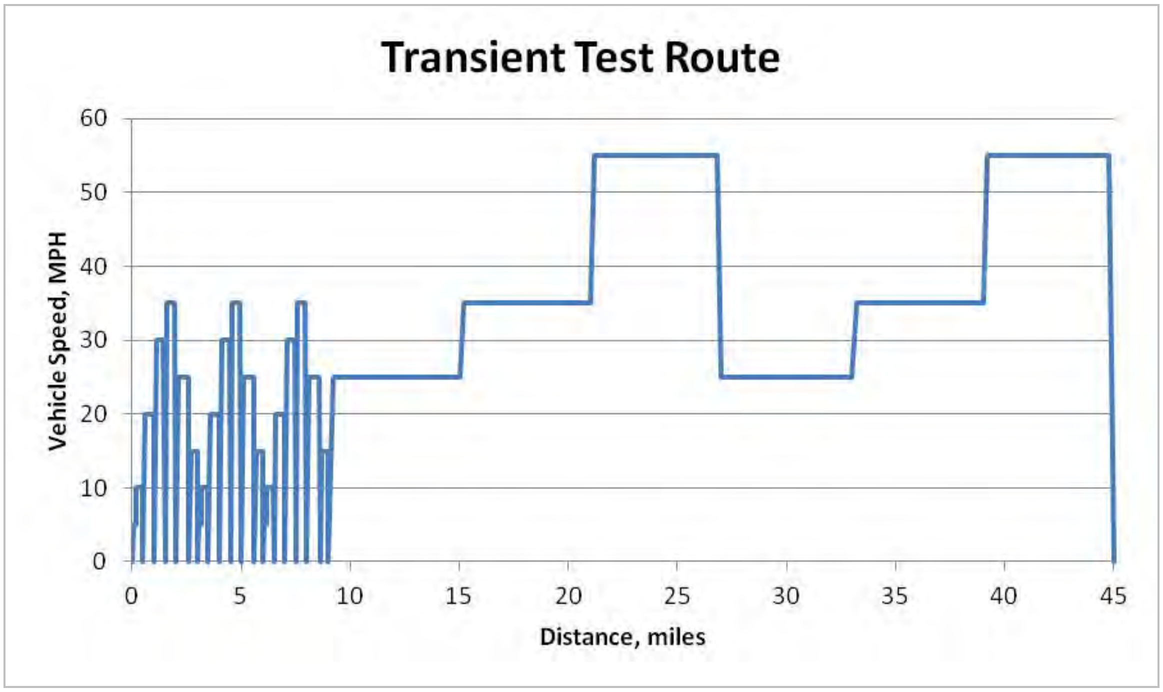

Figure 5. Transient Style Test Route

2.6 MEASURED PARAMETERS

A variety of parameters were measured to ensure consistent operation of all three vehicles throughout testing. Being a lubricant based evaluation, all oil sumps, fuel, and ambient air were instrumented with K-type thermocouples. The importance of lubricant temperature was critical for interpreting results from fluid effects. For components such as the axle differentials, which rely on forced convection from vehicle movement, the stabilization temperature could be an indicator of overall component efficiency. This becomes less so in thermostatically controlled items such as the engine. Regardless, the operating temperature, and therefore viscosity, plays a major role in efficiency changes due to the candidate fluids. In addition to temperatures, a selection of other vehicle operating parameters were monitored through engine control module (ECM) controller-area network (CAN) communications. These included engine oil pressure, injector actuation pressure, engine coolant temperature, engine boost pressure, engine speed, accelerator pedal position, torque converter ratio, transmission gear, transmission output shaft speed, wheel speed, and an ECM calculated fuel consumption rate. These parameters allowed for post-run comparisons to be made to check for consistent vehicle operation. By tracking parameters such as operating temperatures, active gear, pedal actuation, wheel speed, date and time, the possibility of intentionally biasing a SAE J1321 test is reduced. Theoretically, a test could be constructed and run in such a manner so that a vehicle would be driven into an unrealistic operating condition while still meeting the overall speed requirements of a drive cycle. Forcing specific gearing, inappropriate use of braking systems, or inconsistent lubricant warm-up between vehicles could be ways to manipulate test results if not properly tracked and reported. Additional measurements were required by the 2012 revision of SAE J1321 including weather data and static vehicle information to further assist in ensuring enough information is reporting along with the final fuel consumption change to be considered a valid and, of equal importance, applicable result.

2.7 TEST PROCESS

To begin each day of testing, vehicles were inspected for leaks and tire pressure adjusted as required. The fuel weigh tanks were filled to a consistent weight for testing. A warm-up was conducted while operating on the main vehicle fuel tank consisting of a 45 mile (five laps around the test track) route at approximately 50 mph. Following this, vehicles were staged at the test route starting line and underwent a final visual examination before starting the specified route. Speed was monitored by the driver using a dash mounted GPS unit rather than vehicle speedometer. Route time was displayed on a specially developed control box mounted in the cab. This configuration is shown in Figure 6.

Figure 6. Cab Mounted GPS and Route Timer

Vehicles were started on the main fuel tank and idled prior to the starting location. For the Highway Cycle a speed of 25 mph was reached, then the toggle switch on the route timer was activated to start data logging and change to the weigh tank fuel source. The switch activation occurred while idling for the Local Cycle. Once the test route was completed, the switch was deactivated to return to fueling from the main vehicle tank. To measure the fuel consumed, the secondary tank was disconnected from the vehicle and weighed using a load cell. Following this, the tank was refilled to the initial weight in preparation for the next cycle.

3.0 FMTV EVALUATION RESULTS

3.1 VEHICLE OPERATION

Graphical data for vehicle operation is displayed with all runs of a given segment overlaid. Legends provide color coding for each data set. A breakdown of the lap designations used in these legends is provided.

T1B1HyL1

Lap 1,2 or 3

Highway (Hy) or Local (L) route

Baseline (B) 1,2 or Test (T) Segment

Truck (T) 1,2 or 3

It should be noted that logged data was not available for Truck 2 during Baseline 1 for Highway Lap 3 and the entire local cycle. A power failure in the instrumentation logging equipment occurred on that day of testing. This did not impact the weight based fuel consumed measurements taken prior to and at the end of each lap.

3.1.1 Vehicle Speed

The speed of each vehicle was broadcast by the ECM based upon wheel RPM. While minor changes in tire size can impact the rotational rate and apparent vehicle speed, the parameter still provides an indication of the consistency of operation between trucks. For driver control, a GPS based vehicle speed was used from a unit located in the cab for feedback.

During the Highway Cycles, there was a discrepancy in vehicle speed for Truck 2 on the first lap of the Test Segment. The driver accelerated rapidly then returned to the desired speed, likely due to a misinterpretation of course signage. Speed for all highway routes is shown in Figure 7 through Figure 9.

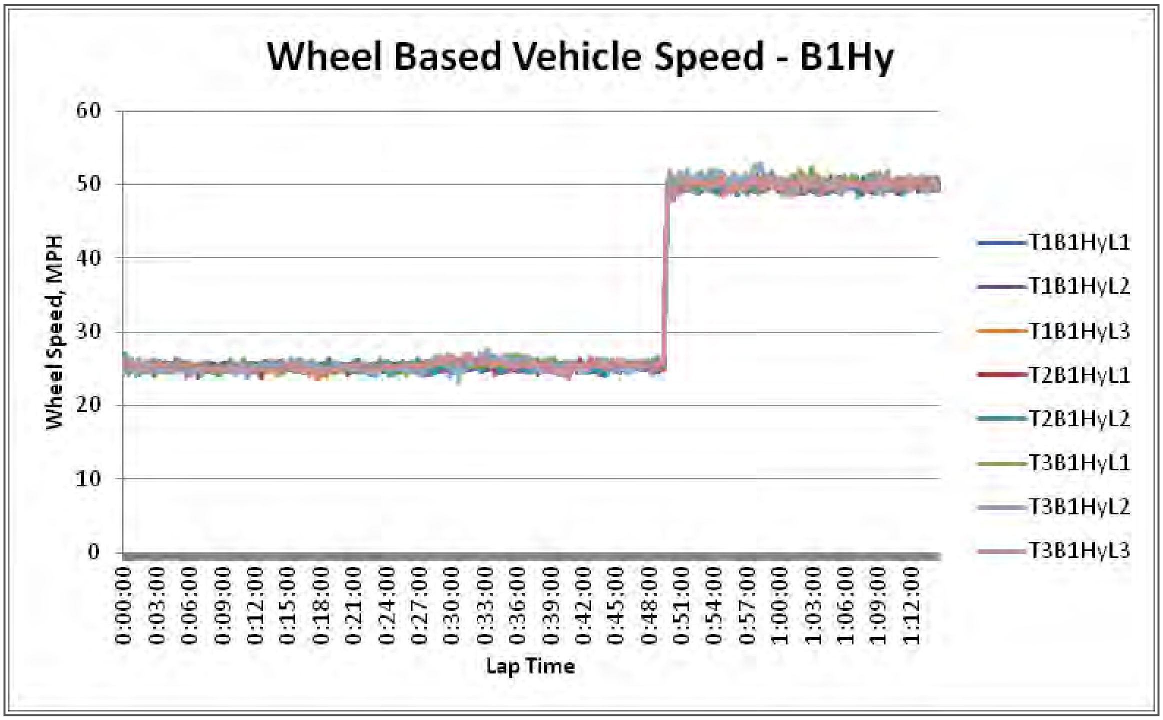

Figure 7. Wheel Based Vehicle Speed, Baseline 1 Highway

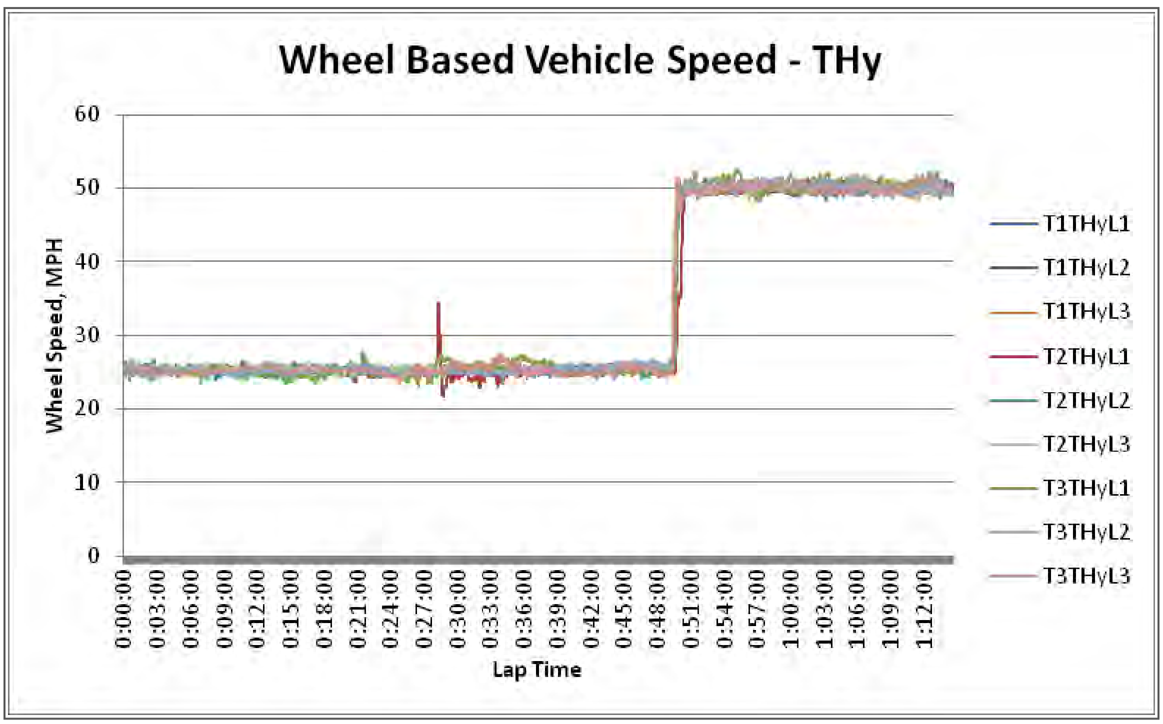

Figure 8. Wheel Based Vehicle Speed, Test Segment Highway

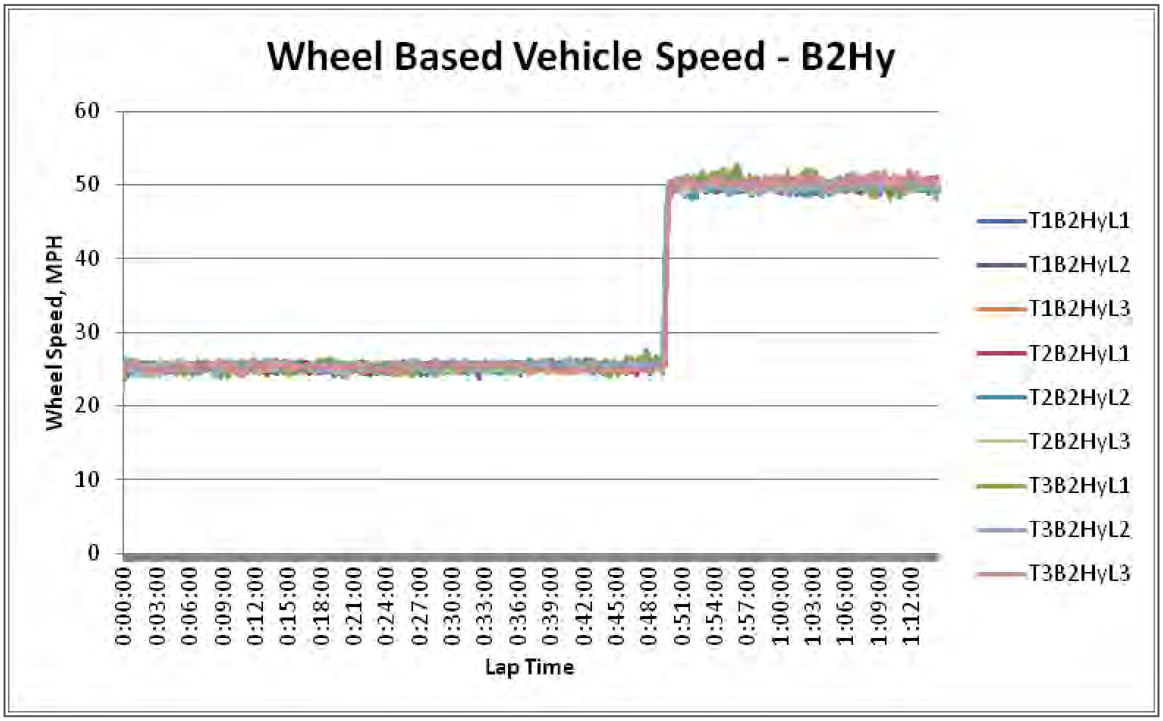

Figure 9. Wheel Based Vehicle Speed, Baseline 2 Highway

The repeated accelerations over the first nine miles of the Local Cycle show a great deal of consistency between the three trucks. Some overshoot occurred during the accelerations to higher speeds, but was quickly corrected. Available speed data indicates that the vehicles were operated in a reasonably consistent manner through the program. This is shown in Figure 10 through Figure 12.

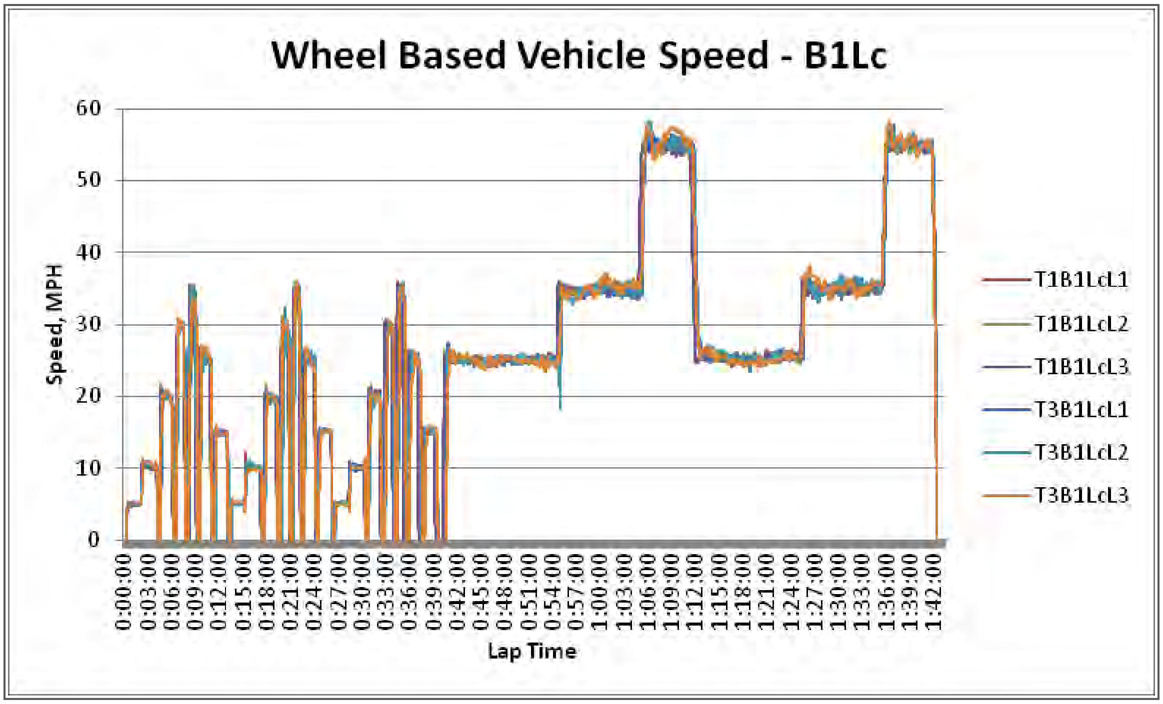

Figure 10. Wheel Based Vehicle Speed, Baseline 1 Local

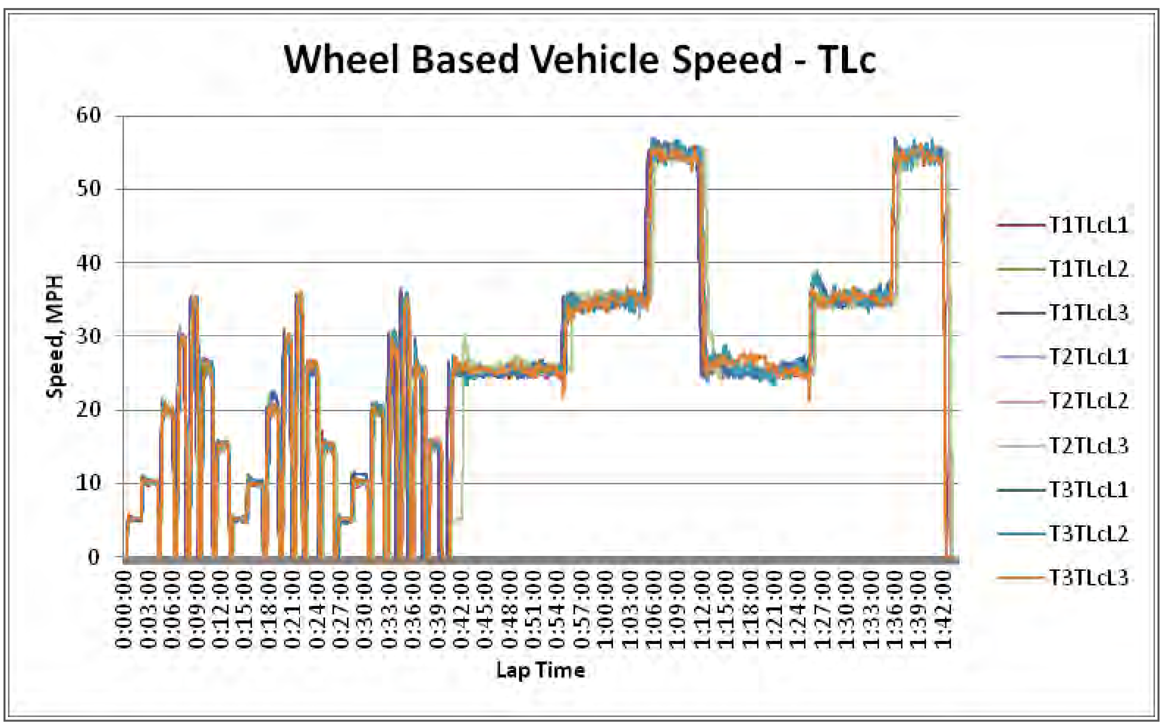

Figure 11. Wheel Based Vehicle Speed, Test Segment Local

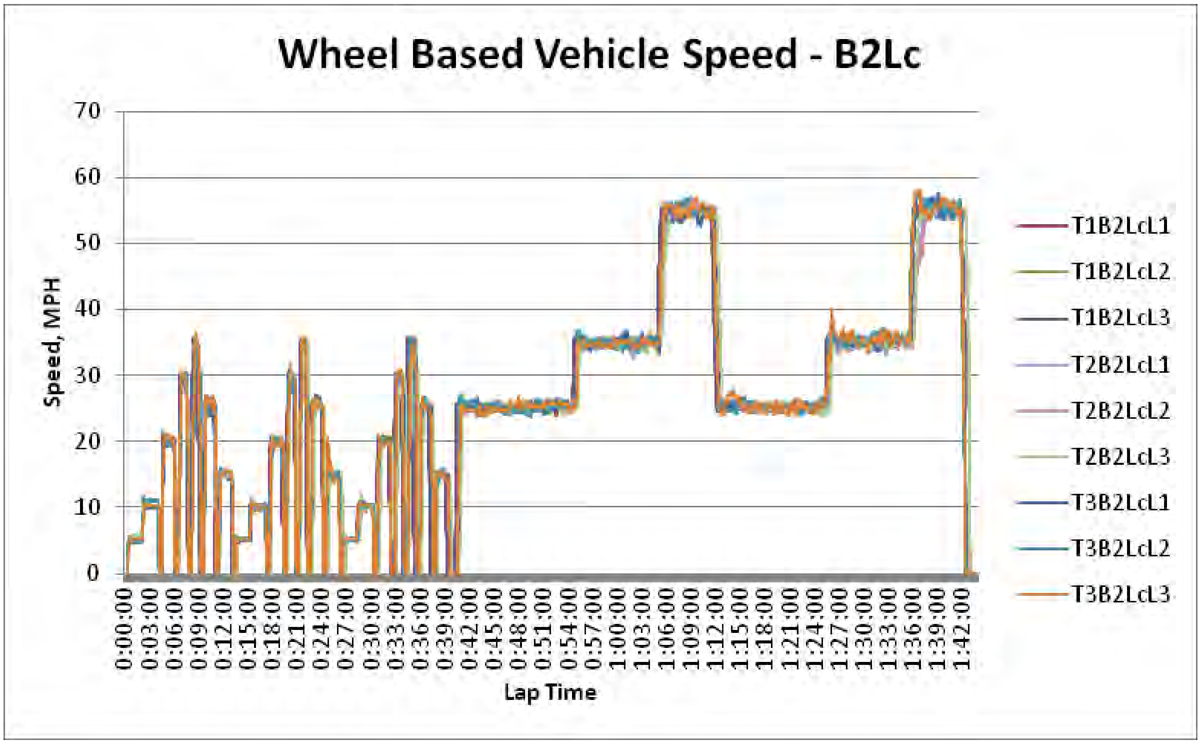

Figure 12. Wheel Based Vehicle Speed, Baseline 2 Local

3.1.2 Engine Oil Temperature

Oil temperature in the engine sump was measured using a K-type thermocouple inserted into the drain plug of the oil pan. Despite some variation between vehicles in the form of an unexplained temperature off-set, the response of all vehicles are similar to speed changes. Oil temperature graphs are shown in Figure 13 through Figure 18.

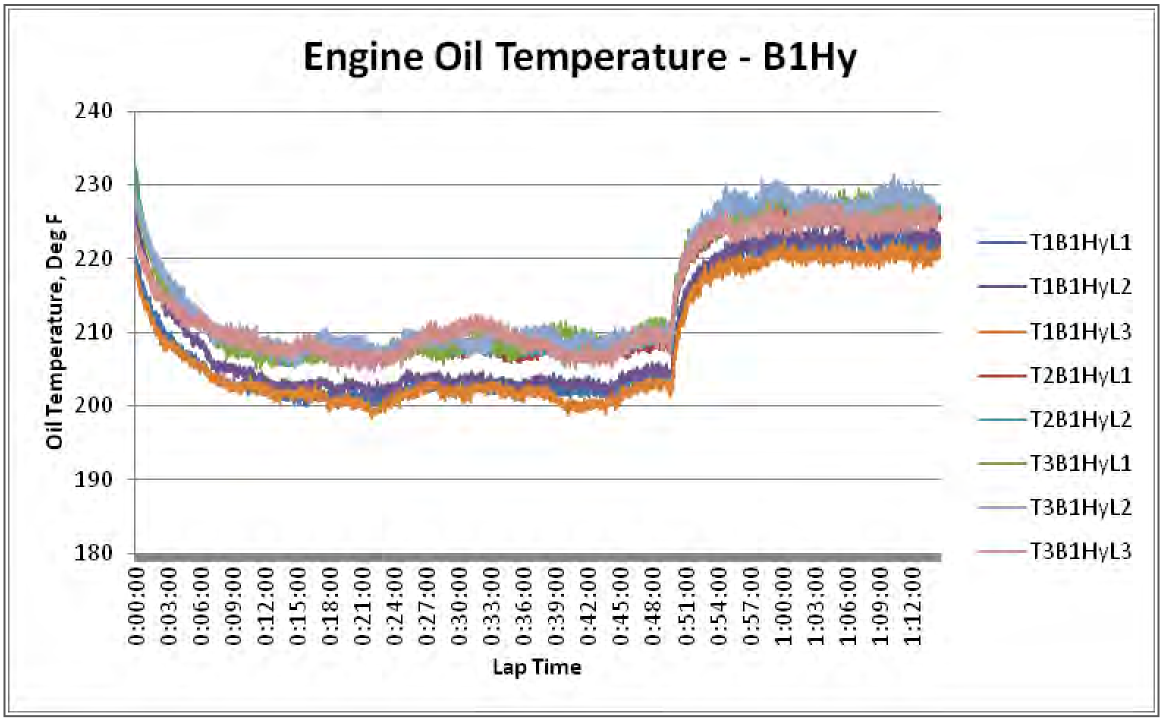

Figure 13. Engine Oil Temperature, Baseline 1 Highway

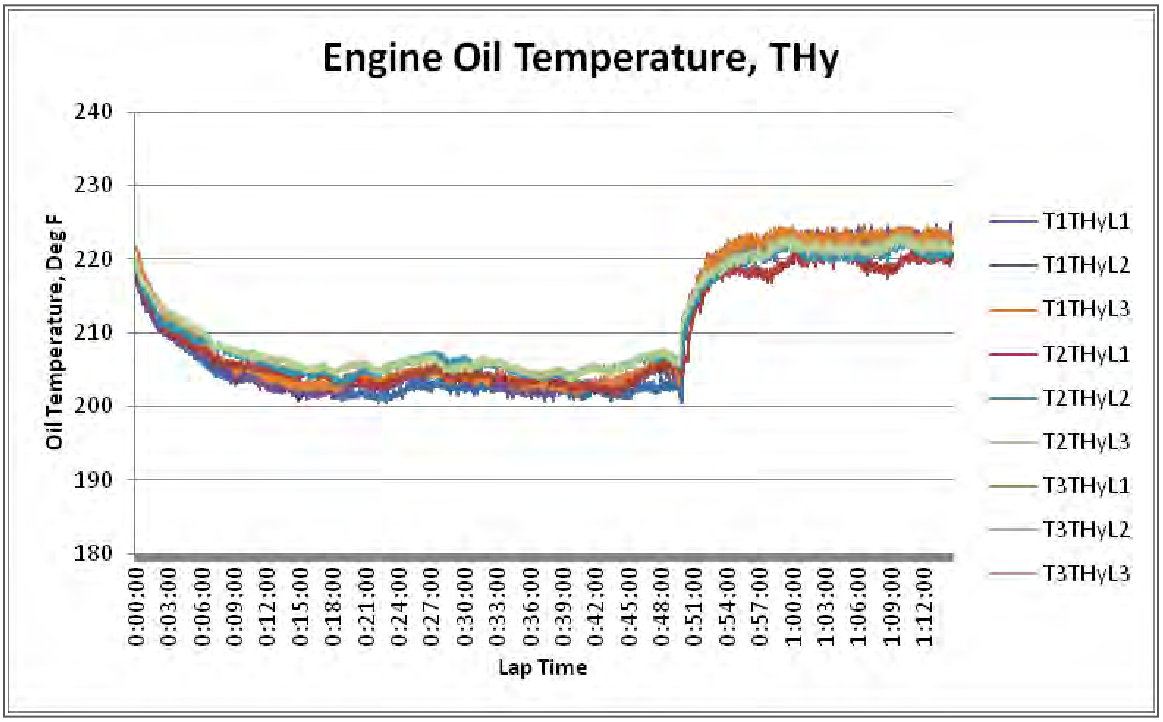

Figure 14. Engine Oil Temperature, Test Segment Highway

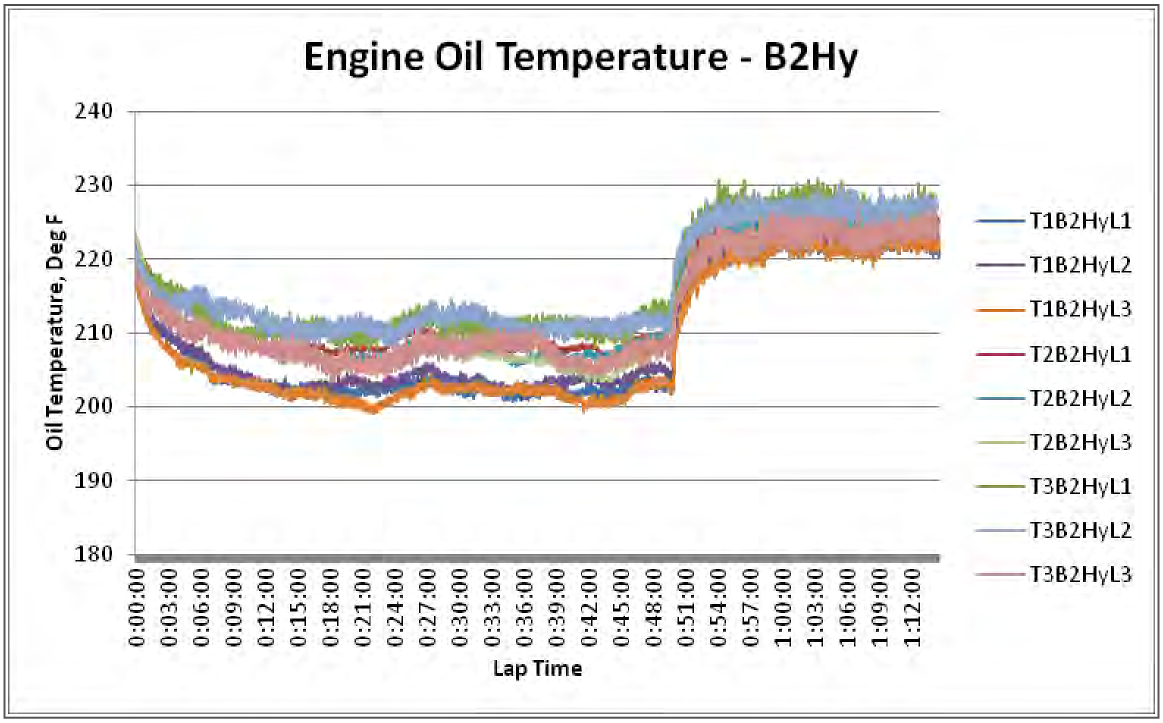

Figure 15. Engine Oil Temperature, Baseline 2 Highway

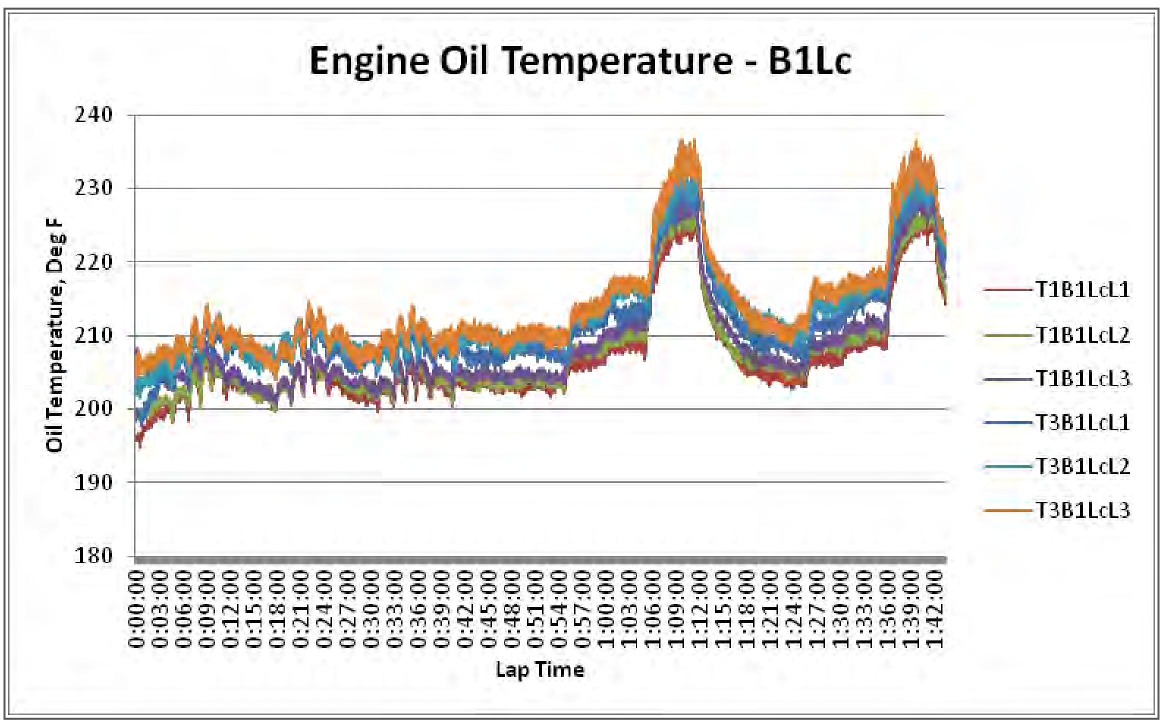

Figure 16. Engine Oil Temperature, Baseline 1 Local

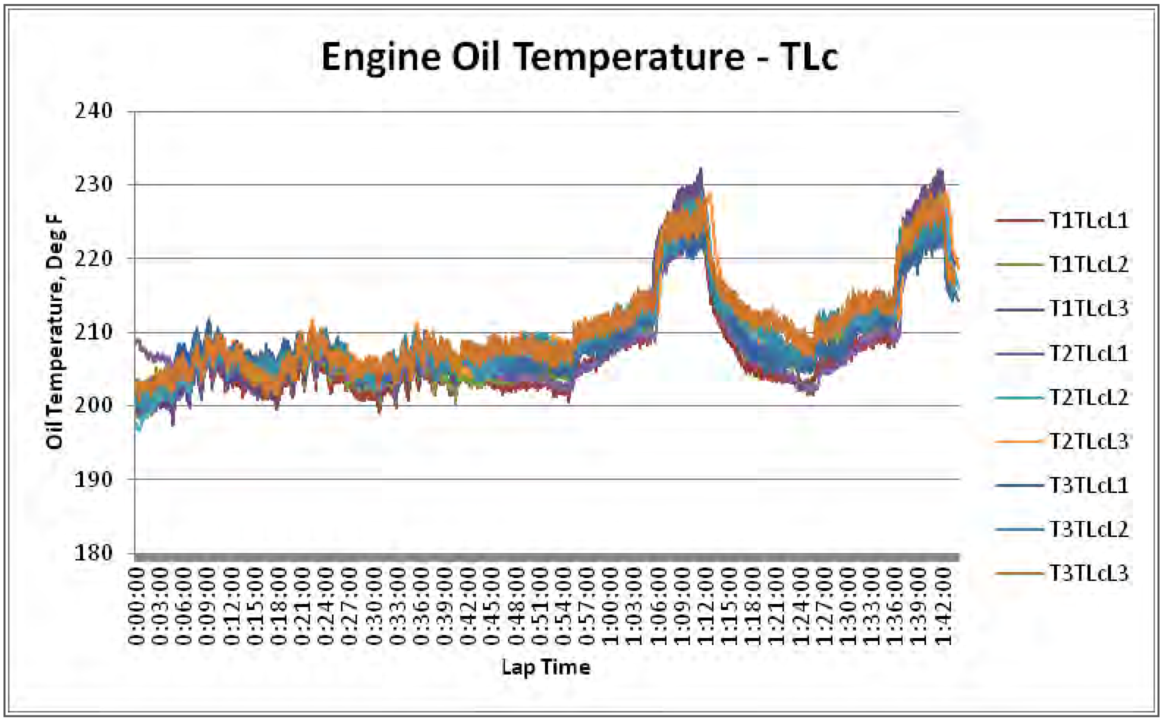

Figure 17. Engine Oil Temperature, Test Segment Local

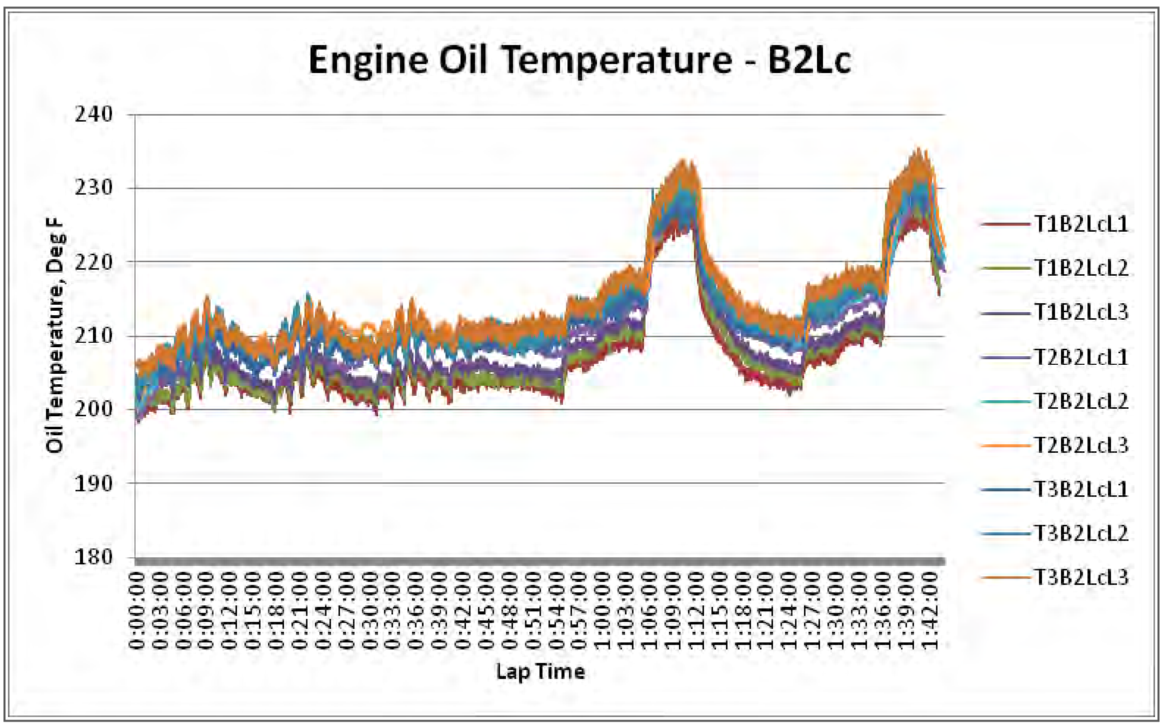

Figure 18. Engine Oil Temperature, Baseline 2 Local

3.1.3 Transmission Oil Temperature

Transmission oil temperature is shown along with the ambient air temperature measured from the control truck. This provides a reference for temperature changes between laps. The big drop in ambient temperature for lap 3 appears to represent the passage of a cold front, also accompanied with higher wind speeds. This helps to explain the occurrences such as the lower temperature seen in Baseline 1 during the third lap. There are temperature spikes which occur during the Local Cycle while the vehicle is idling. While stopped, the heat produced from the vehicle is warming the area that the thermocouple is located. Once moving again, the measured temperature returns to ambient conditions. Transmission oil temperatures are shown in Figure 19 through Figure 24.

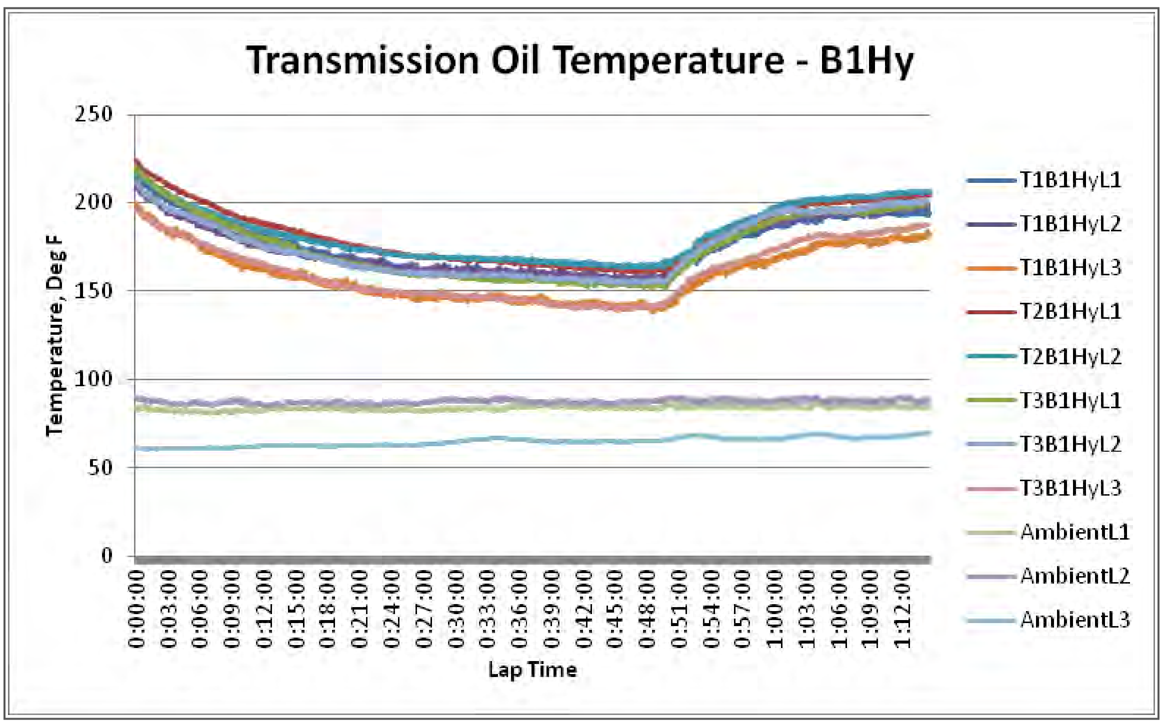

Figure 19. Transmission Oil Temperature, Baseline 1 Highway

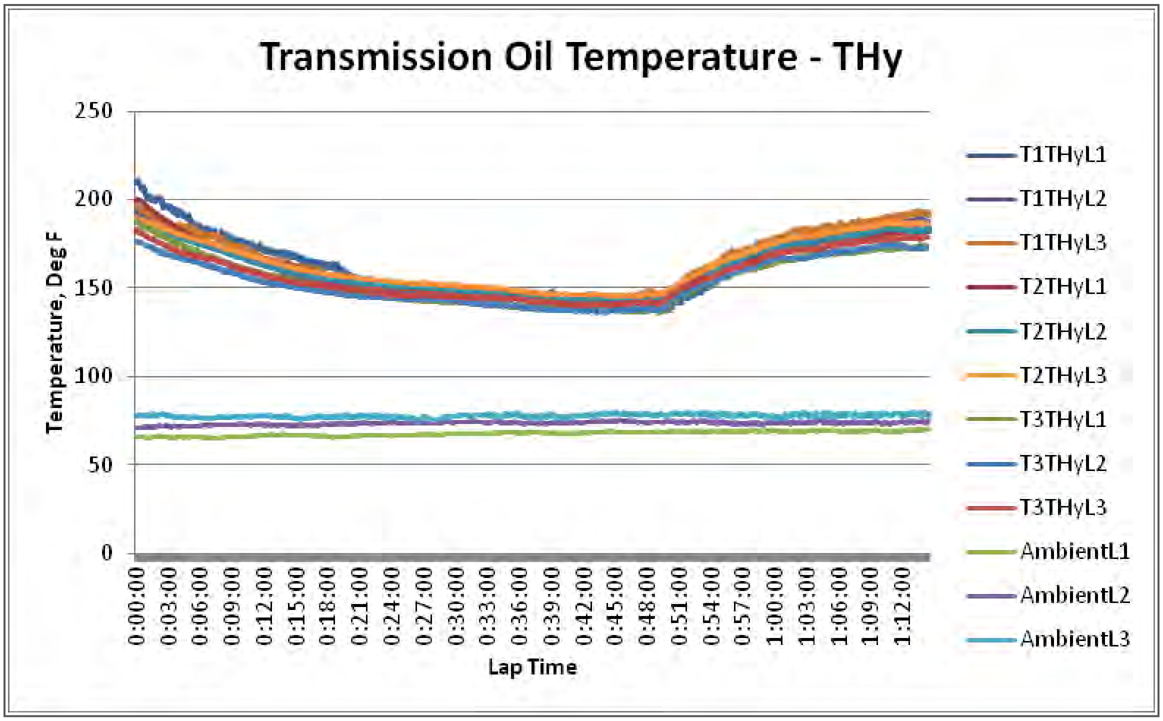

Figure 20. Transmission Oil Temperature, Test Segment Highway

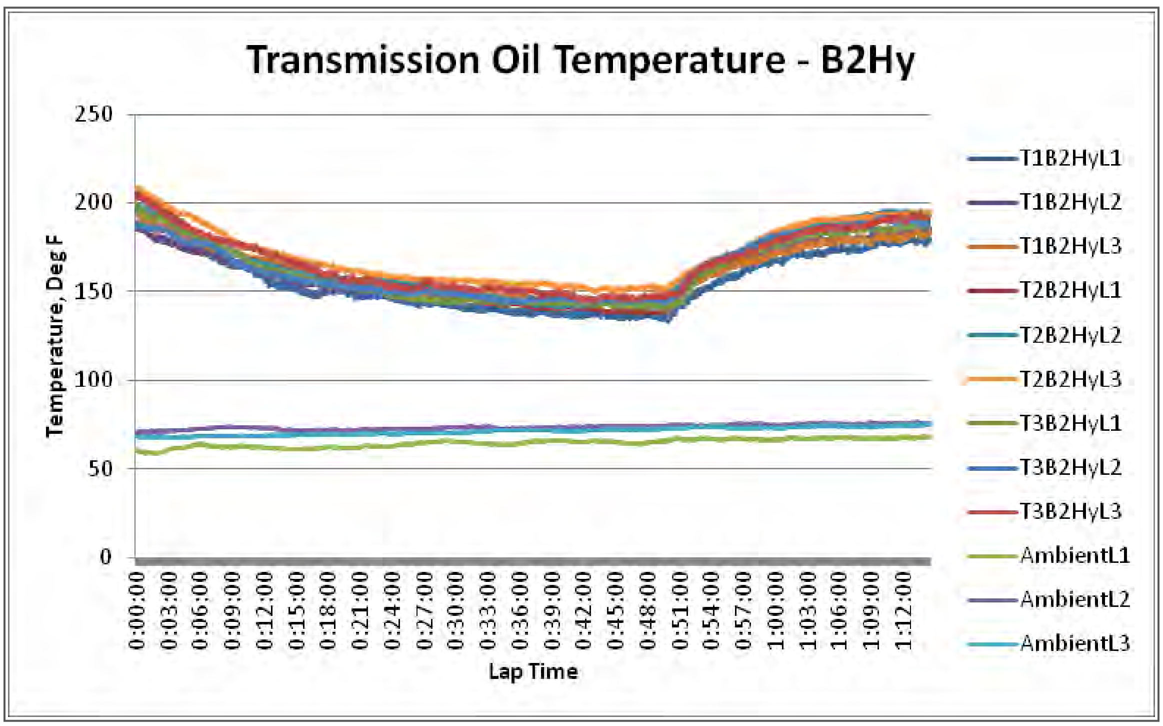

Figure 21. Transmission Oil Temperature, Baseline 2 Highway

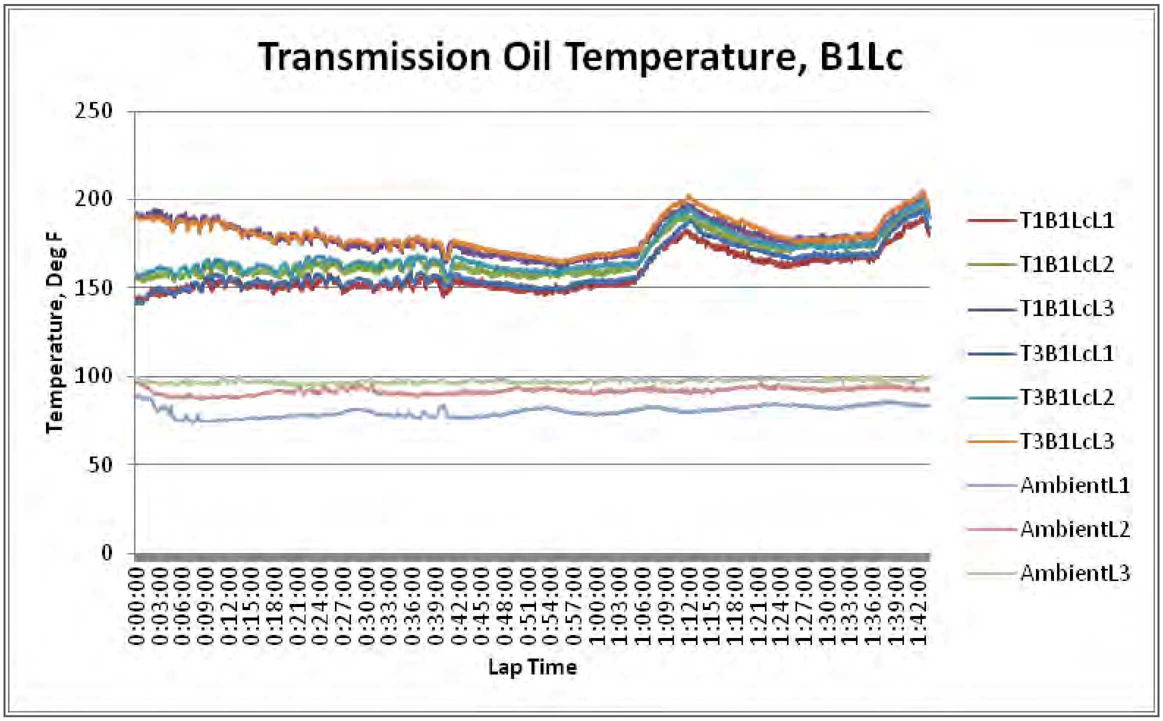

Figure 22. Transmission Oil Temperature, Baseline 1 Local

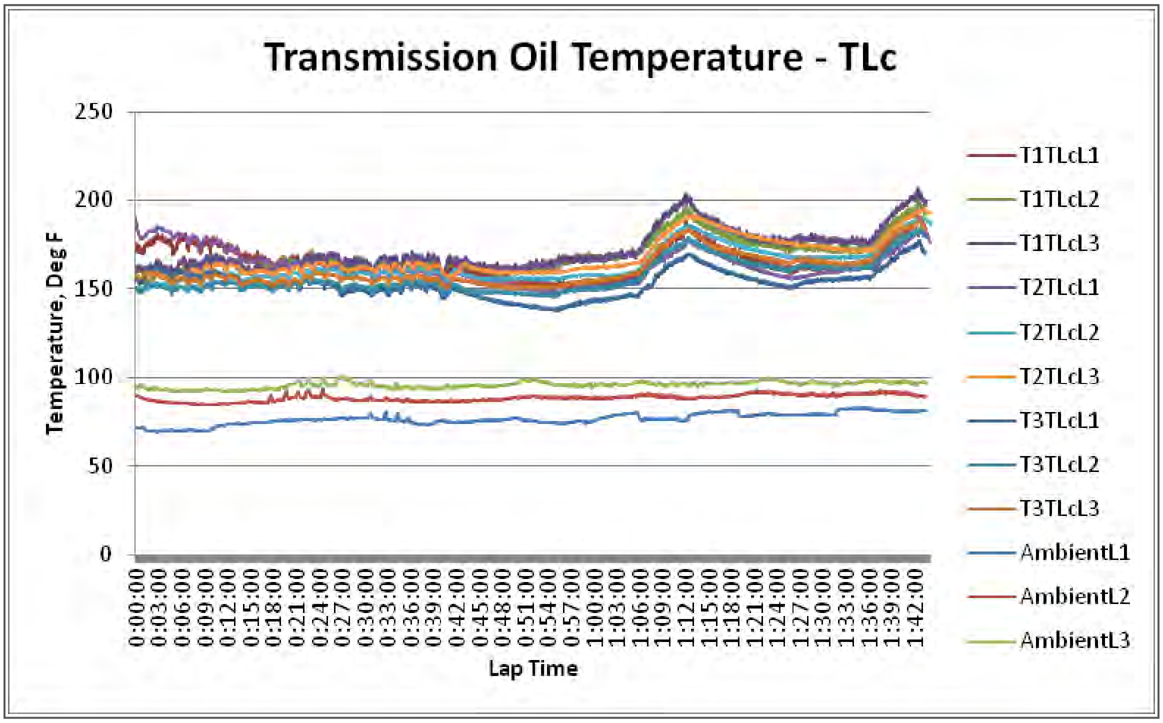

Figure 23. Transmission Oil Temperature, Test Segment Local

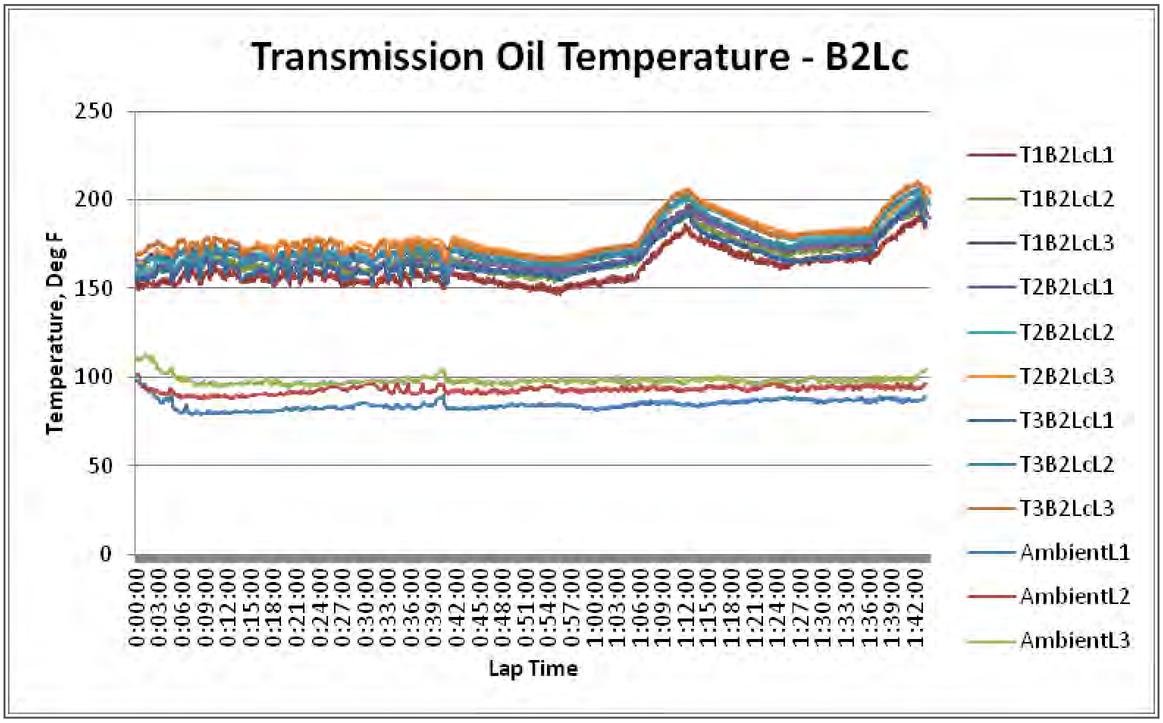

Figure 24. Transmission Oil Temperature, Baseline 2 Local

3.1.4 Front Axle Temperature

Lubrication is separate in the front axle for the differential and each individual wheel hub. Temperature data was recorded only for the differential and is shown in Figure 25 through Figure 30.

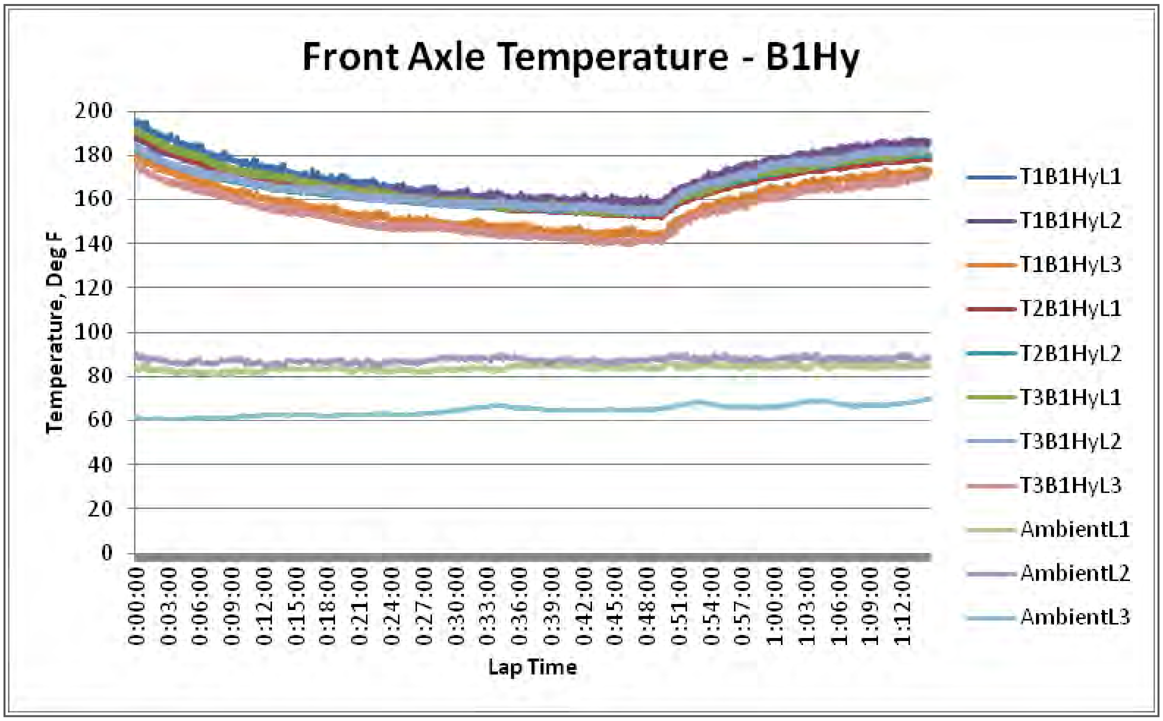

Figure 25. Front Axle Temperature, Baseline 1 Highway

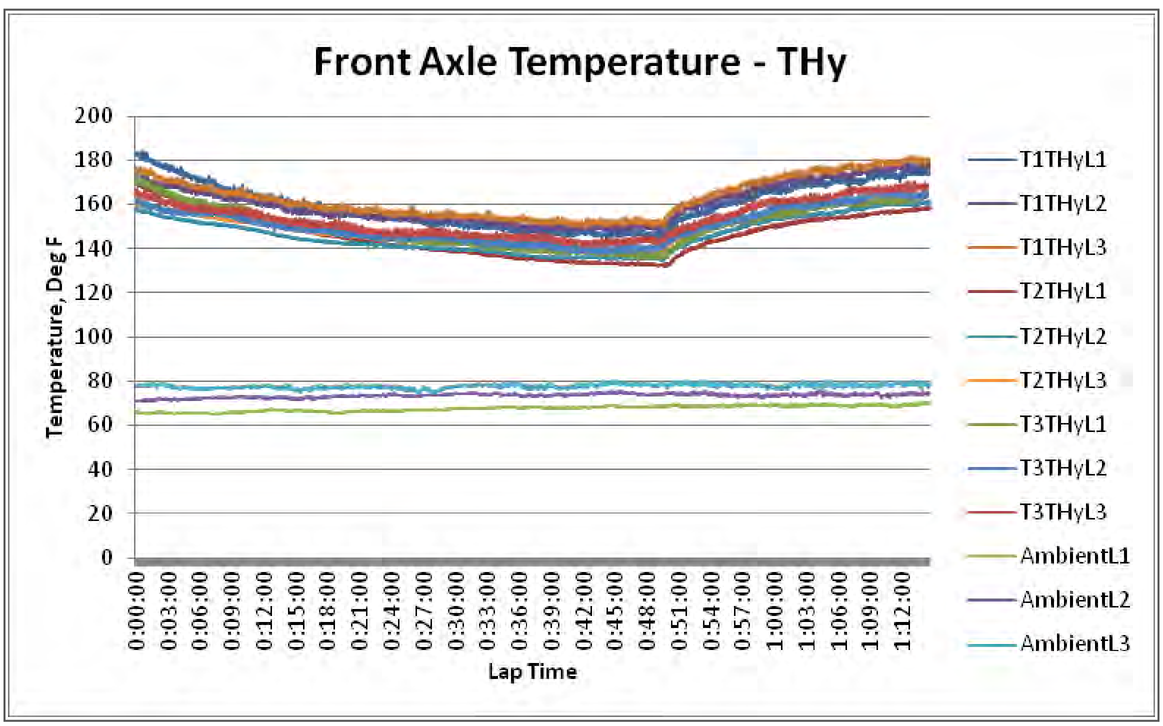

Figure 26. Front Axle Temperature, Test Segment Highway

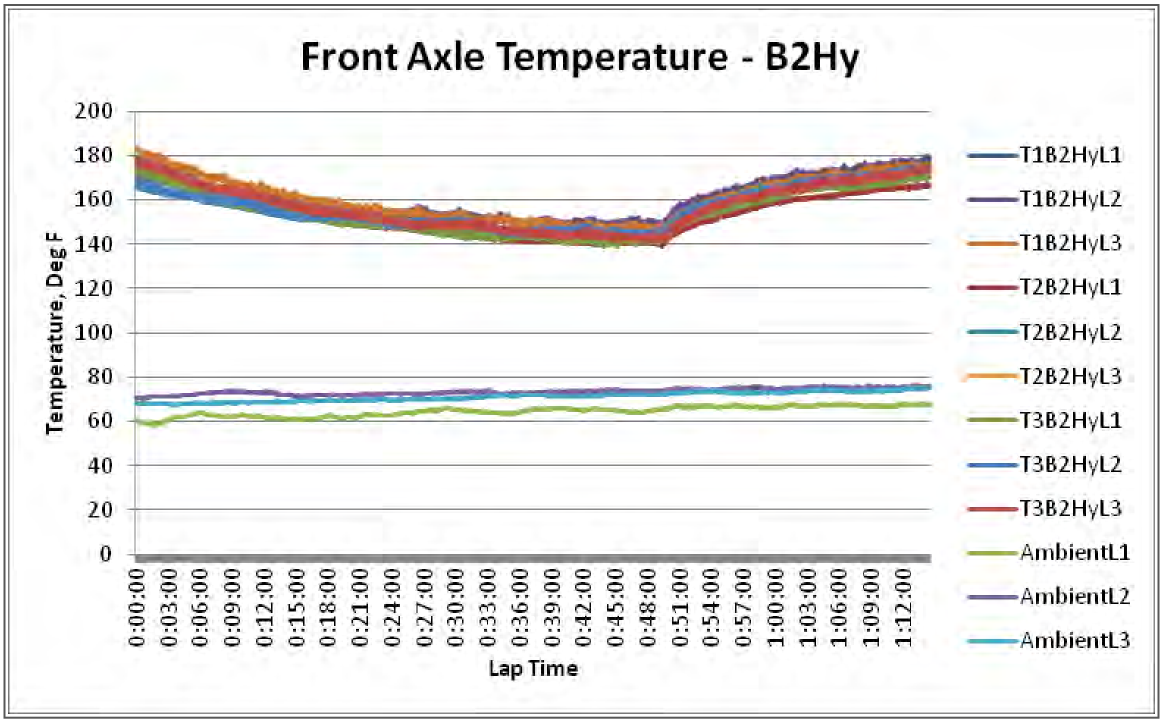

Figure 27. Front Axle Temperature, Baseline 2 Highway

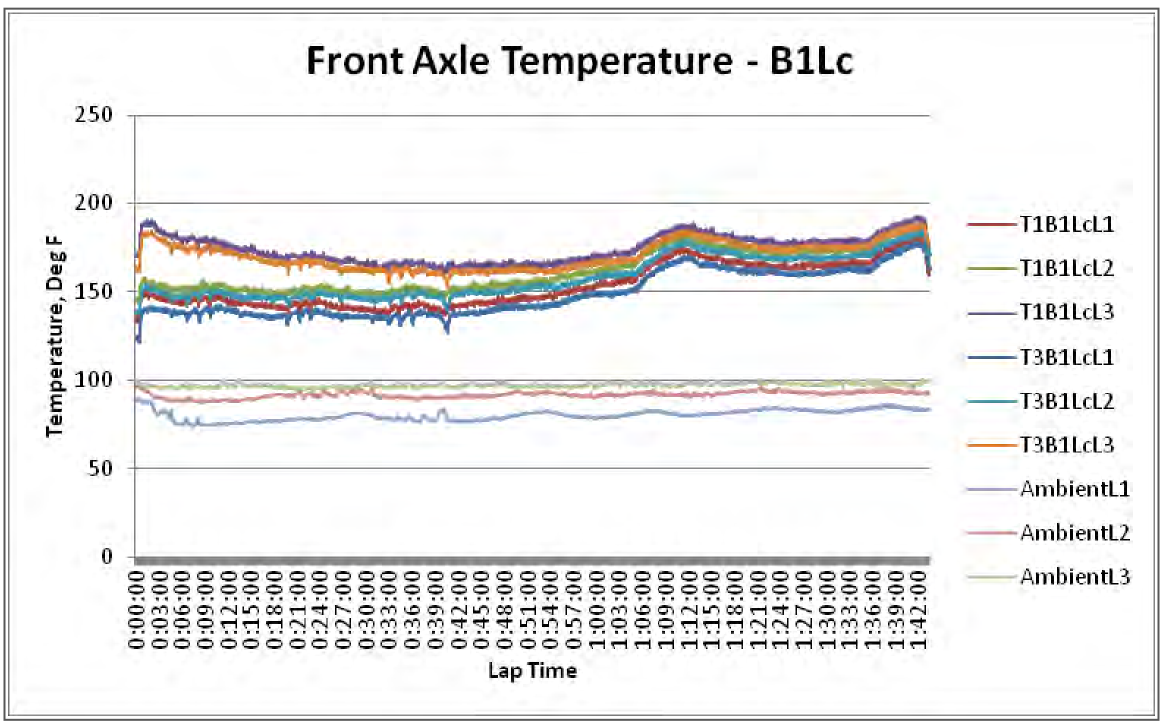

Figure 28. Front Axle Temperature, Baseline 1 Local

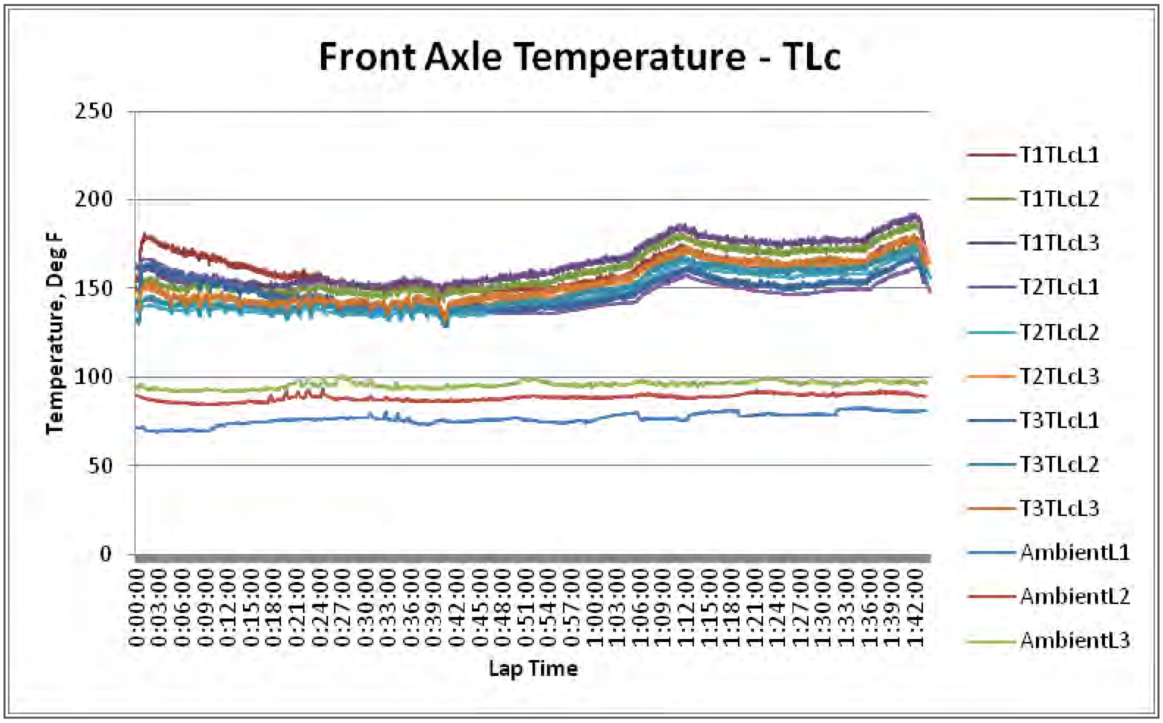

Figure 29. Front Axle Temperature, Test Segment Local

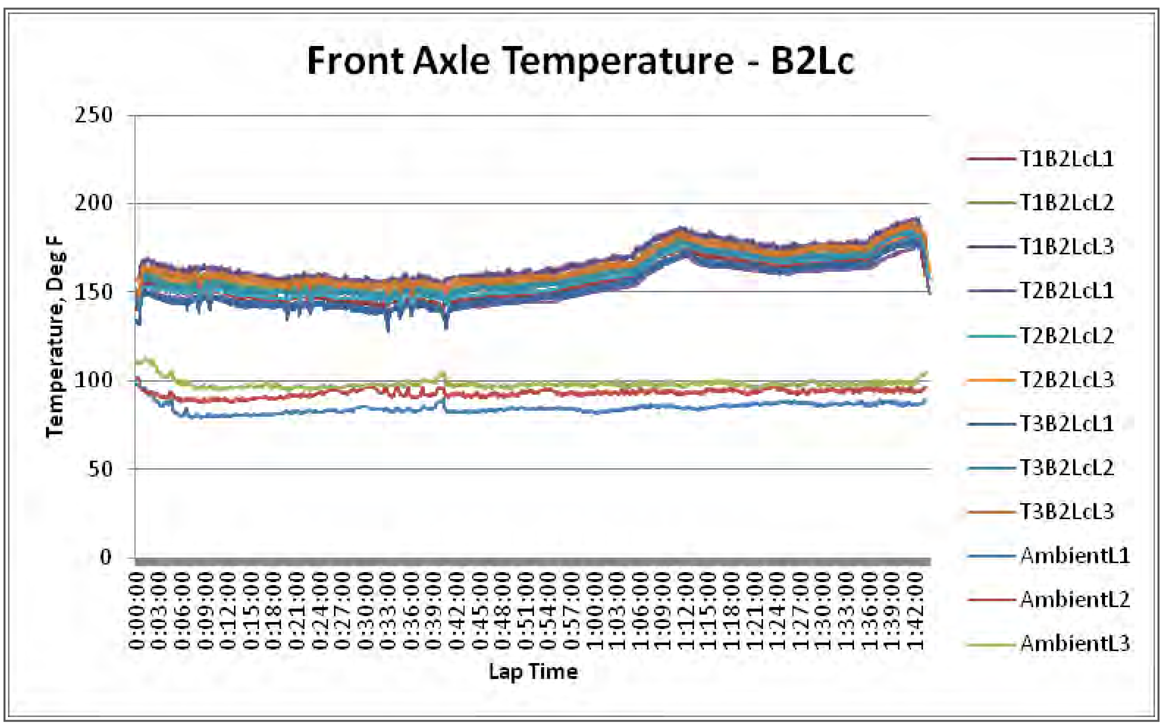

Figure 30. Front Axle Temperature, Baseline 2 Local

3.1.5 Intermediate Axle Temperature

The temperature of the intermediate axle typically operated higher than that of the other two. In addition to the power being split between the two wheels, the intermediate axle is responsible for the split between the rear tandem. In both the intermediate and rear axles, the wheel hub lubrication and differential lubrication are connected. Intermediate axle temperatures are shown in Figure 31 through Figure 36.

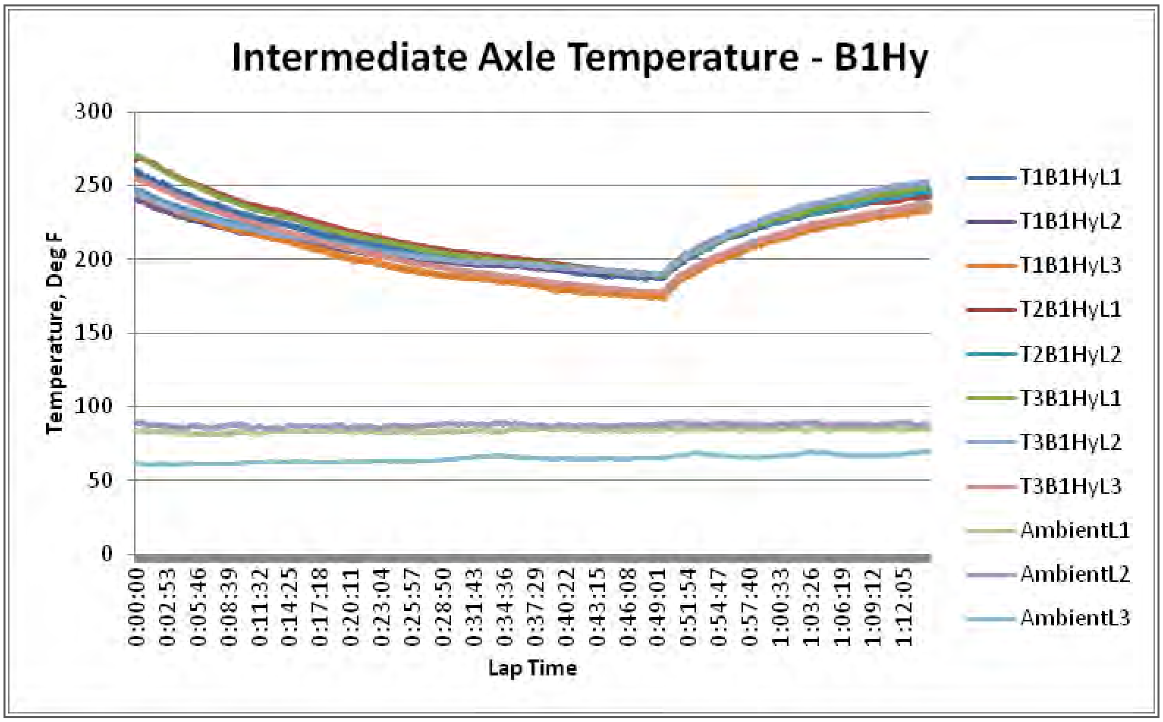

Figure 31. Intermediate Axle Temperature, Baseline 1 Highway

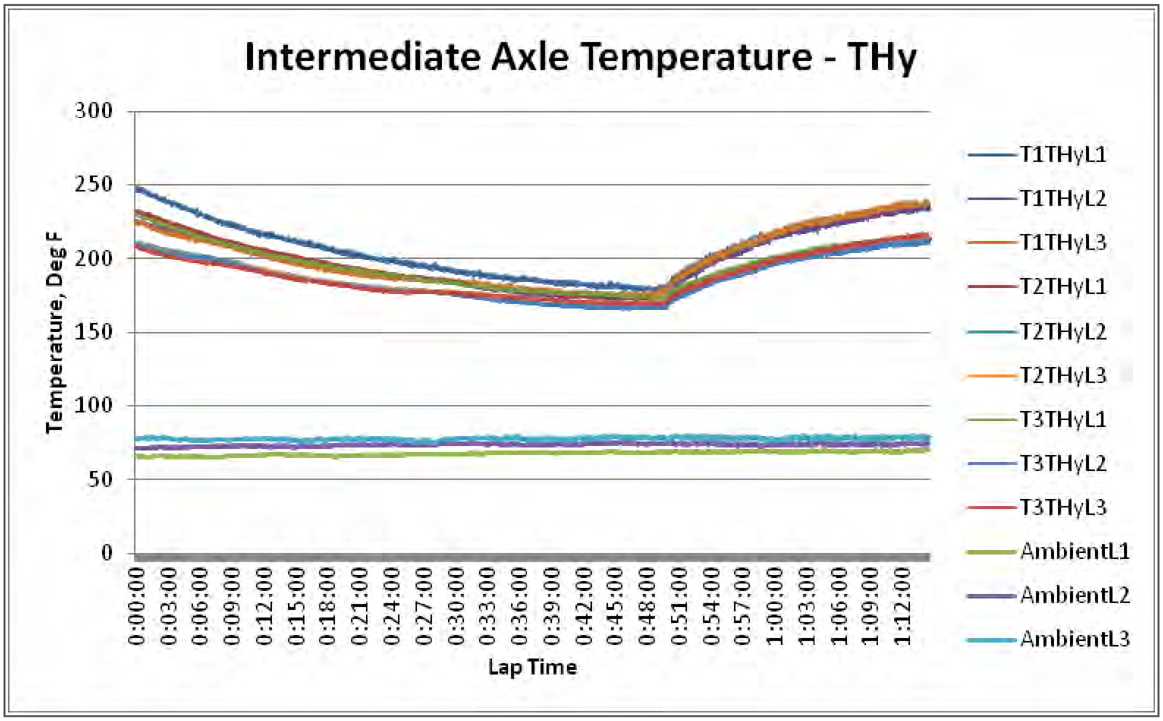

Figure 32. Intermediate Axle Temperature, Test Segment Highway

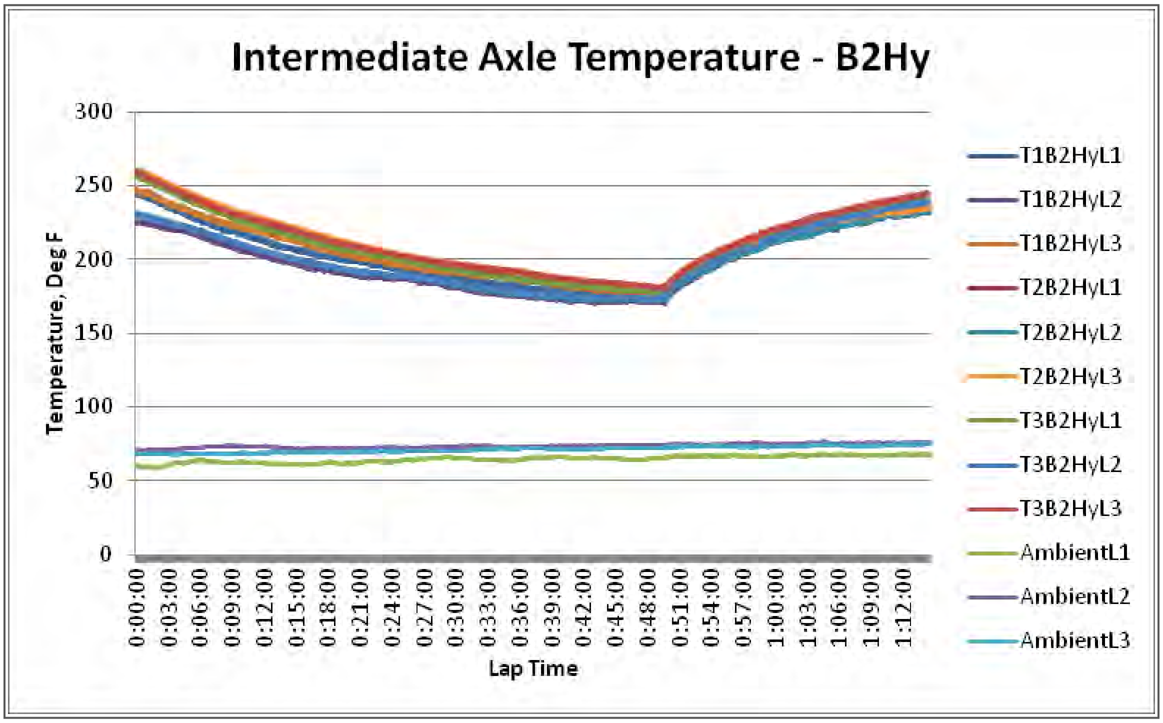

Figure 33. Intermediate Axle Temperature, Baseline 2 Highway

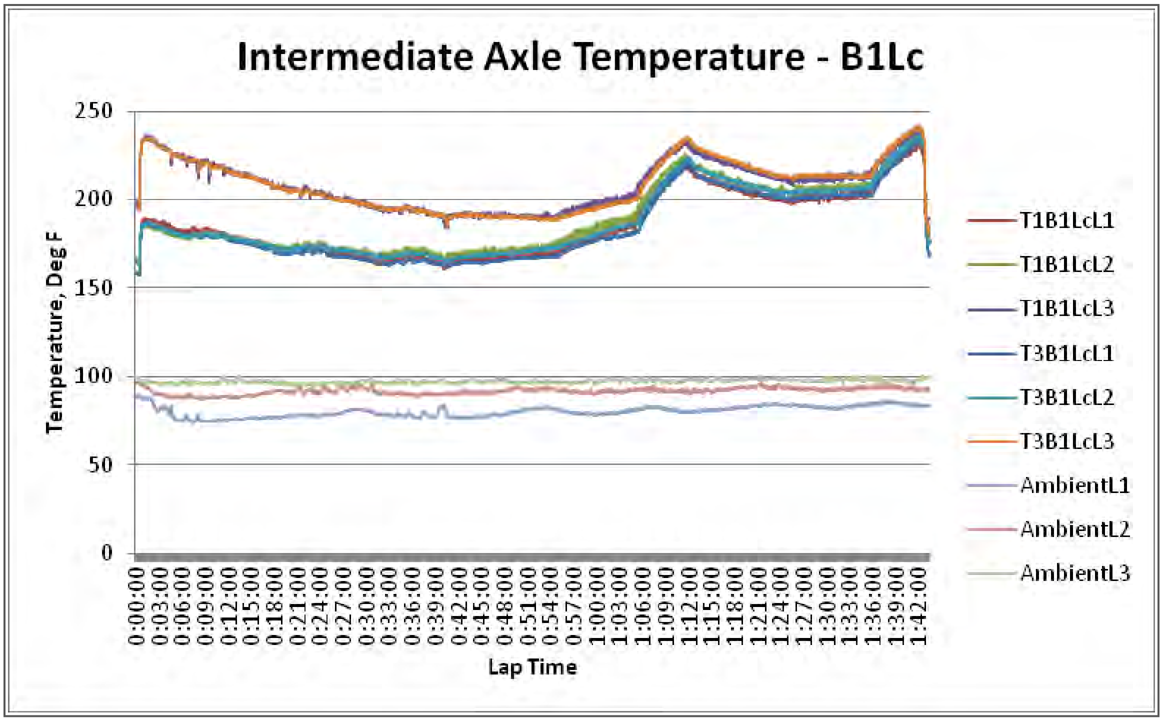

Figure 34. Intermediate Axle Temperature, Baseline 1 Local

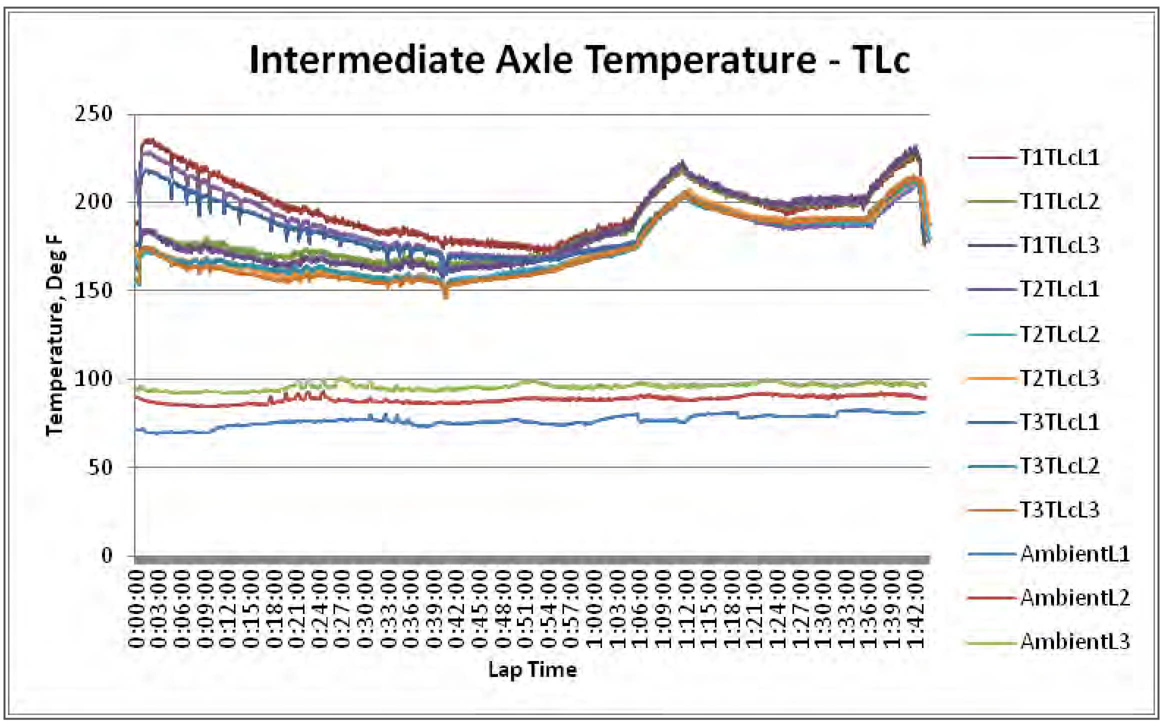

Figure 35. Intermediate Axle Temperature, Test Segment Local

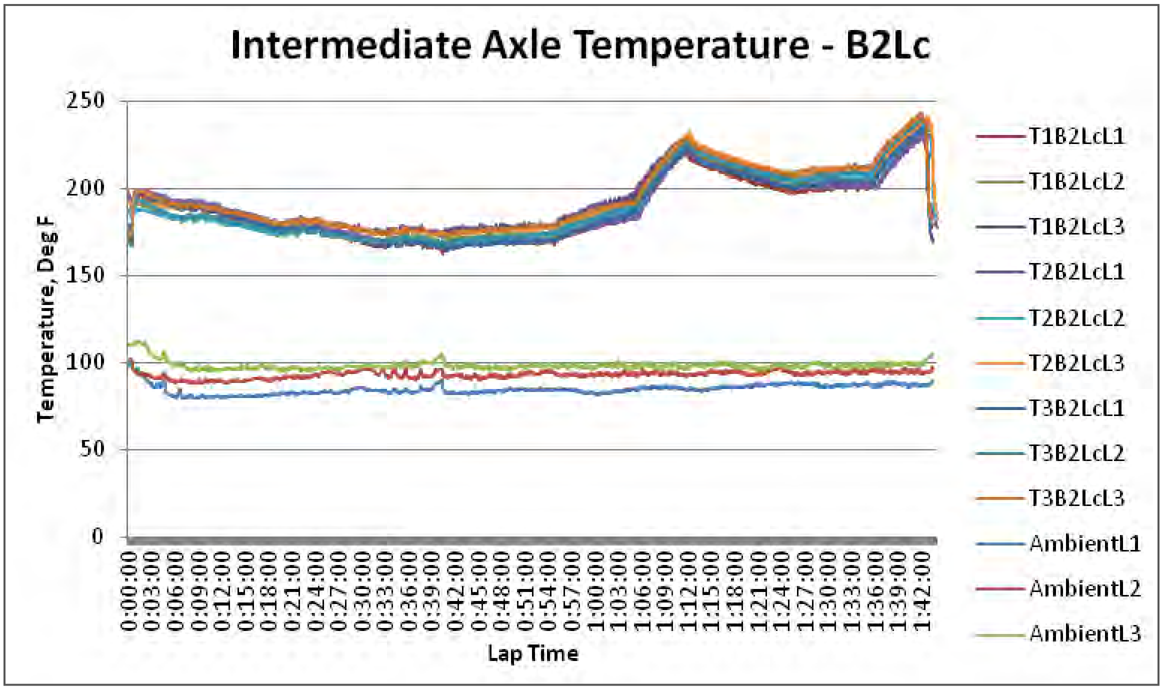

Figure 36. Intermediate Axle Temperature, Baseline 2 Local

3.1.6 Rear Axle Temperature

The rear axle temperature is shown in Figure 37 through Figure 42.

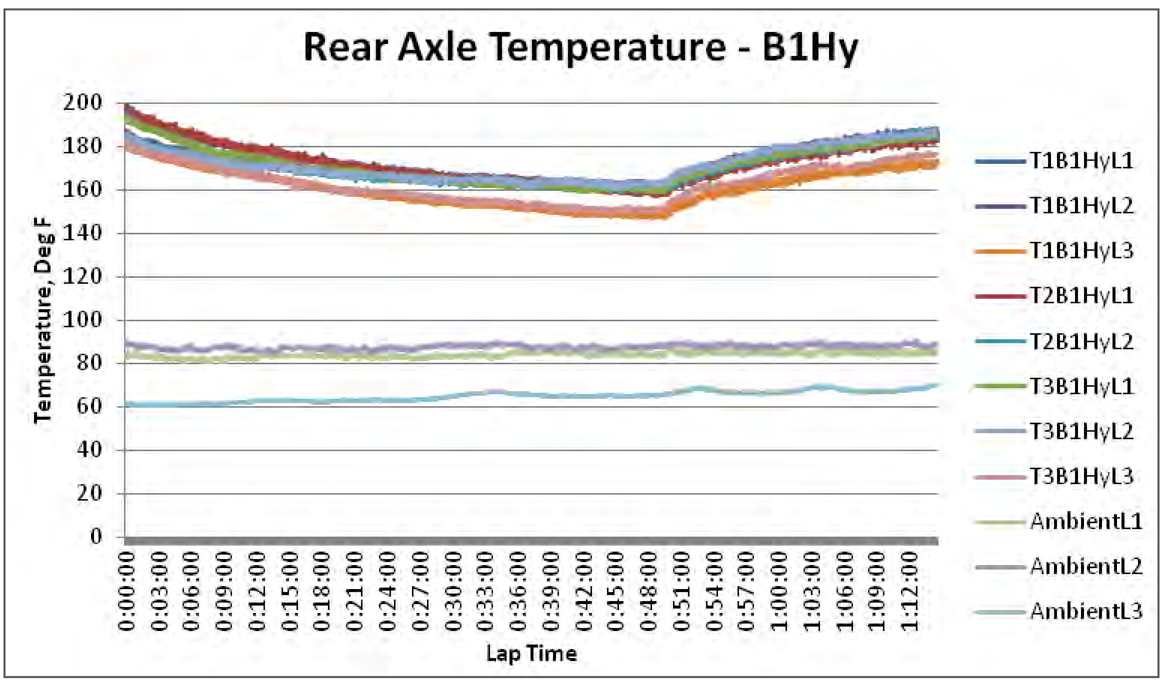

Figure 37. Rear Axle Temperature, Baseline 1 Highway

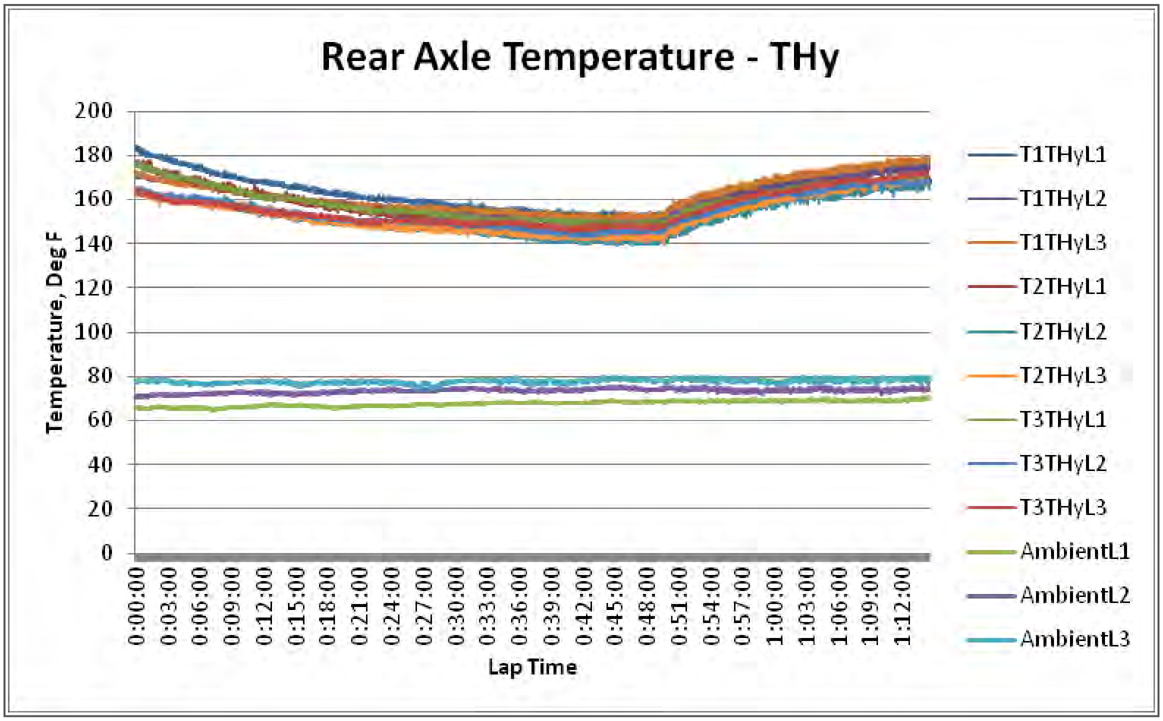

Figure 38. Rear Axle Temperature, Test Segment Highway

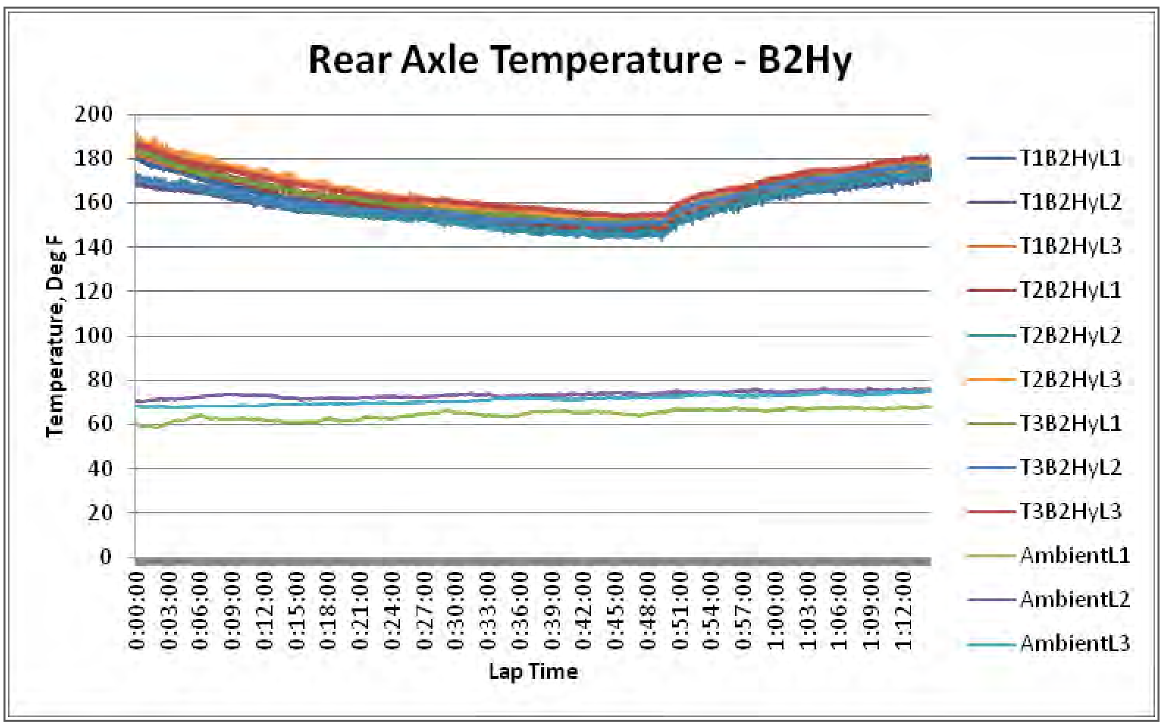

Figure 39. Rear Axle Temperature, Baseline 2 Highway

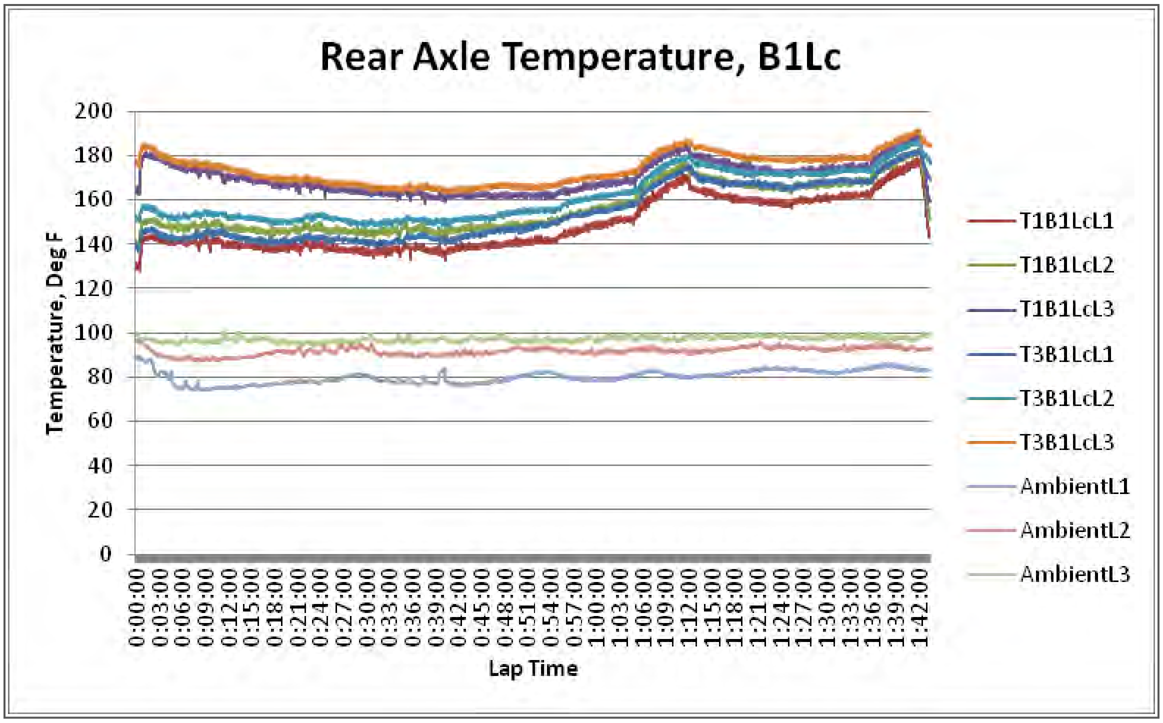

Figure 40. Rear Axle Temperature, Baseline 1 Local

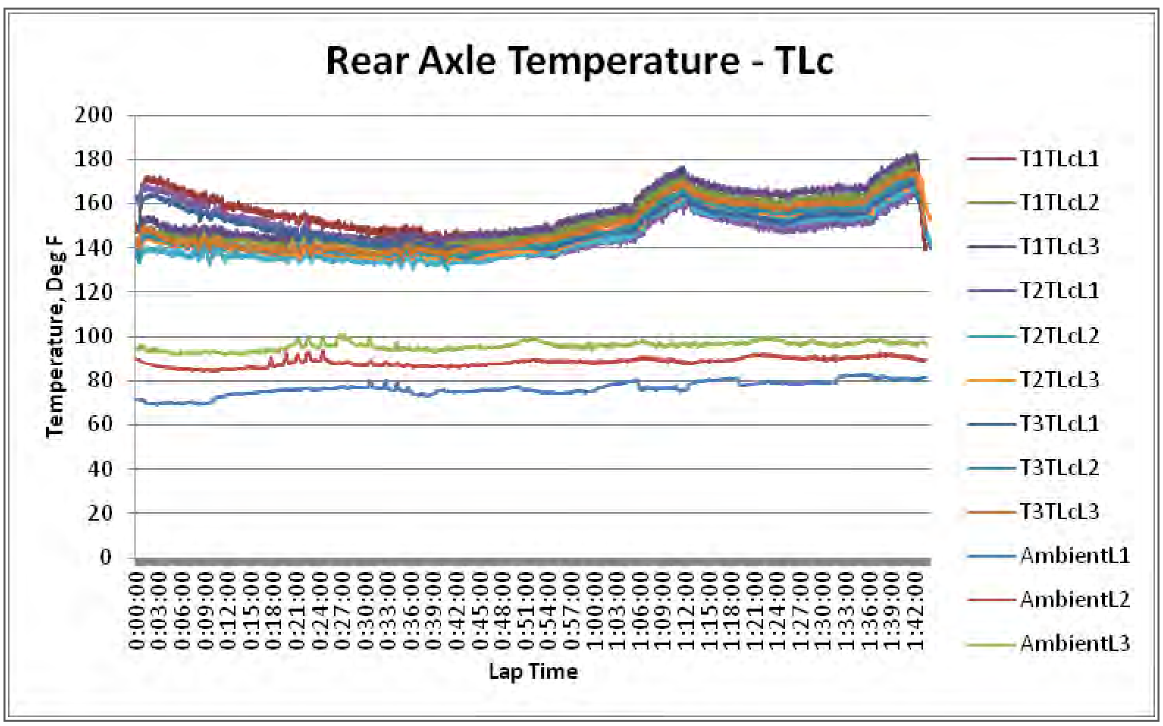

Figure 41. Rear Axle Temperature, Test Segment Local

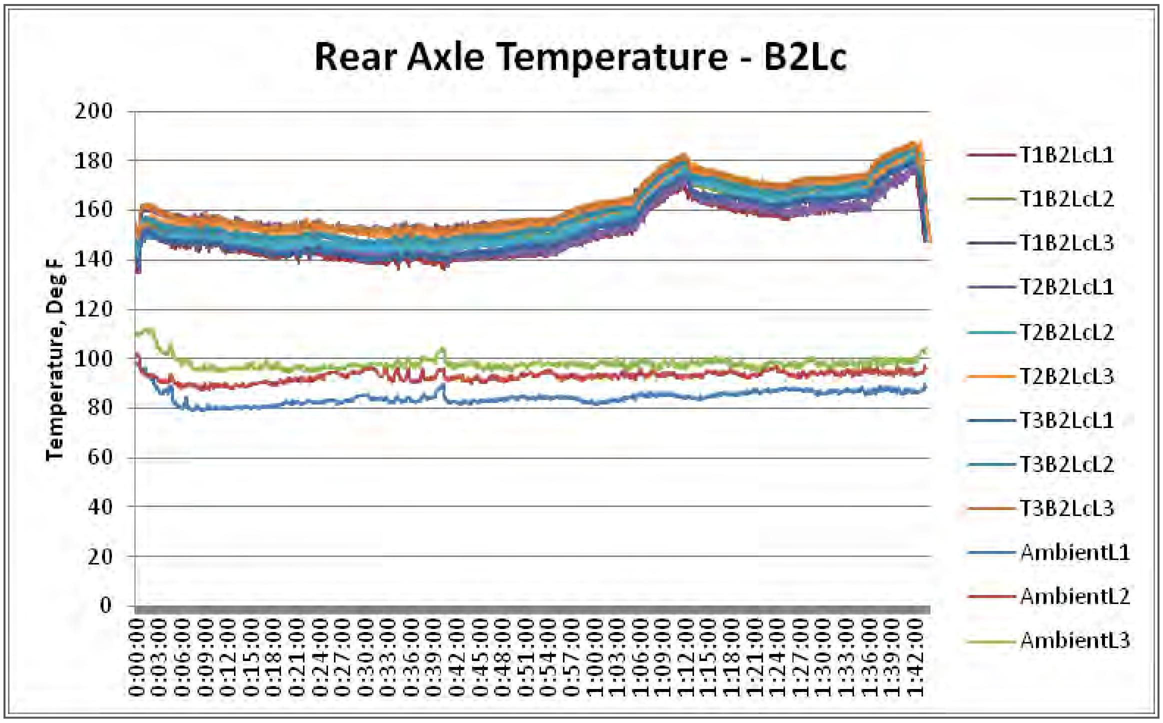

Figure 42. Rear Axle Temperature, Baseline 2 Local

3.1.7 Wind Speed

The measured wind speed at the test route start/finish location is shown in Figure 43. While it is desirable to operate when test conditions produce a wind speed of less than 12 mph and a difference between runs of less than 5 mph, the availability of the test facility did not make this feasible. Wind conditions were recorded for informational purposes.

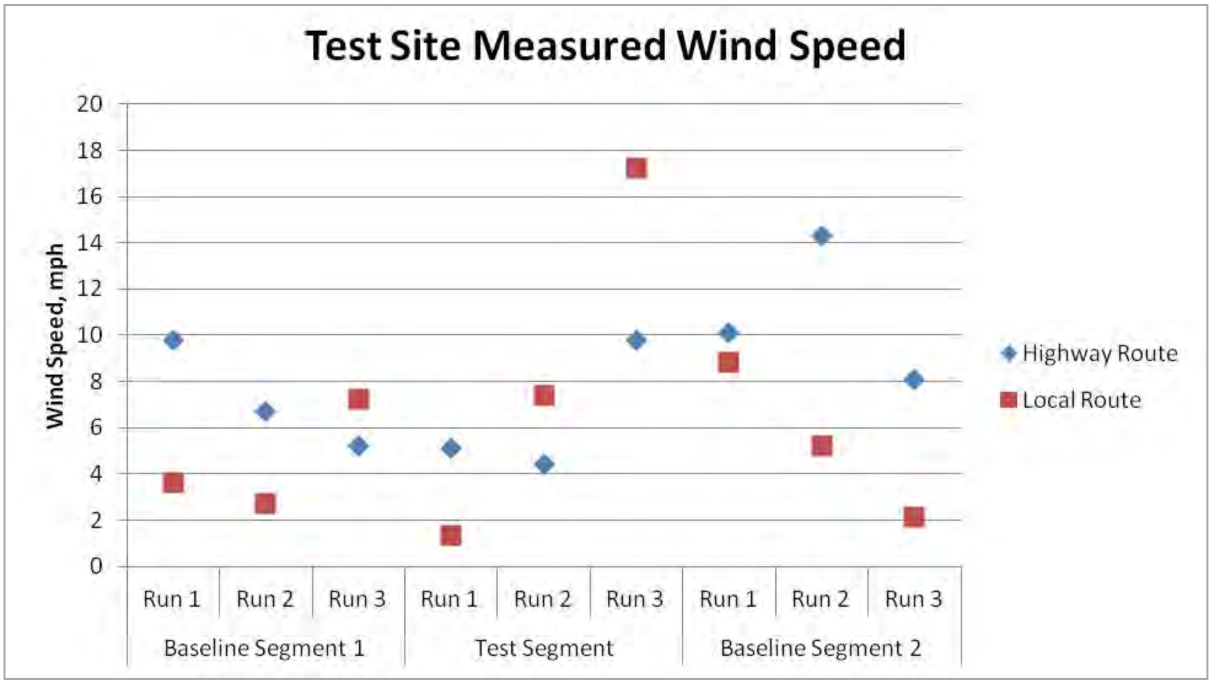

Figure 43. Test Site Measured Wind Speed

3.2 FUEL CONSUMPTION CHANGES

While comparison of temperature data helps to validate the consistency of vehicle operation, the total fuel consumed by each truck is the most important parameter measured. The improvement in fuel consumption for the Test Segment is independently compared to both Baselines. Results are shown in Table 5. Graphical representation is shown in Figure 44 and Figure 45. Full calculations and data sheets of results are provided in APPENDIX A.

Table 5. Fuel Consumption Improvement

Cycle	Comparison	Truck 2		Truck 3	
		% Improvement	C.I.	% Improvement	C.I.
Highway	Baseline1	6.04%	±0.79%	4.81%	±0.88%
	Baseline2	6.23%	±1.62%	7.19%	±1.34%
Local	Baseline1	7.19%	±0.76%	7.12%	±1.43%
	Baseline2	7.62%	±0.43%	9.20%	±1.35%

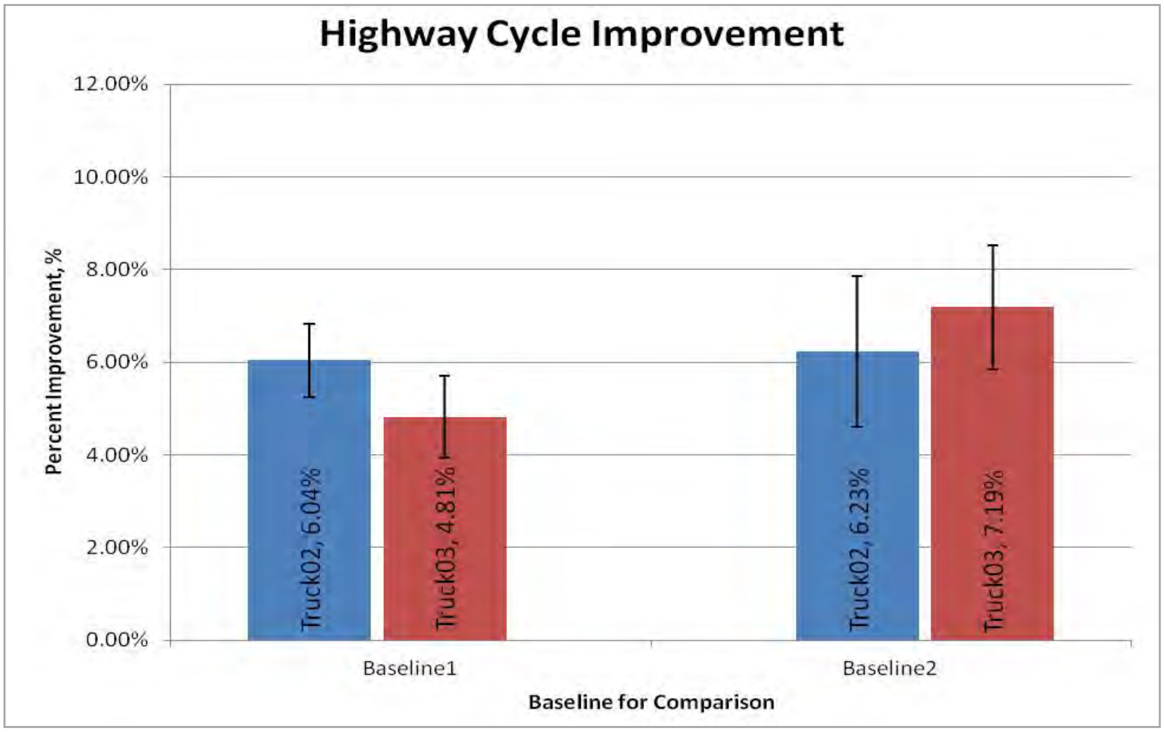

Figure 44. Highway Cycle Fuel Consumption Change

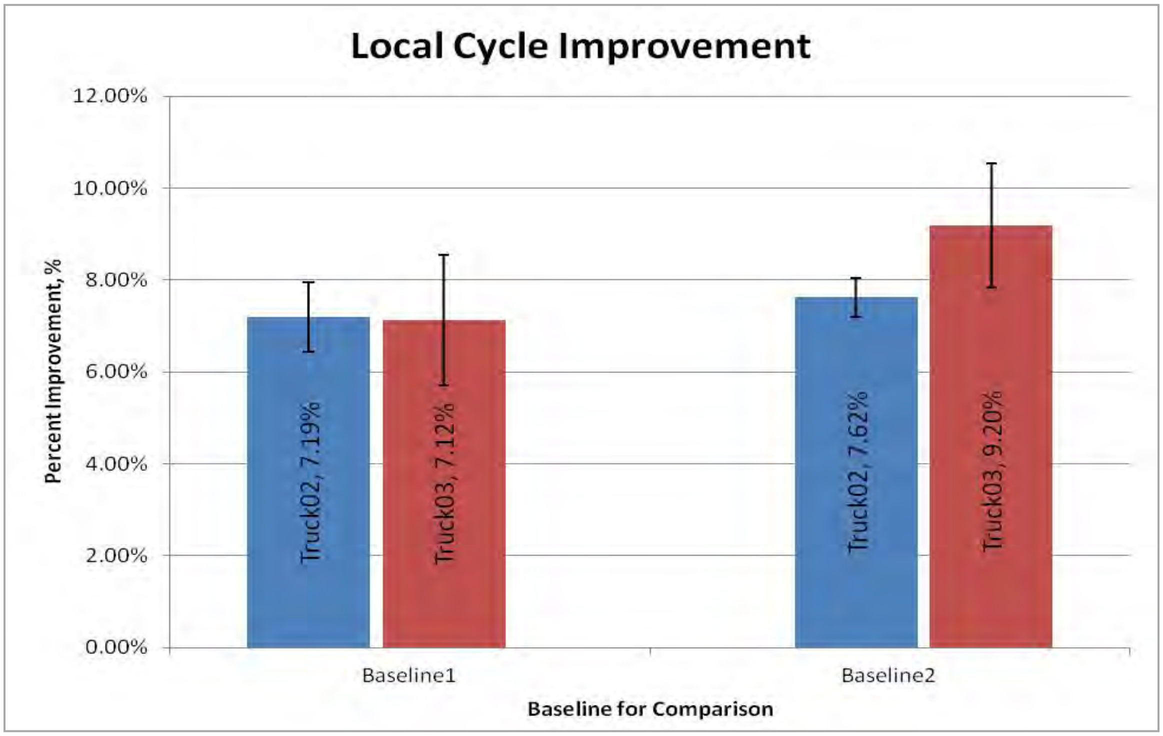

Figure 45. Local Cycle Fuel Consumption Change

4.0 AXLE SURVEY

An additional area of interest for the development of an efficient axle lubricant is the hardware in which it will be used. Differing geometry within an axle assembly may impact the responsiveness to a change in fluid. Table 6 provides a summary of a number of current ground vehicles and their axle make, ratio, and differential type. It should be noted that amboid and hypoid are both variations of a spiral bevel gear set, but with the input shaft intersecting the ring gear above or below the axle centerline. Axle ratios given are for the overall assembly. In many cases, this includes a wheel hub reduction (as was the case with the FMTVs tested).

Table 6. Survey of Current Military Equipment Axles

Vehicle	Axle Make (GAWR)	Drive Axles	Axle Ratio	Differential
M1097 HMMWV	AM General (6500)	2	5.24:1 (2.731/1.92)	Hypoid
M1083A1P2 FMTV (J1321 Vehicle)	Meritor RF-611 (19,000)	2 or 3	7.8:1 (3.7/2.1)	Amboid
M1070 HET	Axle Tech (formerly Rockwell) (23,600)	4	7.36:1 (1.59/4.63)	Spiral Bevel
M1070A1 HET	Axle Tech 5000	4	6.945:1	Spiral Bevel
M1074/M1075 PLS	Axle Tech (formerly Rockwell) SVI 5MR (26,455)	5	6.0:1	Spiral Bevel
BAE RG33 4X4	Axle Tech 4000 Series	2	7.56:1	Spiral Bevel
BAE RG33L 6X6	Axle Tech 4000 Series F (18,700) I&R (20,000)	3	5.68:1 (1.42/4.0)	Spiral Bevel
BAE RG3I	F Meritor 3311 (11,464) R Meritor 3321 (11,464)	2	5.68:1 (1.59/3.58)	Spiral Bevel
BAE RG3I A2E	Axle Tech 400 Series F (15,432) R (22,046)	2	—	Spiral Bevel
BAE CAIMAN		2		
Category I, 4X4	Arvin Meritor R611 (F &R)		6.14:1 (2.92/2.1)	Amboid
Category II, 6X6	Arvin Meritor R611 (F&R)		6.14:1 (2.92/2.1)	Amboid
MTV, 6X6	Arvin Meritor		6.18:1 (1.78/3.46)	Amboid
MAXX Pro PLUS	Arvin Meritor F MX-18-120 (18,000) R MX – 21-160 (21,000) or R MX-23-160 (23,000)	2	—	Spiral Bevel

Based upon a view of the current fleet, the overall size of the axle is in the middle of the smaller HMMWV and large HET vehicles.

5.0 CONCLUSION AND RECOMMENDATIONS

Based upon the measured changes in fuel consumption for in-vehicle testing, there are significant potential savings associated with advanced powertrain lubricants. A vehicle level improvement in the 6-7% range with no required hardware changes provides an appealing reduction in fuel, logistical, and financial burdens for the U.S. Army. Future investigation into lower viscosity gear oils may produce additional fuel consumption benefits, but must be balanced with ensuring that adequate protection is provided for contact surfaces. Laboratory tests should be utilized for this purpose. Since the axle is typically only cooled through forced convection, the energy balance reached through efficiency and heat loss determines a great deal of how a fluid impacts fuel consumption. If a fluid is too low in viscosity, inadequate film thickness may result in increased friction and heat while at the same time result in decreased churning losses in the bulk fluid. A higher viscosity fluid may heat from the bulk churning, but keep localized gear temperatures lower due to an improved film thickness. It's recommended that future work be conducted in a laboratory setting, where the ability to control external cooling and internal loading is much greater than full-vehicle testing conducted in the field. This would allow for a range of operating conditions and temperatures to be isolated and the resulting efficiency data can be used to determine if duty-cycle effects the relative efficiencies of candidate lubricants. If duty-cycle doesn't effect the relative efficiency of candidate lubricants, then a single, simplified cycle can be used to predict lubricant derived efficiency gains.

6.0 REFERENCES

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3. Technical Manual Operator's Instructions: M1083 Series, 5 TON, 6x6, Medium Tactical Vehicles (MTV), TM-9-2320-366-10-1, 1998

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10. Kolekar, Anant S., Andrew V. Olver, Adam E. Sworski, and Frances E. Lockwood. 203-209. <www.elsevier.com/locate/triboint>.

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APPENDIX A.

SAE J1321 Fuel Consumption Calculations

SAE J1321 Data Analysis
- Fuel Economy Improvement Testing Vs Baseline 1: Truck 2 Highway Cycle

Baseline Segment1			
Fuel Consumed, lbs			
Run	Truck 2	Control 1	T/C
1	38.75	41.30	0.9383
2	38.75	41.30	0.9383
3	39.95	42.40	0.9422

Test Segment			
Fuel Consumed, lbs			
Run	Truck 2	Control 1	T/C
1	37.70	42.75	0.8819
2	38.30	43.15	0.8876
3	37.95	42.70	0.8888

Summary Stats		
	Baseline	Test
Mean T/C	0.9396	0.8861
Number of Data Points	3	3
Standard Deviations	0.0023	0.0037
Variances	0.0000052	0.0000136
Difference in Means	0.0535	

F-Test for Equal Variances	
Baseline T/C Variance	0.00001
Test T/C Variance	0.00001
F test stat (test/baseline)	2.60166
F low	0.02564
F high	39.00000
Are Variances Equal ?	**yes**

T-Test with Equal Variances (2-tailed)	
Pooled St dev	0.00307
t-crit	2.776
t-stat	21.355
Is Fuel Economy Improved ?	**yes**
P-value	0.0000
lower CI bound	0.046544
upper CI bound	0.060455

T-Test with Unequal Variances (2-tailed)	
df (nu)	3.340
t-crit	3.007
t-stat	21.355
Is Fuel Economy Improved ?	**yes**
P-value	0.0001
lower CI bound	0.045966
upper CI bound	0.061033

CI t-critical	0.000
CI std err term	0.00000

Test Result			
	Nominal	Confidence Interval	
Fuel Saved	**5.69%**	**±**	**0.74%**
Improvement	**6.04%**	**±**	**0.79%**

SAE J1321 Data Analysis
- Fuel Economy Improvement Testing Vs Baseline 2: Truck 2 Highway Cycle

Baseline Segment2			
Fuel Consumed, lbs			
Run	Truck 2	Control 1	T/C
1	40.45	42.55	0.9506
2	40.05	42.80	0.9357
3	39.00	41.60	0.9375

Test Segment			
Fuel Consumed, lbs			
Run	Truck 2	Control 1	T/C
1	37.70	42.75	0.8819
2	38.30	43.15	0.8876
3	37.95	42.70	0.8888

Summary Stats		
	Baseline	Test
Mean T/C	0.9413	0.8861
Number of Data Points	3	3
Standard Deviations	0.0081	0.0037
Variances	0.0000663	0.0000136
Difference in Means	0.0552	

F-Test for Equal Variances	
Baseline T/C Variance	0.00007
Test T/C Variance	0.00001
F test stat (test/baseline)	0.20512
F low	0.02564
F high	39.00000
Are Variances Equal ?	yes

T-Test with Equal Variances (2-tailed)	
Pooled St dev	0.00632
t-crit	2.776
t-stat	10.699
Is Fuel Economy Improved ?	yes
P-value	0.0004
lower CI bound	0.040891
upper CI bound	0.069550

T-Test with Unequal Variances (2-tailed)	
df (nu)	2.787
t-crit	3.324
t-stat	10.699
Is Fuel Economy Improved ?	yes
P-value	0.0024
lower CI bound	0.038064
upper CI bound	0.072378

CI t-critical	2.776
CI std err term	0.00516

Test Result		
	Nominal	Confidence Interval
Fuel Saved	**5.87%**	**± 1.52%**
Improvement	**6.23%**	**± 1.62%**

SAE J1321 Data Analysis
- Fuel Economy Improvement Testing Vs Baseline 1: Truck 2 Local Cycle

Baseline Segment1			
	Fuel Consumed, lbs		
Run	Truck 2	Control 1	T/C
1	44.90	47.55	0.9443
2	44.70	47.60	0.9391
3	44.00	47.00	0.9362

Test Segment			
	Fuel Consumed, lbs		
Run	Truck 2	Control 1	T/C
1	42.75	48.75	0.8769
2	43.10	49.20	0.8760
3	44.00	50.15	0.8774

Summary Stats		
	Baseline	Test
Mean T/C	0.9398	0.8768
Number of Data Points	3	3
Standard Deviations	0.0041	0.0007
Variances	0.0000168	0.0000005
Difference in Means	0.0631	

F-Test for Equal Variances	
Baseline T/C Variance	0.00002
Test T/C Variance	0.00000
F test stat (test/baseline)	0.02819
F low	0.02564
F high	39.00000
Are Variances Equal ?	**yes**

T-Test with Equal Variances (2-tailed)	
Pooled St dev	0.00294
t-crit	2.776
t-stat	26.257
Is Fuel Economy Improved ?	**yes**
P-value	0.0000
lower CI bound	0.056400
upper CI bound	0.069738

T-Test with Unequal Variances (2-tailed)	
df (nu)	2.113
t-crit	4.090
t-stat	26.257
Is Fuel Economy Improved ?	**yes**
P-value	0.0011
lower CI bound	0.053245
upper CI bound	0.072894

CI t-critical	2.776
CI std err term	0.00240

Test Result			
	Nominal	Confidence Interval	
Fuel Saved	**6.71%**	**±**	**0.71%**
Improvement	**7.19%**	**±**	**0.76%**

SAE J1321 Data Analysis
- Fuel Economy Improvement Testing Vs Baseline 2: Truck 2 Local Cycle

Baseline Segment2			
Fuel Consumed, lbs			
Run	Truck 2	Control 1	T/C
1	44.80	47.35	0.9461
2	44.40	47.10	0.9427
3	44.60	47.35	0.9419

Test Segment			
Fuel Consumed, lbs			
Run	Truck 2	Control 1	T/C
1	42.75	48.75	0.8769
2	43.10	49.20	0.8760
3	44.00	50.15	0.8774

Summary Stats		
	Baseline	Test
Mean T/C	0.9436	0.8768
Number of Data Points	3	3
Standard Deviations	0.0023	0.0007
Variances	0.0000051	0.0000005
Difference in Means	0.0668	

F-Test for Equal Variances	
Baseline T/C Variance	0.00001
Test T/C Variance	0.00000
F test stat (test/baseline)	0.09349
F low	0.02564
F high	39.00000
Are Variances Equal ?	yes

T-Test with Equal Variances (2-tailed)	
Pooled St dev	0.00167
t-crit	2.776
t-stat	49.121
Is Fuel Economy Improved ?	yes
P-value	0.0000
lower CI bound	0.063035
upper CI bound	0.070588

T-Test with Unequal Variances (2-tailed)	
df (nu)	2.371
t-crit	3.718
t-stat	49.121
Is Fuel Economy Improved ?	yes
P-value	0.0001
lower CI bound	0.061755
upper CI bound	0.071869

CI t-critical	2.776
CI std err term	0.00136

Test Result			
	Nominal	Confidence Interval	
Fuel Saved	**7.08%**	**±**	**0.40%**
Improvement	**7.62%**	**±**	**0.43%**

SAE J1321 Data Analysis
- Fuel Economy Improvement Testing Vs Baseline 1: Truck 3 Highway Cycle

Baseline Segment1			
Fuel Consumed, lbs			
Run	Truck 3	Control 1	T/C
1	39.40	41.30	0.9540
2	39.30	41.30	0.9516
3	40.45	42.40	0.9540

Test Segment			
Fuel Consumed, lbs			
Run	Truck 3	Control 1	T/C
1	39.10	42.75	0.9146
2	39.20	43.15	0.9085
3	38.65	42.70	0.9052

Summary Stats		
	Baseline	Test
Mean T/C	0.9532	0.9094
Number of Data Points	3	3
Standard Deviations	0.0014	0.0048
Variances	0.0000020	0.0000231
Difference in Means	0.0438	

F-Test for Equal Variances	
Baseline T/C Variance	0.00000
Test T/C Variance	0.00002
F test stat (test/baseline)	11.74468
F low	0.02564
F high	39.00000
Are Variances Equal ?	yes

T-Test with Equal Variances (2-tailed)	
Pooled St dev	0.00354
t-crit	2.776
t-stat	15.150
Is Fuel Economy Improved ?	yes
P-value	0.0001
lower CI bound	0.035759
upper CI bound	0.051806

T-Test with Unequal Variances (2-tailed)	
df (nu)	2.338
t-crit	3.758
t-stat	15.150
Is Fuel Economy Improved ?	yes
P-value	0.0022
lower CI bound	0.032922
upper CI bound	0.054643

CI t-critical	2.776
CI std err term	0.00289

Test Result			
	Nominal	Confidence Interval	
Fuel Saved	**4.59%**	**±**	**0.84%**
Improvement	**4.81%**	**±**	**0.88%**

SAE J1321 Data Analysis
- Fuel Economy Improvement Testing Vs Baseline 2: Truck 3 Highway Cycle

Baseline Segment2			
	Fuel Consumed, lbs		
Run	Truck 3	Control 1	T/C
1	41.70	42.55	0.9800
2	41.45	42.80	0.9685
3	40.60	41.60	0.9760

Test Segment			
	Fuel Consumed, lbs		
Run	Truck 3	Control 1	T/C
1	39.10	42.75	0.9146
2	39.20	43.15	0.9085
3	38.65	42.70	0.9052

Summary Stats		
	Baseline	Test
Mean T/C	0.9748	0.9094
Number of Data Points	3	3
Standard Deviations	0.0059	0.0048
Variances	0.0000344	0.0000231
Difference in Means	0.0654	

F-Test for Equal Variances	
Baseline T/C Variance	0.00003
Test T/C Variance	0.00002
F test stat (test/baseline)	0.67063
F low	0.02564
F high	39.00000
Are Variances Equal ?	yes

T-Test with Equal Variances (2-tailed)	
Pooled St dev	0.00536
t-crit	2.776
t-stat	14.937
Is Fuel Economy Improved ?	yes
P-value	0.0001
lower CI bound	0.053247
upper CI bound	0.077561

T-Test with Unequal Variances (2-tailed)	
df (nu)	3.850
t-crit	2.820
t-stat	14.937
Is Fuel Economy Improved ?	yes
P-value	0.0001
lower CI bound	0.053058
upper CI bound	0.077750

CI t-critical	2.776
CI std err term	0.00438

Test Result			
	Nominal	Confidence Interval	
Fuel Saved	**6.71%**	**±**	**1.25%**
Improvement	**7.19%**	**±**	**1.34%**

SAE J1321 Data Analysis
- Fuel Economy Improvement Testing Vs Baseline 1: Truck 3 Local Cycle

Baseline Segment1			
Fuel Consumed, lbs			
Run	Truck 3	Control 1	T/C
1	45.50	47.55	0.9569
2	45.60	47.60	0.9580
3	45.35	47.00	0.9649

Test Segment			
Fuel Consumed, lbs			
Run	Truck 3	Control 1	T/C
1	43.90	48.75	0.9005
2	44.25	49.20	0.8994
3	44.55	50.15	0.8883

Summary Stats		
	Baseline	Test
Mean T/C	0.9599	0.8961
Number of Data Points	3	3
Standard Deviations	0.0043	0.0067
Variances	0.0000188	0.0000453
Difference in Means	0.0638	

F-Test for Equal Variances	
Baseline T/C Variance	0.00002
Test T/C Variance	0.00005
F test stat (test/baseline)	2.40400
F low	0.02564
F high	39.00000
Are Variances Equal ?	yes

T-Test with Equal Variances (2-tailed)	
Pooled St dev	0.00566
t-crit	2.776
t-stat	13.807
Is Fuel Economy Improved ?	yes
P-value	0.0002
lower CI bound	0.051004
upper CI bound	0.076680

T-Test with Unequal Variances (2-tailed)	
df (nu)	3.418
t-crit	2.973
t-stat	13.807
Is Fuel Economy Improved ?	yes
P-value	0.0004
lower CI bound	0.050095
upper CI bound	0.077589

CI t-critical	2.776
CI std err term	0.00462

Test Result			
	Nominal	Confidence Interval	
Fuel Saved	**6.65%**	**±**	**1.34%**
Improvement	**7.12%**	**±**	**1.43%**

SAE J1321 Data Analysis
- Fuel Economy Improvement Testing Vs Baseline 2: Truck 3 Local Cycle

Baseline Segment2			
	Fuel Consumed, lbs		
Run	Truck 3	Control 1	T/C
1	46.15	47.35	0.9747
2	46.20	47.10	0.9809
3	46.40	47.35	0.9799

Test Segment			
	Fuel Consumed, lbs		
Run	Truck 3	Control 1	T/C
1	43.90	48.75	0.9005
2	44.25	49.20	0.8994
3	44.55	50.15	0.8883

Summary Stats		
	Baseline	Test
Mean T/C	0.9785	0.8961
Number of Data Points	3	3
Standard Deviations	0.0034	0.0067
Variances	0.0000113	0.0000453
Difference in Means	0.0824	

F-Test for Equal Variances	
Baseline T/C Variance	0.00001
Test T/C Variance	0.00005
F test stat (test/baseline)	4.01665
F low	0.02564
F high	39.00000
Are Variances Equal ?	yes

T-Test with Equal Variances (2-tailed)	
Pooled St dev	0.00532
t-crit	2.776
t-stat	18.979
Is Fuel Economy Improved ?	yes
P-value	0.0000
lower CI bound	0.070359
upper CI bound	0.094473

T-Test with Unequal Variances (2-tailed)	
df (nu)	2.938
t-crit	3.221
t-stat	18.979
Is Fuel Economy Improved ?	yes
P-value	0.0004
lower CI bound	0.068429
upper CI bound	0.096403

CI t-critical	2.776
CI std err term	0.00434

Test Result			
	Nominal	Confidence Interval	
Fuel Saved	**8.42%**	**±**	**1.23%**
Improvement	**9.20%**	**±**	**1.35%**