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# GASOLINE DIRECT INJECTION (GDI) ENGINE WEAR TEST DEVELOPMENT

## Final Report

**August 2022**

**COORDINATING RESEARCH COUNCIL, INC.**
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**SOUTHWEST RESEARCH INSTITUTE®**
**San Antonio, Texas**
**Fuels and Lubricants Research Division**

# GASOLINE DIRECT INJECTION (GDI) ENGINE WEAR TEST DEVELOPMENT

## Final Report

**CRC Project No. AVFL-28**
**SwRI Project No. 08.25750, Phase III**

**Conducted for:**

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As per the contract, this report is presented as a scientific paper ready for Journal submission. This will give an excellent project overview. Additional supporting data and project specifics are given in the appendices.

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## ACRONYMS

ACEA - Association des Constructeurs Européens d'Automobiles (French)
- European Automobile Manufacturers' Association (English)

API - American Petroleum Institute

ASTM - American Society of Testing Materials

ILSAC - International Lubricants Standardization and Approval Committee

SAE - Society of Automotive Engineers

SLA - Surface Layer Activation

## 1.0 ABSTRACT

Almost all engine lubrication wear tests based on ILSAC and ACEA specifications were developed for engines and operating conditions representative of port fuel injection (PFI) engine technology. The automotive industry has trended away from the PFI engine towards gasoline direct injection (GDI) technology with approximately 40 percent of passenger cars sold in 2014 having GDI engines, many of which are turbo-charged. These turbo-charged GDI engines often produce more severe operating conditions than PFI engines due to their higher operating temperatures, cylinder pressures, and specific torques. In addition, most turbo GDI engines are downsized, therefore operating at higher loads for a greater portion of their operating cycle. Some vehicles use alternative combustion cycles or stop-start technology which further subjects the engine and lubricants to higher levels of stress compared to conventional PFI engines.

In an effort to guide the development of engine lubrication wear tests in the next ILSAC and ACEA categories, the balance shaft bearings, exhaust buckets, exhaust camshaft, fuel cams and top ring face of a modern turbo charged GDI engine, a Ford 2.0L Ecoboost engine, were irradiated. The irradiation of these engine components resulted in the formation of isotopes, depending on the component material. However, there are not sufficiently different materials in an engine to undertake the testing of all these components at the same time, therefore, three separate engine tests had to be undertaken. Phase I of this work was reported in October 2017 and Phase II in September 2019. This report covers Phase III. In all three Phases, a series of in-field operating conditions were selected and the engine operated at these conditions using both a SAE 5W-30 oil and a SAE 0W-16 oil with the same additive package. Using the SwRI® Radioactive Tracer Technology (RATT®), the level of radioactive particles in the oil present due to wear of the irradiated engine components, can be detected and the strength of the signal for each isotope can be correlated with the mass of wear material in the oil. All engine run-in and testing was completed using lube certified EEE fuel to ensure repeatability between Phases.

The first attempt at running the engine for Phase II resulted in an engine failure caused by loss of the balance shaft bearings. Following this, a second engine was sourced and run without having the balance shaft bearings removed, irradiated and reinstalled. In this Phase III work, the balance shaft bearings have been included in the irradiated parts tested.

Results for Phase III showed wear in all the engine components irradiated and tested in the engine. Five of the 20-engine cycles showed wear across all irradiated engine components. There was no clear difference in component wear between steady state and transient test cycles. Roughly half of the operating conditions resulted in higher wear in the measured engine components using SAE 0W-16 oil over SAE 5W-30 oil.


## 2.0 INTRODUCTION

Tests designed by ASTM for inclusion in the current API/ILSAC oil specifications dictate modern oil formulations. Many of the oils available to consumers only meet the minimum standard of quality specified. Additionally, these tests serve as a readily available, standardized, and well administrated method to test engine lubricant performance in situations other than API/ILSAC certification. These tests often provide a test-bed for research in this area or formulating lubricants to exceed the current requirements. The current low-temperature valve-train wear test procedure (Sequence IVA, ASTM D6891), as part of the ILSAC GF-5 oil specification, requires the use of a naturally-aspirated, a port fuel injected, a 3 valve per 4-cylinder, a low-compression 2.4L Nissan engine first in service in 1988. Significant advances in mechanical engine design, combustion strategies, materials, and coatings have been made since 1988 resulting in lubricants for modern engines operating in conditions which this dated test cannot emulate.

The replacement tests developed for ILSAC GF6 require the use of a naturally aspirated, port fuel injected engine using a 4 valve per 4-cylinder 1.5L Toyota Engine. While this is certainly an improvement over the previous version of the test with respect to modern engine architecture, it does not provide a method of testing lubricants in the unique environment encountered in gasoline direct injected turbocharged engines. GDI engines are found in nearly all new passenger cars being sold today, and are expected to continue to expand across model lines as consumer demand for higher power and regulatory demand for lower emissions and higher fuel economy continues. GDI engines produce significantly higher abrasive soot content in the oil and higher levels of sump fuel dilution, along with unique pre-ignition phenomenon, higher pressures, power densities, and lubricant temperatures, all of which present new challenges for oil formulations.

In any engine, there are numerous components that could exhibit wear, and different engine conditions result in different wear rates of these components in various ways. In addition, the wear of each engine component is influenced by mechanical design, metallurgy, surface finish, coatings, and/or lubrication strategies. The Sequence IVA, IVB and Sequence X are currently the only approved tests specifically designed for gasoline engine wear. These tests measure valve-train wear (IVA and IVB) and chain wear (X). With modern engine design to production schedules of 5-6 years, it is clear that modern GDI engine tests need to be developed for additional engine component wear testing over and above the Sequence IVB and X wear tests.

In an effort to guide the development of engine lubrication wear tests in the next API/ILSAC and ACEA categories, CRC funded a program in two phases to investigate wear of engine components in a modern turbo charged GDI engine, a Ford 2.0L Ecoboost engine. In Phase I of this work, the rings, the liner, and the rod bearings were irradiated and the engine was assembled on a test stand. The irradiation of these engine components results in different isotopes being formed, depending on the material from which the components are manufactured. Using the SwRI® Radioactive Tracer Technology (RATT®), the level of radioactive particles in the oil present due to wear of the irradiated engine components, can be detected, and the strength of the signal for each isotope can be correlated with the mass of wear material in the oil. A test matrix was developed to operate the engine through a series of in-field operating conditions expected to create wear of the engine components. The aim of the project was to discover which engine conditions created wear in which engine components, thereby guiding future wear test development. The engine was operated at these conditions using both the recommended lubricant grade for the engine – SAE 5W-30 and a low viscosity lubricant - SAE 0W-16 to investigate effects of reduced viscosity. The same additive package was used in both oils to ensure observed differences were an artifact of viscosity grade only. Phase I of this work was reported in October 2017. In Phase II, reported in September 2019, the main bearings, balance shaft bearings and turbocharger thrust washer, thrust plate and shaft were irradiated. In Phase III of this work, reported here, the same method, engine, oils and test sequences were used to investigate wear in the balance shaft bearings, exhaust buckets, exhaust camshaft lobes, fuel pump camshaft lobes and top ring face. The top ring face was irradiated as in Phase I and II in order to have a common component between the three Phases and allow correlation between wear results.

During Phase II of this work, the balance shaft bearings failed in the first engine, causing the program to be rerun. Lessons learnt from that failure have been incorporated into this Phase III and the balance shaft bearings were irradiated and run in this Phase III.

## 3.0 SCOPE OF WORK

### 3.1 Test Engine and Test Cell

The engine selected for this work was the Ford 2.0L EcoBoost engine used in the 2012 Ford Explorer. This engine was selected for a number of reasons, including being representative of current and future engine technology (downsizing, turbo, high BMEP), being early in its product life cycle when Phase I of this project began, and guaranteed support from the manufacturer. The engine was installed in a test cell with engine control and absorbing dynamometer. The cell was chosen for its location away from high foot traffic and because it had space for the radiation detector and peripheral equipment. This engine is the same as currently used for the Low Speed Pre-Ignition (LSPI) test developed for the ILSAC GF6 oil specification, therefore, the project team had a high level of familiarity with the engine and its control systems. This engine, like many turbo charged down-sized engines, has a tendency for LSPI. In order to reduce the chance of engine damage, aftermarket pistons were chosen as they have more material below the oil control ring and therefore less prone to damage from LSPI events. Both OEM and aftermarket pistons are shown in Figure 1 for comparison.

**Figure 1. Comparison of OEM Piston (left) and Aftermarket Piston (right)**

In Phase I, a slave engine was used to develop the test cycles to be run and LSPI events were avoided by working closely with Ford in order to program the ECU appropriately. All target operating points of interest were achieved with knock-avoidance. Operating temperatures were maintained below critical levels, in part achieved through the use of a cooling fan directed at the turbocharger.

## 3.2 Test Fuels and Lubricants

### *3.2.1 Test Fuels*

Lube Certification EEE fuel from Haltermann was used for all engine run-in and testing. This fuel was chosen so as to increase repeatability as this fuel is certified for industry engine testing. In addition, the aim of this project was to identify wear in engine components under different engine conditions to aid future test development, as such, using the test fuel was a logical approach. This fuel has been used in all three Phases of this work.

### *3.2.2 Test Lubricants*

Testing was conducted using two oils containing the same additive package - a SAE 5W-30 and a SAE 0W-16. The oils were low LSPI dexos1™ Gen2 oils. The SAE 5W-30 was selected as this is the manufacturer-recommended lubricant for the Ford 2.0L Ecoboost engine. The SAE 0W-16 was selected as this represents the current lubricant trend of reducing viscosity. Using the same additive package for both oils ensured that difference in wear rates were attributable to the change in viscosity only. Viscometrics for the lubricant blends are given in Table 1.

**Table 1. Test Lubricant Viscometrics**

| Lubricant | Temperature (°C) | ASTM D7042 | | |
|---|---|---|---|---|
| | | Dynamic (cP) | Kinematic (cSt) | Density (kg/m$^3$) |
| SAE 5W-30 | 40 | 57.264 | 69.706 | 0.822 |
| | 100 | 9.631 | 12.346 | 0.780 |
| SAE 0W-16 | 40 | 28.462 | 34.859 | 0.817 |
| | 100 | 5.477 | 7.066 | 0.775 |

## 3.3 Engine Run-in

Prior to running the engine through the designed test matrix of operating conditions, the engine was run-in using the SAE 5W-30 oil for 76 hours following a Ford recommended 8-hour break-in procedure. The break-ins consisted of several low to moderate load steady state conditions in increments between 1,500 rpm and 5,000 rpm. The 8-hour break-in procedure was repeated until the engines were run-in for 76 hours in order to replicate that done in Phase I and II of the work. In Phase I no oil filter was fitted during the break-in or the engine testing phase of this project. This was to ensure all wear particles collected in the lubricating oil were available to pass through the radiation detector. A small change was made in Phase II and III in that an oil filter was fitted for the first 8 hours of engine run-in in order to collect any initial large particles generated. The oil filter was removed after the first 8 hours and was not used for the remainder of the run-in or engine testing.

## 3.4 Engine Testing

Following the run-in, the engine oil was drained and the engine flushed before being re-filled with SAE 5W-30 oil. Fresh oil was used at the start of each day in order to maintain repeatability across the test matrix and ensure the effect of oil aging was negated from the results. Initially, three baseline steady state conditions were run – low load at low, medium and high speed. The medium speed baseline steady state condition was run every time the SAE 5W-30 oil was run in the engine, as a baseline point of reference.

Testing conditions were developed to subject the engine and oil to severe conditions and/or to subject the engine to anticipated high wear events. They were chosen to be representative of the anticipated most severe wear conditions for the engine when operated in the field. Engine temperature and torque set points are shown in Table 2, with engine operating conditions shown in Table 3. The turbo was replaced half way through the testing as a preventative measure against failure, just as in Phase I and II.

Each of the operating conditions were tested using both the SAE 5W-30 and the SAE 0W-16 oils. After each set of conditions were run using SAE 5W-30 oil, the engine was drained, flushed with SAE 0W-16 and then filled with SAE 0W-16 oil before the same engine conditions were repeated. Once completed, the next set of conditions were run using SAE 5W-30 after flushing with SAE 5W-30 oil. This allowed direct comparison at the same stage of overall engine wear. The only exception to this was that the cold start condition was run every morning when the engine had been idle overnight. In addition, after the initial baseline steady state conditions were run on the first day, the “Baseline Steady State Mid Speed” was repeated each time the SAE 5W-30 oil was in the engine. This was used as a baseline point of reference. In total, 97.5 hours of engine testing were performed in this program in order to directly replicate the test sequences undertaken in Phase I and Phase II.

**Table 2. Engine Temperature and Torque Set Points**

| Temperature (˚C) Set Points | | | | | | Engine Torque (N-m) Set Points | | |
|---|---|---|---|---|---|---|---|---|
| **Test Point** | **Very Cold** | **Cold** | **Warm** | **Hot** | **Very Hot** | **Engine Speed (rpm)** | **Low Load** | **High Load** |
| Oil Gallery Temp | 25 | 60 | 70 | 95 | 120 | Low - 2000 | 50 | 280 |
| Coolant Temp | 35 | 57 | 70 | 90 | 100 | Medium - 3500 | 50 | 330 |
| Charge Air Temp | 15 | 27 | 30 | 35 | 40 | High - 5000 | 50 | 315 |

**Table 3. Engine Operating Conditions**

| Operation Condition | Description |
|---|---|
| Baseline: Steady State, Low Speed | Hold engine at low speed and low load for extended period at warm engine temperatures. |
| Baseline: Steady State, Moderate Speed | Hold engine at moderate speed and low load for extended period at warm engine temperatures. |
| Baseline: Steady State, High Speed | Hold engine at high speed and low load for extended period at warm engine temperatures. |
| Cold Start | Once an engine has cooled and settled overnight, start engine and immediately accelerate to max torque for 30 seconds, ramp to low speed/moderate load for one minute, repeat three times. |
| Turbo Transient | Start at low speed/low load and ramp to medium speed/high load at hot engine temperatures, repeat for extended time. |
| Transient Load: Low Speed, Low-High Load | Ramp torque from low to high at low speed and warm engine temperatures |
| Transient Load: High Speed, Low-High Load | Ramp torque from low to high at high speed and warm engine temperatures |
| Transient Load: High Speed, High-Low Load | Ramp torque from high to low at high speed and warm engine temperatures |
| Transient Speed: Low Load, Low-High Speed | Ramp engine speed from low to high at low engine torque and warm engine temperatures |
| Transient Speed: High Load, Low-High Speed | Ramp engine speed from low to high at high engine torque and warm engine temperatures |
| Transient Speed: High Load, Low to High Speed, 115°C Oil | Ramp engine speed from low to high at high engine torque and hot engine temperatures |
| Trailer Tow | Start at low speed/max load, decrease load incrementally below max load, increase speed at just below max load curve to high speed/high load, increase load incrementally above max load (causing engine lugging), allow engine to slow to low speed/high load, reduce load to just under max load (to prevent engine stall), repeat for extended time. Hot engine temperatures. |
| Trailer Tow, 115°C Oil | Start at low speed/max load, decrease load incrementally below max load, increase speed at just below max load curve to high speed/high load, increase load incrementally above max load (causing engine lugging), allow engine to slow to low speed/high load, reduce load to just under max load (to prevent engine stall), repeat for extended time. Oil temperatures elevated 5-10°C above standard trailer tow cycle. Air intake temperature also elevated 20°C. |
| Boundary Lubrication | Start at max load and moderate engine speed. Hold WOT while slowly ramping engine speed to idle. Warm engine temperatures. |
| Stop-Start, 4hr Hot Temp | Hot start, immediate hard acceleration at high load to moderate speed for 20 sec, drop to low load/ moderate speed for 10 sec, stop engine, hot soak 1 min, repeat for extended period of time. Hot engine temperatures. |
| Stop-Start | Hot start, immediate hard acceleration at high load to moderate speed for 20 sec, drop to low load/ moderate speed for 10 sec, stop engine, hot soak 1 min, repeat for extended period of time. |
| Stop-Start, Very Cold | Hot start, immediate hard acceleration at high load to moderate speed for 20 sec, drop to low load/ moderate speed for 10 sec, stop engine, hot soak 1 min, repeat for extended period of time. Very cold engine temperatures. |
| Wide Open Throttle (WOT) Transient Cold | Ramp engine speed from low to high speed at high engine torque and cold engine temperatures |
| WOT: Steady State, 2500rpm | Hold engine at low speed and high load for extended period at warm engine temperatures. |
| WOT: Steady State, 3500rpm | Hold engine at high speed and high load for extended period at warm engine temperatures. Normal boost. |
| WOT: Steady State, 5000rpm | Hold engine at high speed and high load for extended period at cold engine temperatures. Normal boost. |
| WOT: 3500rpm Max. Boost | Hold engine at high speed and high load for extended period at cold engine temperatures. Maximum boost. |
| WOT: 5000rpm Max. Boost | Hold engine at high speed and high load for extended period at cold engine temperatures. Maximum boost. |

### 3.5 Balance Shaft Bearings

In Phase II of this work, the first engine failed due to the balance shaft bearings failing. At the time, it was concluded that this failure was due to the balance shafts being a non-serviceable part. As the shell bearings had been removed from the assembled part, sent for irradiation, and then reassembled they had already been crushed on initial assembly. It was believed this likely resulted in them not seating correctly on the assembly prior to install in the engine.

Subsequent investigation at the start of this Phase III concluded that the backlash on these balance shaft modules was set at the factory using shims as the module was fitted. In order to be able to include irradiated balance shaft bearings in the Phase III, Ford provided SwRI with the drawing for the special tool to be able to set this backlash. After manufactured by SwRI, Ford worked with SwRI to train their technician on how to use the tool.

Due to the Phase II experience with balance shaft bearings, additional testing of this reassembly was undertaken. A near end of life engine was taken and the balance shaft bearings removed and then replaced using the new backlash setting tool. This was successful and the engine ran well. Following this, a set of balance shaft bearings were removed from a balance shaft module and irradiated. These were then placed back in the engine using the tool and again the engine ran well with no failure. The reason for checking this with irradiated bearings was due to a small concern that the heat of the bulk irradiation process could have affected the bearings and caused the failure. After both these additional tests, the project team was happy to move forward with the full set of irradiations and engine build and test.

## 4.0 METALLURGICAL ANALYSIS

In this Phase III, the exhaust camshaft lobes, fuel pump camshaft lobes, exhaust buckets and balance shaft bearings were the focus for the wear study. The top rings were also irradiated and wear measured for them in order to correlate the testing in all three Phases of the project. Detailed metallurgical information for these components are listed in Table 4, obtained using Energy-Dispersive X-ray Spectroscopy (EDS) on a Scanning Electron Microscope (SEM).

**Table 4. Elemental Analysis of Wear Components**

| Component | Percent Mass Concentration by Element % | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Al | Si | V | Cr | Mn | Fe | Cu | Sn | Mo |
| Balance Shaft Bearings | 81.62 | 9.92 | 0.20 | | 0.12 | 1.23 | 0.72 | 6.04 | 0.16 |
| Exhaust Buckets | 0.32 | 0.30 | | 0.77 | 0.95 | 97.66 | | | |
| Exhaust Cam Lobes | | 1.92 | | 0.12 | 0.69 | 96.92 | | | 0.34 |
| Fuel Pump Lobes | | 1.92 | | 0.12 | 0.69 | 96.92 | | | 0.34 |
| Top Ring Face | 0.57 | 0.42 | | 98.35 | | 0.66 | | | |

### 4.1 Balance Shaft Bearings

There are 2 balance shaft bearings for each of the 2 balance shafts. The bearings are approximately 1 inch in diameter and ¾ of an inch wide. The bearings are made of an aluminum-tin matrix with no backing material. There is an oil hole and an oil channel in each bearing half.

### 4.2 Exhaust Buckets

The intake and exhaust valves have buckets on top of them and the valvetrain runs on the surface of these buckets. These buckets can also wear due to rotation in their bore. These buckets are predominantly steel, as shown in Table 4.

### 4.3 Exhaust Cam Lobes

This engine has two overhead camshafts; one for intake and one for exhaust valves. Each camshaft has eight lobes as it is an in-line four-cylinder engine and each combustion chamber has two intake and two exhaust valves. The camshaft is predominantly steel, as shown in Table 4.

### 4.4 Fuel Pump Lobes

The intake camshaft has an additional section on the end of it that has one rotational surface containing three lobes. These lobes compress the fuel pump three times for each camshaft rotation. The camshaft is predominantly steel, as shown in Table 4.

### 4.5 Top Ring Face

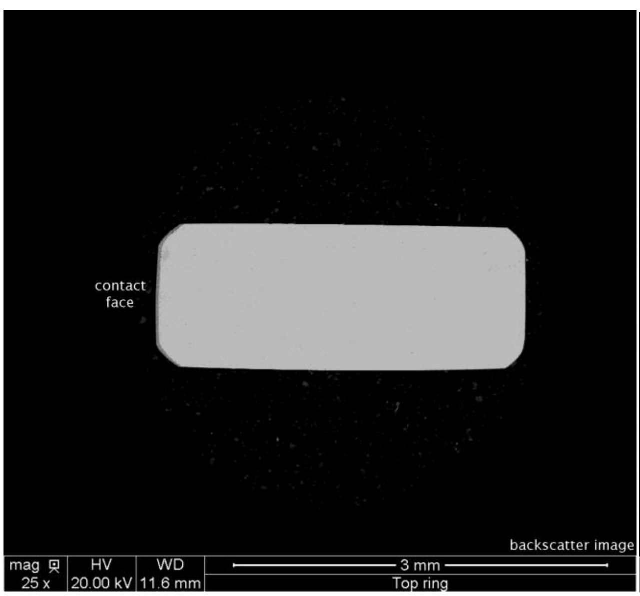



**Figure 2. Top Ring Cross Section**

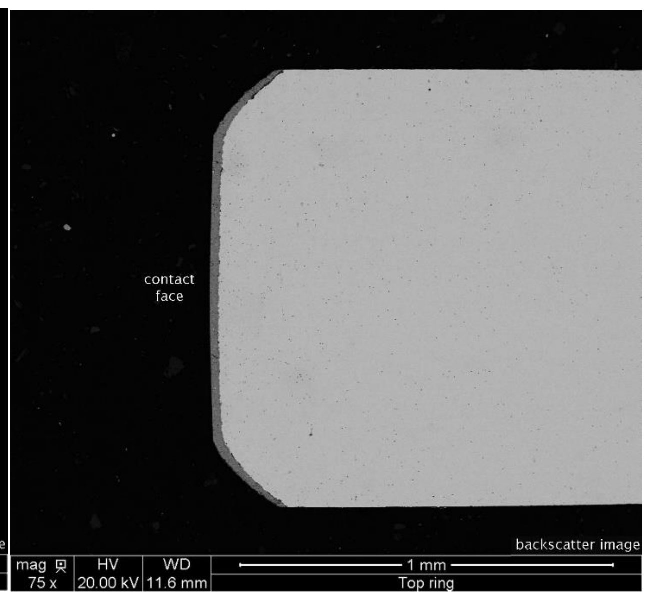



**Figure 3. Top Ring Contact Face**

A top piston ring was sectioned and placed in the XRF to obtain the images in Figure 2. The ring is a rectangular cross section with rounded corners and a slight barrel on the contact face. The ring bulk material is iron and the contact face of the ring comprises a chromium based coating that extends from the top, across the face, to the bottom, as shown in Figure 3. Figure 3 also shows pockets of black material within the coating on the top ring face. These pockets are elemental molybdenum and are largely concentrated where the peripheral coating connects with the parent ring substrate. The molybdenum is likely present to improve durability and/or flexibility of the adhesion between the hard chromium coating and the base iron material. Full elemental analysis is given in Table 4.

## 5.0 ENGINE COMPONENT ACTIVATION

There was substantial overlap in the component metallurgy, as shown in Table 4. This influenced the decision on how to activate the components in order to obtain distinct isotopes for detection of wear particles in the oil. Some components were bulk activated and others were surface layer activated (SLA) using different activation beams, as summarized in Table 5 and discussed below. Details of these bulk activations are shown in Table 6. In addition, the size of the intake and exhaust camshafts precluded them from being bulk activated as this would have resulted in radioactivity levels too high for safe handling.

**Table 5. Summary of Test Part, Activation Technique and Resulting Isotopes**

| Part | Activation Technique | Parent Isotope | Active Isotope |
|---|---|---|---|
| Balance Shaft Bearings | Bulk neutron bombardment | Sn | Sn-113 |
| Exhaust Buckets | Bulk neutron bombardment | Fe | Fe-59 |
| Exhaust Cam Lobes | Proton bombardment | Fe | Co-56 |
| Fuel Pump Lobes | Deuteron bombardment | Fe | Co-57 |
| Top Ring Face | Neutron bombardment | Cr | Cr-51 |

### 5.1 Bulk Activated Components

#### *5.1.1 Balance Shaft Bearings*

In previous work, as many parts as possible have been placed into one canister for bulk irradiation. This is because it is cheaper to irradiate one canister than two. However, due to the additional testing that was undertaken with the balance shaft bearings, two canisters each with a full set of bearings were manufactured. This was to ensure the bearings experienced the same heat profile in both the feasibility test as well as the final test.

#### *5.1.2 Exhaust Buckets*

Only 4 of the 8 exhaust buckets were irradiated to limit total activity of the engine for personnel protection purposes. The 4 irradiated buckets were installed on cylinders 1 and 2. Exhaust buckets and exhaust cam lobes were irradiated instead of intake buckets and cam lobes because exhaust valve springs are stiffer than intake springs, producing greater wear loading. The exhaust buckets were placed in one separate canister for irradiation and not with the balance shaft bearings, as discussed above in section 5.1.1.

**Table 6. Total Activity for Bulk Activation Parts**

| Bulk Activation Products | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Component** | **Mass (g)** | **Original Nuclide** | **Mass (g)** | **Process** | **Product Nuclide** | **Activity** | **Half Life** |
| Exhaust Buckets | 136.55 | Fe-56 | 133.36 | (n,G)-> | Fe-59 | 14.88 µCi | 44.5 days |
| Balance Shaft Bearings | 62.11 | Sn-112 | 0.220 | (n,G)-> | Sn-113 | 25.32 µCi | 64.9 days |
| Reactor neutron flux = 6.811e12 per $cm^2s$ | | | | | | | |
| Irradiation time = 60hrs | | | Delay for short life decays = 7 days | | | | |

## 5.2 Surface Layer Activated Parts

Surface Layer Activation (SLA) is desirable when several components consist of the same metallurgy and unique isotopes are required for independent part tracking. SLA can also be helpful in limiting the total activity of the tested assembly. Unsafe dosage fields can result from excessive bulk activation of test parts. SLA is a targeted process and therefore results in an activated area on the surface of the test part rather than the test part becoming homogenously activated. The targeted nature of the process creates much higher specific activity (isotopes per unit mass) than a comparable bulk activation. This can be extremely beneficial when looking at low wear interfaces. In this project the top ring face, exhaust cam lobes and fuel pump cam lobes underwent an SLA process to generate unique isotopes from all parts. This was necessary as the top rings, exhaust cam lobes, and fuel pump cam lobes were all ferrous components. Although the top ring face is mostly Cr, the bulk top ring material is ferrous. Details of these SLA activations are shown in Table 7.

### *5.2.1 Exhaust Cam Lobes*

Both camshafts were made from the same material and were therefore surface activated with different beams. The exhaust cam was surface activated using a Proton beam and the surface activation was on all eight cam lobes over the full width of the lobe and half a centimeter either side of the highest point.

### *5.2.2 Fuel Pump Lobes*

In order to obtain a different isotope from the exhaust camshaft, the fuel pump cams were surface activated using a Deuteron beam. All three fuel pump cams were activated over the full width of the lobe and half a centimeter either side of the highest point.

### 5.2.3 *Top Ring Face*

Neutron beam was chosen at a low energy level of 9MeV to produce Cr-51 on the ring surface. A Deuteron beam would have produced Mn-52, which only has a half-life of 5.6 days, which was not sufficient to complete the testing. The reason for using surface layer activation of the ring face instead of bulk activation of the ring was to only activate the Cr on the ring face and not the Fe on the ring sides. This eliminated the possibility of Fe-59 from the ring sides interfering with the Fe-59 measurement for the exhaust buckets.

**Table 7. Surface Layer Activated (SLA) Parts**

| Surface Layer Activated Products | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Component** | **Activation Area** | **Depth of Activity** | **Original Nuclide** | **Process** | **Product Nuclide** | **Activity** | **Half Life** |
| Exhaust Camshaft Lobes | Full width at 1cm | 60µm | Fe | Proton Beam | Co-56 | 3.0308 µCi/µm | 77.2 days |
| Fuel Pump Cam Lobes | Full width at 1 cm | 60µm | Fe | Deuteron Beam | Co-57 | 3.8836 µCi/µm | 272 days |
| Top Rings | 4* full ring face | 60µm | Cr | Neutron Beam | Cr-51 | 1.490 µCi/µm | 27.7 days |

## 6.0 ENGINE 2 RESULTS AND DISCUSSION

Wear values for each irradiated engine part were compiled for all of the test conditions, comparing the SAE 5W-30 and SAE 0W-16 lubricants. Figures 4-8 depict the wear trend for the balance shaft bearings, exhaust buckets, exhaust camshaft, fuel pump cams and top ring face for both lubricants over the full test matrix. For clarity, only those results giving measurable wear values with consideration to the measurement technique have been included in the graphs and these values are noted on the graph titles. Table 8 shows a matrix of irradiated engine component vs. engine test sequence giving a concise overview of noticeable wear. Wear values included in Figures 4-8 are shown as gray cells in Table 8.

‘Cold Start’ was run 10 times on each oil in order to obtain sufficient data points for analysis. This was because cold start could only be run for 210 seconds before the engine began to warm up.

‘Stop-Start’ was a severe ramp up to 3500rpm and therefore only run 4 times during the test sequence. In order to obtain sufficient data points for analysis, this was repeated once for each oil, giving a total of 8 data points for each oil.

The same logic was also applied to two of the transient cycles (‘Transient Load, High Speed, Low-High Load’ and ‘Transient Speed, High Load, Low-High Speed’). This was not done for all the cycles in order to save engine test time for other sequences and because the repeatability of the data obtained for those repeated cycles gave confidence in the results of those not repeated.

Baseline steady state conditions, as noted in lines 1-3 of Table 3, were run prior to the start of the test matrix. The moderate speed steady state condition was run each time the engine was filled with SAE 5W-30 oil. This was used to monitor the wear rates to ensure no significant change occurred throughout the test program. Steady state wear was achieved throughout the testing.

**Table 8. Matrix of Wear of Irradiated Engine Part vs. Engine Test Sequence**

| Description | Balance Shaft Bearings | Exhaust Buckets | Exhaust Camshaft | Fuel Pump Cams | Top Ring Face |
|---|---|---|---|---|---|
| Cold Start | | | | | |
| Turbo Transient | | | | | |
| Transient Load: Low Speed, Low-High Load | | | | | |
| Transient Load: High Speed, Low-High Load | | | | | |
| Transient Load: High Speed, High-Low Load | | | | | |
| Transient Speed: Low Load, Low-High Speed | | | | | |
| Transient Speed: High Load, Low-High Speed | | | | | |
| Transient Speed: High Load, Low-High Speed, 115°C Oil | | | | | |
| Trailer Tow | | | | | |
| Trailer Tow, 115°C Oil | | | | | |
| Boundary Lubrication | | | | | |
| Stop-Start, 4hr Hot Temp | | | | | |
| Stop-Start | | | | | |
| Stop-Start, Very Cold | | | | | |
| Wide Open Throttle (WOT) Transient Cold | | | | | |
| WOT: Steady State, 2500rpm | | | | | |
| WOT: Steady State, 3500rpm | | | | | |
| WOT: Steady State, 5000rpm | | | | | |
| WOT: 3500rpm, Max. Boost | | | | | |
| WOT: 5000rpm, Max. Boost | | | | | |

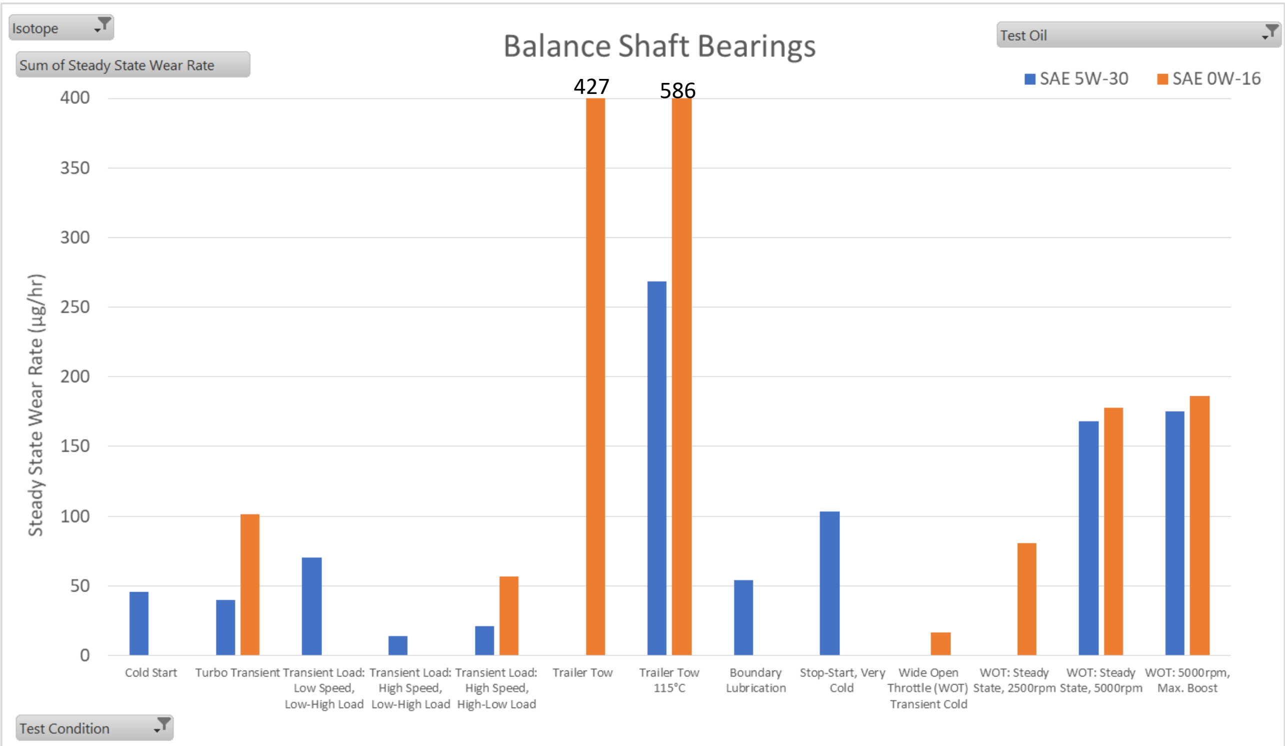



**Figure 4. Balance Shaft Bearing Wear for Test Cycles Showing Greater than 10µg/hr on Either Oil.**

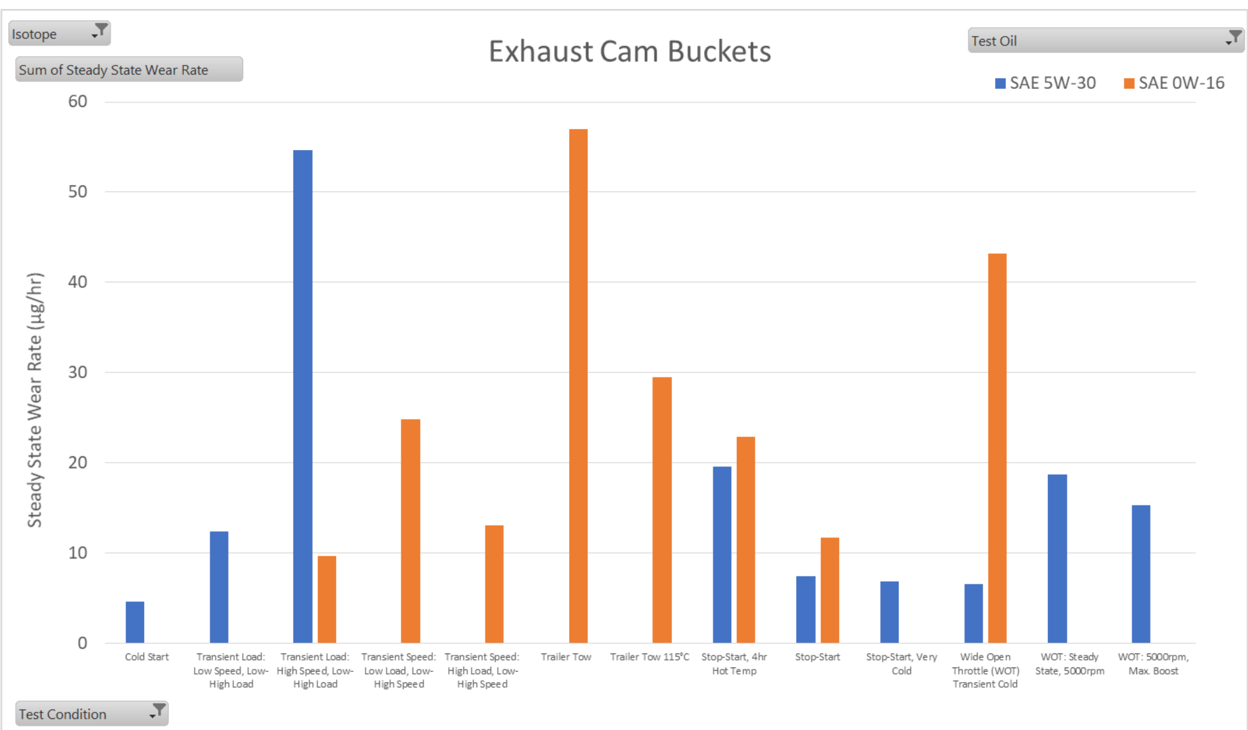



**Figure 5. Exhaust Buckets Wear for Test Cycles Showing all Wear on Either Oil.**

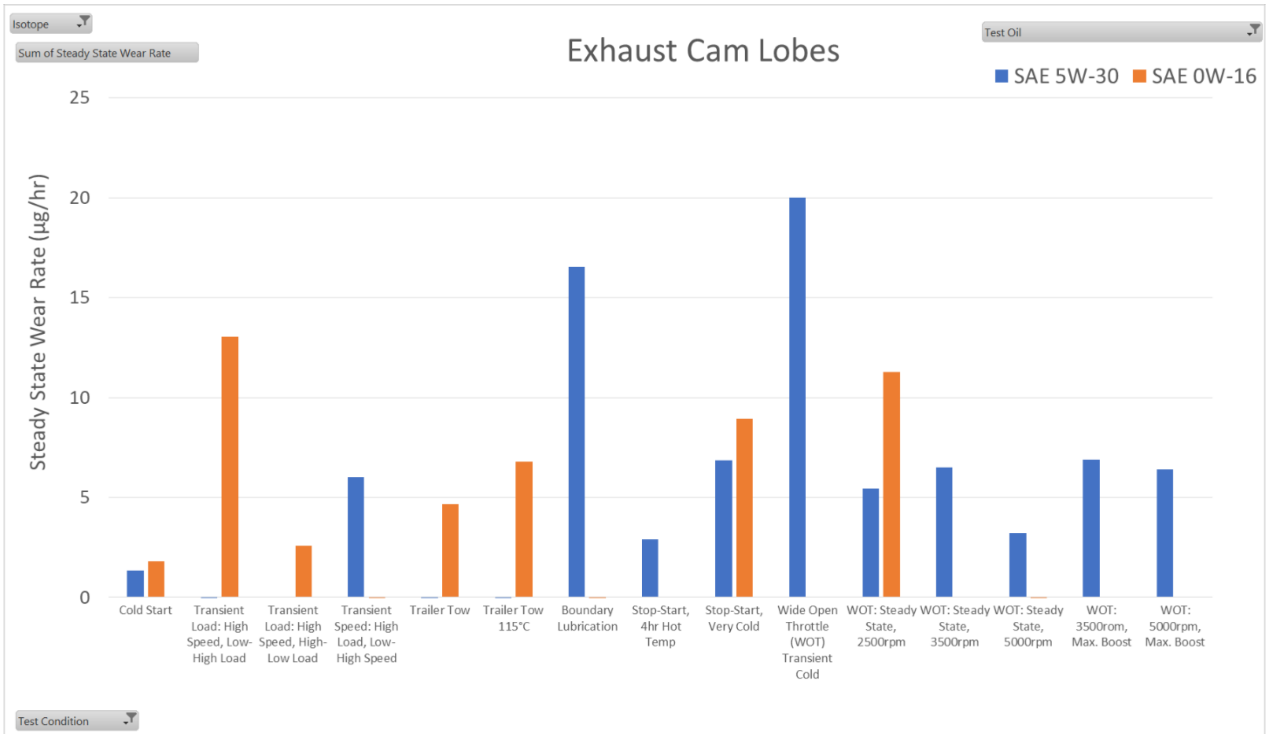



**Figure 6. Exhaust Cam Lobe Wear for Test Cycles Showing Greater than 1µg/hr on Either Oil.**

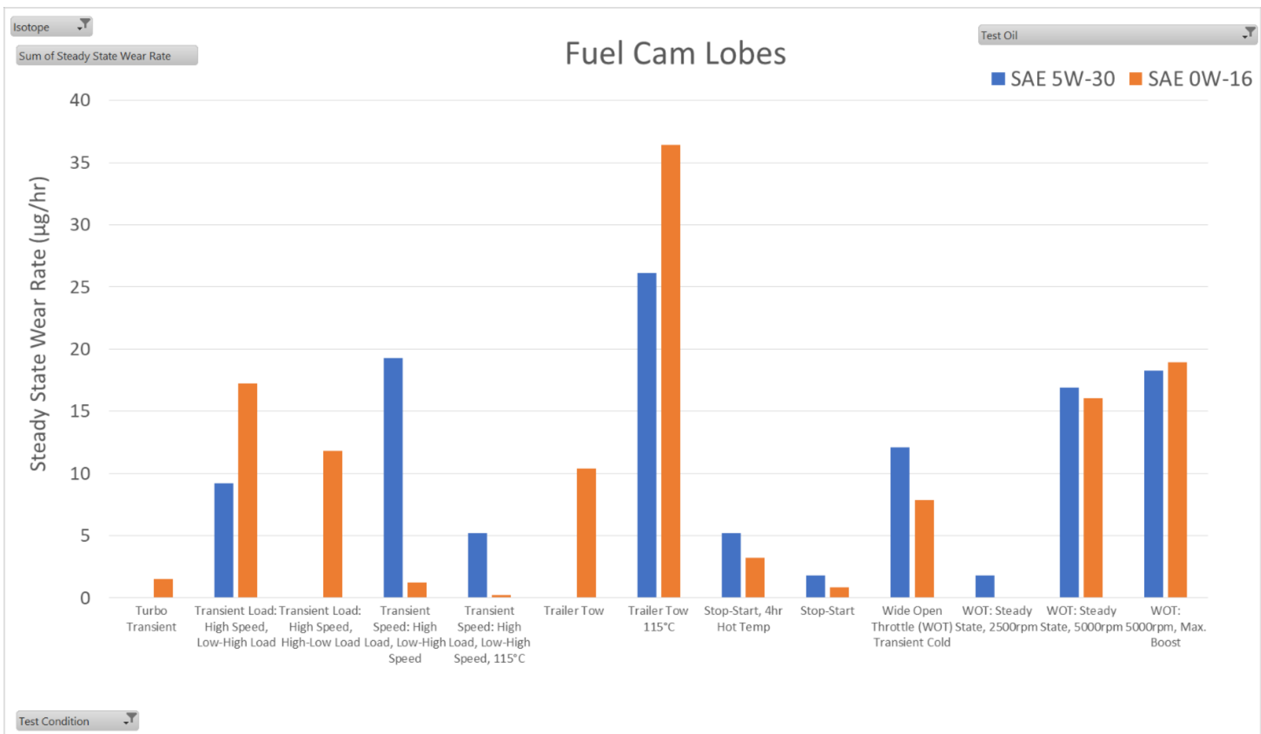



**Figure 7. Fuel Cam Lobes Wear for Test Cycles Showing Greater than 1µg/hr on Either Oil.**

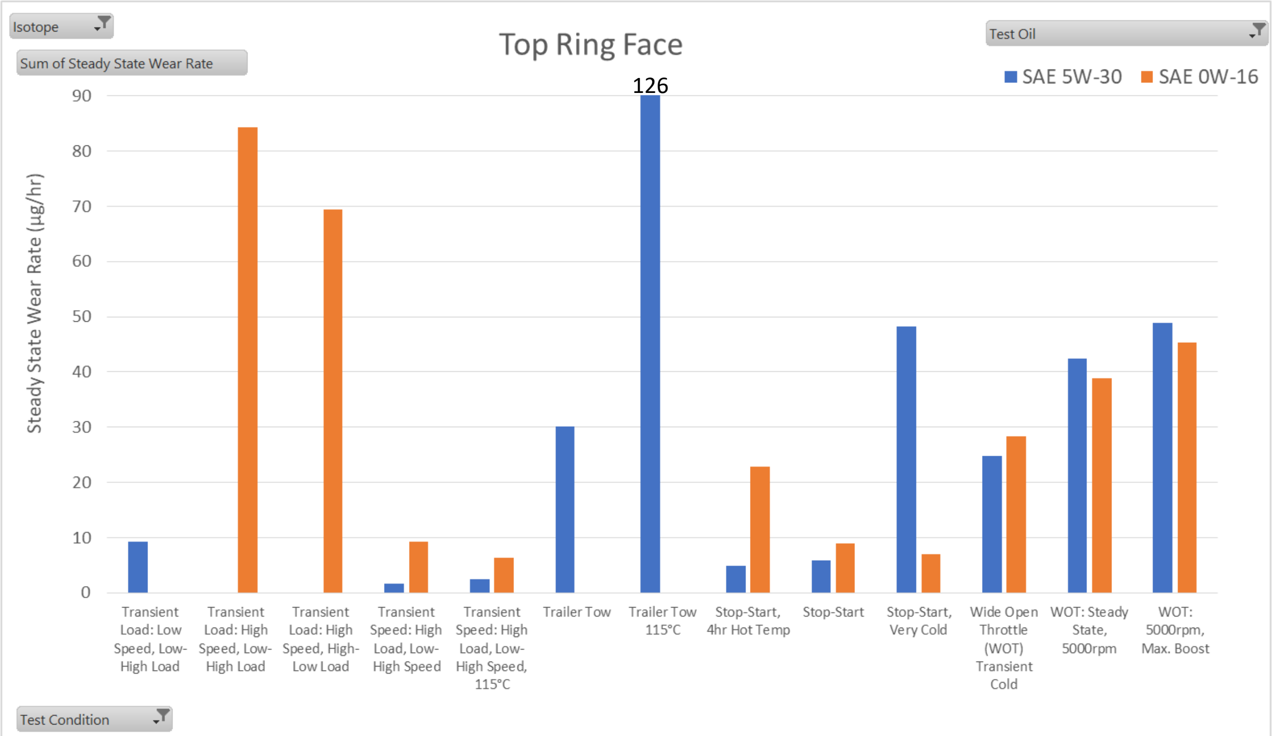



**Figure 8. Top Ring Face Wear for Test Cycles Showing Greater than 5µg/hr on Either Oil**

Table 8 shows that all operating cycles exhibited appreciable wear on at least one of the irradiated engine components. Five of the operating conditions showed wear across all irradiated engine parts; Transient Load: 'High Speed, Low-High Load', 'Trailer Tow', 'Trailer Tow, 115°C', Wide Open Throttle (WOT) Transient Cold' and 'WOT: Steady State, 5000rpm'.

Although it may be expected that the SAE 0W-16 lubricant would give higher wear across all operating conditions and engine components tested, this did not prove to be the case, with roughly half the engine operating cycles giving higher component wear for the SAE 5W-30 oil. In many cases, wear was observed with the SAE 5W-30 where no wear was observed with the SAE 0W-16. One very noticeable difference to this trend was the balance shaft bearings during 'Trailer Tow' and 'Trailer Tow, 115°C' where the wear was exceptionally high with the SAE 0W-16 lubricant. However, for these cycles there was no wear on the top ring face using SAE 0W-16 and there was wear, particularly high with the 'Trailer Tow, 115°C', using the SAE 5W-30 lubricant.

The test sequence that systematically displayed the highest wear in Phase I and II was 'Cold Start'. However, the components tested in this Phase, did not show high wear for 'Cold Start', with the fuel cam lobes and top ring face showing no wear.

Other observations are that the exhaust cam buckets in general showed more wear than the exhaust cam lobes, even though these two parts are running against each other. One explanation could be that wear on the sides of the buckets also occur as they rotate. The balance shaft bearings showed the highest wear, in general, of all components tested during this Phase.

## 7.0 CONCLUSIONS

A project was undertaken to investigate the wear of balance shaft bearings, exhaust cam buckets, exhaust cam lobes, fuel cam lobes and top ring face in a Ford 2.0L Ecoboost engine using Radioactive Tracer Technology® to track real time wear of the components individually. The results clearly show the operating cycles that created significant wear in the irradiated engine components.

A significant amount of data was produced for the five irradiated engine components across the engine operating test matrix. The main findings are:

- All irradiated engine components displayed wear during this Phase III of engine testing
- There was a wide range of the number of irradiated components showing wear across the engine test cycles, from as low as only one component through to all five irradiated components.
- In five of the 20 engine test cycles all irradiated components exhibited measurable wear.
- Comparing the wear rates using SAE 5W-30 and SAE 0W-16 oils, lower viscosity lubricant resulted in higher wear in only roughly half the engine test cycles.
- In general, transient engine operating conditions created similar wear to steady state conditions
- The cold start cycles operated at the beginning of every day did NOT show the highest wear rates using this combination of engine components, as occurred in previous work using different engine components.

# APPENDIX A

# Engine Specifications

| Item | Specification |
| --- | --- |
| **Engine** | |
| Displacement | 2.0L (122 Cubic Inch Displacement (CID)) |
| No. cylinders | 4 |
| Bore/stroke | 87.5 mm (3.4449 in) - 83.1 mm (3.2717 in) |
| Fire order | 1-3-4-2 |
| Oil pressure (hot @ 2,000 rpm) | 200 kPa (29.01 psi) - 268 kPa (38.87 psi) |
| Compression ratio | 9.3:1 |
| Spark plug | NGK T4025R |
| Spark plug gap | 0.8 mm (0.0315 in) |
| Engine weight (without accessory drive components) | 141 kg (311 lb) |
| **Cylinder Block** | |
| Cylinder bore diameter | 87.5 mm (3.4449 in) - 87.53 mm (3.4461 in) |
| Cylinder bore maximum out-of-round | 0.008 mm (0.0003 in) |
| Main bearing bore diameter | 57.018 mm (2.245 in) - 57.040 mm (2.246 in) |
| Head gasket surface flatness | 0.1 mm (0.0039 in) - 0.05 mm (0.002 in)/200 mm (7.874 in) x 200 mm (7.874 in) |
| **Piston and Connecting Rod** | |
| Piston diameter (grade 1) | 87.465 mm (3.4435 in) - 87.475 mm (3.4439 in) |
| Piston diameter (grade 2) | 87.4725 mm (3.4438 in) - 87.4875 mm (3.4444 in) |
| Piston diameter (grade 3) | 87.485 mm (3.4443 in) - 87.495 mm (3.4447 in) |
| Piston-to-cylinder bore clearance | 0.0225 mm (0.0009 in) - 0.0475 mm (0.0019 in) |
| Piston ring groove width - compression (top) | 1.23 mm (0.0484 in) - 1.25 mm (0.0492 in) |
| Piston ring groove width - compression (bottom) | 1.23 mm (0.0484 in) - 1.25 mm (0.0492 in) |
| Piston ring groove width - oil ring | 2.03 mm (0.0799 in) - 2.05 mm (0.0807 in) |
| Piston skirt coating thickness | 0.009 mm (0.0004 in) - 0.019 mm (0.0007 in) |
| Piston pin diameter | 22.497 mm (0.8857 in) - 22.5 mm (0.8858 in) |
| Piston pin length | 55.7 mm (2.1929 in) - 56 mm (2.2047 in) |
| Piston-to-pin clearance | 0.0035 mm (0.0001 in) - 0.045 mm (0.0018 in) |
| Piston pin-to-connecting rod clearance | 0.003 mm (0.0001 in) - 0.018 mm (0.0007 in) |
| Piston ring width — compression (top) | 1.2 mm (0.05 in) |

| Item | Specification |
|---|---|
| Piston ring width — compression (bottom) | 1.2 mm (0.05 in) |
| Piston ring width — oil | 2 mm (0.08 in) |
| Piston ring gap (in bore) — compression (top) | 0.17 mm (0.0067 in) - 0.27 mm (0.0106 in) |
| Piston ring gap (in bore) — compression (bottom) | 0.45 mm (0.0177 in) - 0.65 mm (0.0256 in) |
| Piston ring gap (in bore) — oil | 0.15 mm (0.0059 in) - 0.45 mm (0.0177 in) |
| Connecting rod bearing-to-crankshaft clearance | 0.027 mm (0.0011 in) - 0.052 mm (0.002 in) |
| Connecting rod bearing thickness | 1.495 mm (0.0589 in) - 1.519 mm (0.0598 in) |
| Connecting rod crankshaft bore diameter | 55.025 mm (2.1663 in) - 55.045 mm (2.1671 in) |
| Connecting rod pin bore diameter | 22.510 mm (0.8862 in) - 22.516 mm (0.8865 in) |
| Connecting rod length (center -to-center) | 155.869 mm (6.1366 in) |
| Connecting rod side clearance (assembled to crank) | 2.59 mm (0.1020 in) - 3.69 mm (0.1453 in) |
| Axial clearance | 0.014 mm (0.0006 in) - 0.36 mm (0.0142 in) |
| **Crankshaft** | |
| Main bearing journal diameter | 51.978 mm (2.0464 in) - 52.002 mm (2.0473 in) |
| Balance shaft | No details available |
| Main bearing clearance | 0.016 mm (0.0006 in) - 0.046 mm (0.0018 in) |
| Connecting rod journal diameter | 51.980 mm (2.0465 in) - 52 mm (2.0472 in) |
| End play | 0.22 mm (0.0087 in) - 0.45 mm (0.0177 in) |
| **Cylinder Head** | |
| Cylinder head gasket surface flatness | 0.08 mm (0.0031 in) maxim overall, a maximum of 0.05 mm (0.0020 in)<br>within 150 mm (5.9055 in) and a maximum of 0.025 mm (0.0010 in)<br>within 25 mm (0.9843 in) |
| Maximum valve lift @ 0 lash — exhaust | 6.9 mm (0.2717 in) |
| Maximum valve lift @ 0 lash — intake | 7.9 mm (0.3110 in) |
| Valve guide diameter | 5.509 mm (0.2169 in) - 5.539 mm (0.2181 in) |
| Valve seat width - intake/exhaust | 1.40 mm (0.0551 in) - 1.50 mm (0.0591 in) |
| Valve seat angle | 45° |
| Valve seat runout | 0.075 mm (0.003 in) |
| Valve lash adjuster bore diameter | 31 mm (1.2205 in) - 31.03 mm (1.2217 in) |
| Cam bore diameter | 25.015 mm (0.9848 in) - 25.04 mm (0.9858 in) |

| Item | Specification |
|---|---|
| **Valve** | |
| Valve head diameter - intake | 32.5 mm (1.2795 in) |
| Valve head diameter - exhaust | 28 mm (1.1024 in) |
| Valve stem diameter - intake | 5.5 mm (0.2165 in) |
| Valve stem diameter - exhaust | 5.5 mm (0.2165 in) |
| Valve stem-to-guide clearance - intake | 0.03 mm (0.0012 in) - 0.07 mm (0.0028 in) |
| Valve stem-to-guide clearance - exhaust | 0.03 mm (0.0012 in) - 0.07 mm (0.0028 in) |
| Valve face runout | 0.05 mm (0.002 in) |
| Valve face angle | 45.25° - 45.75° |
| **Valve Spring ─ Compression Pressure** | |
| Intake and exhaust (installed) | 17 kg (37.478 lb) |
| Intake (valve open) 9.2 mm (0.3622 in) of lift | 39 kg (85.979 lb) |
| Exhaust (valve open) 9.2mm (0.3622 in) of lift | 42 kg (92.593 lb) |
| Free length | 47.91 mm (1.8862 in) |
| Assembled height | 37.9 mm (1.4921 in) |
| **Valve Tappet** | |
| Diameter | 30.98 mm (1.2197 in) - 30.964 mm (1.2191 in) |
| Tappet-to-valve clearance ─ intake | 0.19mm (0.0075 in) - 0.31 mm (0.0122 in) |
| Tappet-to-valve clearance ─ exhaust | 0.30 mm (0.0118 in) - 0.42 mm (0.0165 in) |
| Tappet-to-bore clearance | 0.02 mm (0.0008 in) - 0.06 mm (0.0024 in) |
| **Camshaft** | |
| Lobe lift ─ intake | - |
| Lobe lift ─ exhaust | - |
| Runout | 0.03 mm (0.0012 in) |
| Thrust clearance | 0.115 mm (0.0045 in) - 0.145 mm (0.0057 in) |
| Journal diameter | 24.96 mm (0.9827 in) - 24.98 mm (0.9835 in) |
| Journal-to-bore clearance | 0.035 mm (0.0014 in) - 0.08 mm (0.0031 in) |

# APPENDIX B

# Controlled and Monitored Engine Parameters

| Controlled Parameters | Unit |
|---|---|
| Engine Speed | rpm |
| Engine Load | Nm |
| Coolant Out Temp | deg C |
| Oil Gallery Temp | deg C |
| Air Charge Temp | deg C |
| Coolant Pressure | kPaG |

| Monitored Parameters | Unit |
|---|---|
| Inlet Air Temp | deg C |
| Inlet Air Press | kPaG |
| Exhaust Back Press | kPaA |
| Humidity | g/kg |
| Coolant Flow | L/m |
| Lambda | unitless |
| Barometric Pressure | kPaA |
| Oil Gallery Pressure | kPaG |
| Oil Head Pressure | kPaG |
| Oil Out Temp | deg C |
| Exhaust Temp | deg C |
| Crank Case Pressure | kPaG |
| Fuel Pressure | kPaG |
| Power | kW |
| Pre-Intercooler Air Pressure | kPaA |
| Ambient Temperature | degC |
| Coolant In Temperature | degC |
| Boost Pressure | kPaA |
| Fuel Temp | deg C |
| Fuel Flow | kg/hr |
| Manifold Absolute Pressure (MAP) | kPaA |

| PCM CAN Bus Parameters | Unit |
|---|---|
| Ignition Timing Advance for #1Cylinder | deg |
| Absolute Throttle Position | % |
| Engine Coolant Temperature | deg C |
| Intake Air Temperature | deg C |
| Equivalence Ratio (Lambda) | unitless |
| Absolute Load Value | % |
| Intake Manifold Absolute Pressure | kPa |
| Fuel Rail Pressure | kPa |
| Accelerator Pedal Position | % |
| Boost Absolute Pressure - Raw Value | kPa |
| Turbocharger Wastegate Duty Cycle | % |
| Actual Intake (A) Camshaft Position | deg |
| Actual Exhaust (B) Camshaft Position | deg |
| Intake (A) Camshaft Position Actuator Duty Cycle | % |
| Exhaust (B) Camshaft Position Actuator Duty Cycle | % |
| Charge Air Cooler Temperature | deg C |

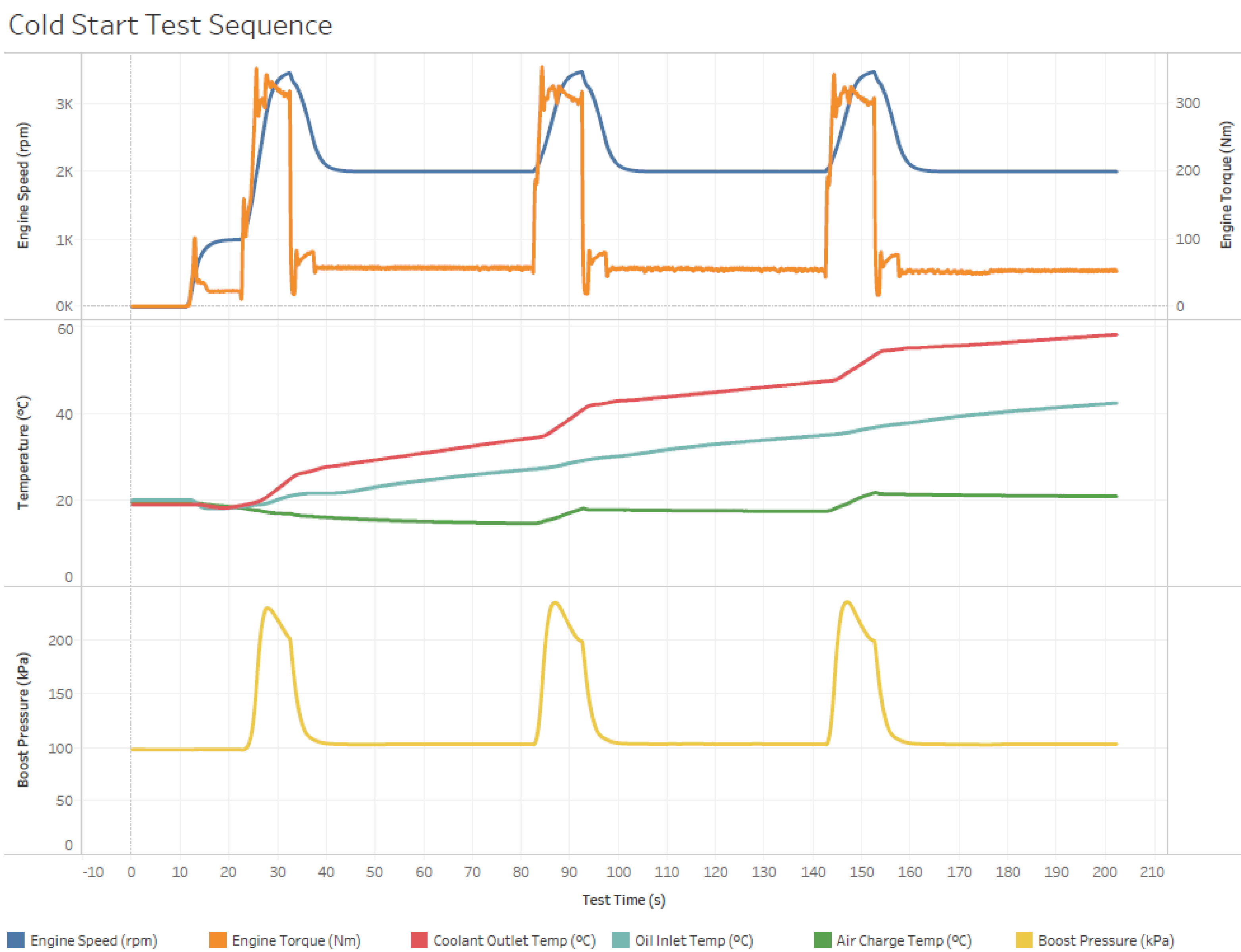
# APPENDIX C

# Test Matrix and Engine Operating Conditions

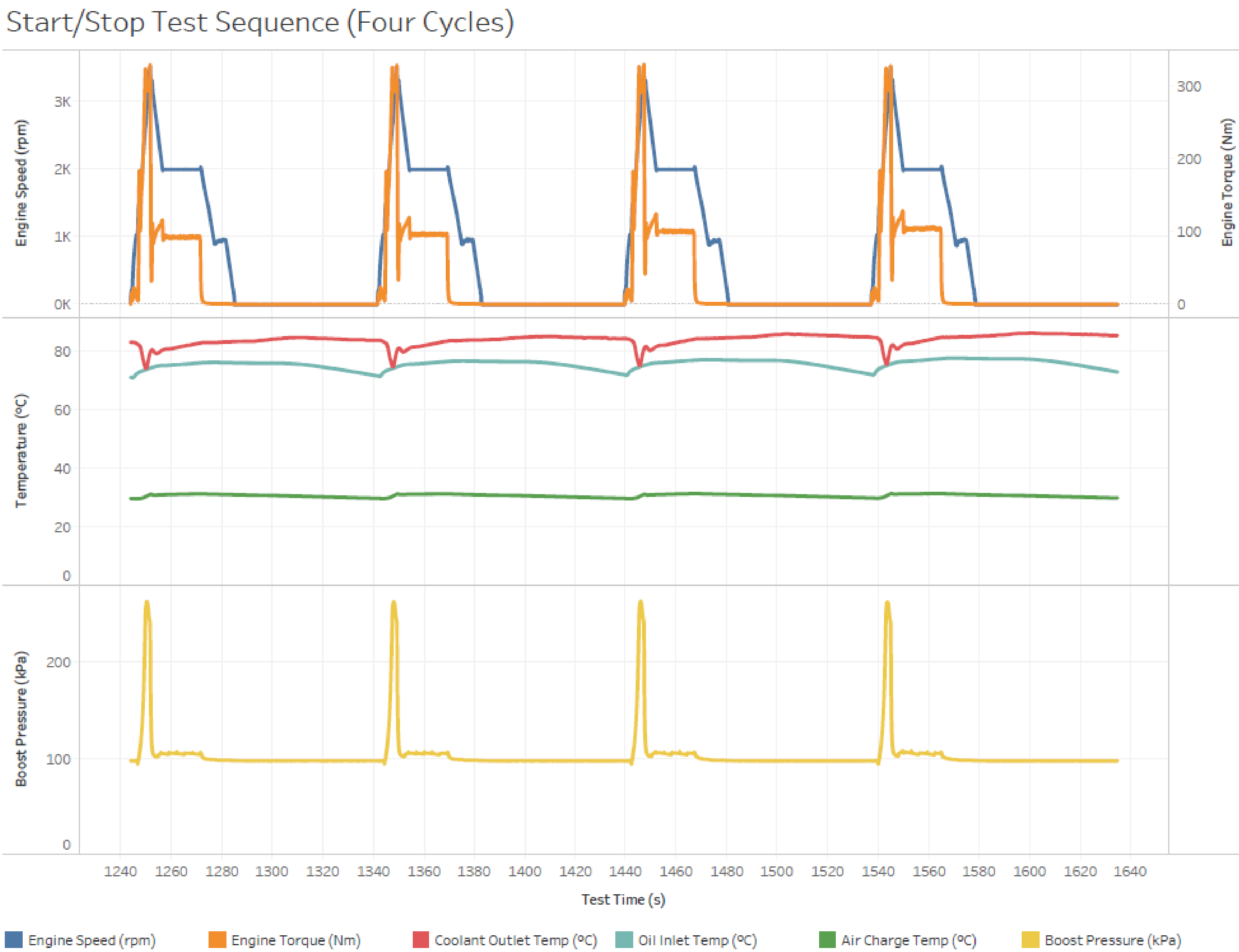
| Test Condition | Oil |
|---|---|
| Note A = SAE 5W-30, B = SAE 0W-16. | |
| Cold Start | A |
| Baseline Steady State Low Speed | A |
| Baseline Steady State Mid Speed | A |
| Baseline Steady State High Speed | A |
| Stop-Start | A |
| *Oil Change to Oil B* | |
| Cold Start | B |
| Stop-Start | B |
| Transient Load, Low Speed, Low to High Load | B |
| *Oil Change to Oil A* | |
| Cold Start | A |
| Transient Load, Low Speed, Low to High Load | A |
| Transient Load, High Speed, Low to High Load | A |
| Baseline Steady State Mid Speed | A |
| *Oil Change to Oil B* | |
| Cold Start | B |
| Transient Load, High Speed, Low to High Load | B |
| Transient Load, High Speed, High to Low Load | B |
| *Oil Change to Oil A* | |
| Cold Start | A |
| Transient Load, High Speed, High to Low Load | A |
| Transient Speed, Low Load, Low to High Speed | A |
| Baseline Steady State Mid Speed | A |
| *Oil Change to Oil B* | |
| Cold Start | B |
| Transient Speed, Low Load, Low to High Speed | B |
| Transient Speed, High Load, Low to High Speed | B |
| *Oil Change to Oil A* | |
| Cold Start | A |
| Transient Speed, High Load, Low to High Speed | A |
| Baseline Steady State Mid Speed | A |
| Cold Start | A |
| Stop-Start | A |
| Baseline Steady State Mid Speed | A |
| *Oil Change to Oil B* | |
| Cold Start | B |
| Stop-Start | B |
| Transient Load, High Speed, Low to High Load | B |
| *Oil Change to Oil A* | |
| Cold Start | A |
| Transient Load, High Speed, Low to High Load | A |
| Transient Speed, High Load, Low to High Speed | A |
| Baseline Steady State Mid Speed | A |
| *Oil Change to Oil B* | |
| Cold Start | B |
| Transient Speed, High Load, Low to High Speed | B |

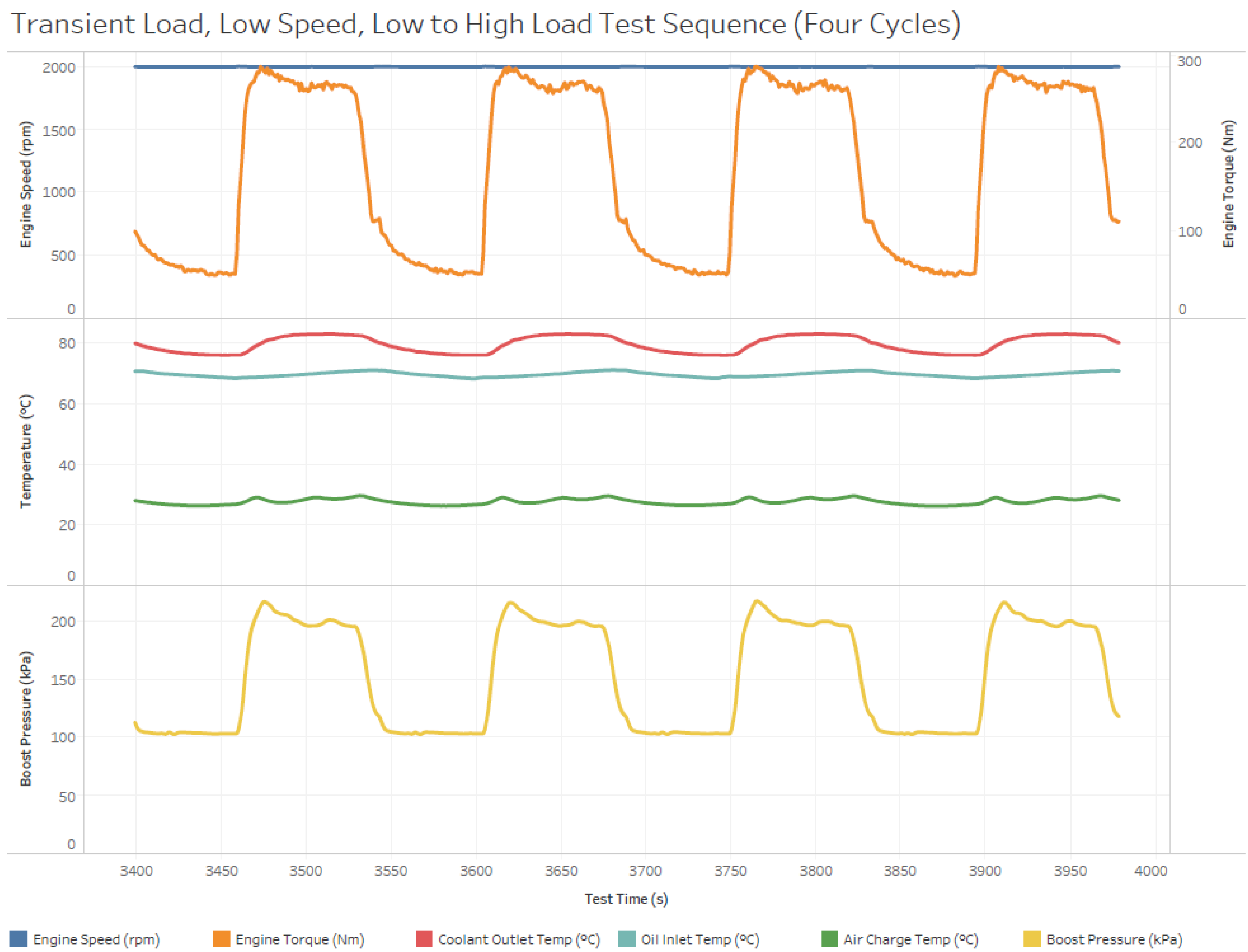
| Test Condition | Oil |
|---|---|
| ***Turbocharger Replacement*** | |
| *Oil Change to Oil A* | |
| Cold Start | A |
| WOT Transient | A |
| Baseline Steady State Mid Speed | A |
| *Oil Change to Oil B* | |
| WOT Transient | B |
| Cold Start | B |
| Trailer Tow | B |
| *Oil Change to Oil A* | |
| Cold Start | A |
| Trailer Tow | A |
| Turbo Transient | A |
| Baseline Steady State Mid Speed | A |
| *Oil Change to Oil B* | |
| Cold Start | B |
| Turbo Transient | B |
| WOT: steady-state, low speed (2500rpm) | B |
| *Oil Change to Oil A* | |
| Cold Start | A |
| WOT: steady-state, low speed (2500rpm) | A |
| Cold Start | A |
| WOT: steady state, moderate speed (3500rpm) | A |
| Baseline Steady State Mid Speed | A |
| *Oil Change to Oil B* | |
| WOT: steady state, moderate speed (3500rpm) | B |
| Cold Start | B |
| WOT: steady state, high speed (5000rpm) | B |
| *Oil Change to Oil A* | |
| WOT: steady state, high speed (5000rpm) | A |
| Cold Start | A |
| Boundary Lubrication | A |
| Baseline Steady State Mid Speed | A |
| *Oil Change to Oil B* | |
| Cold Start | B |
| Boundary Lubrication | B |

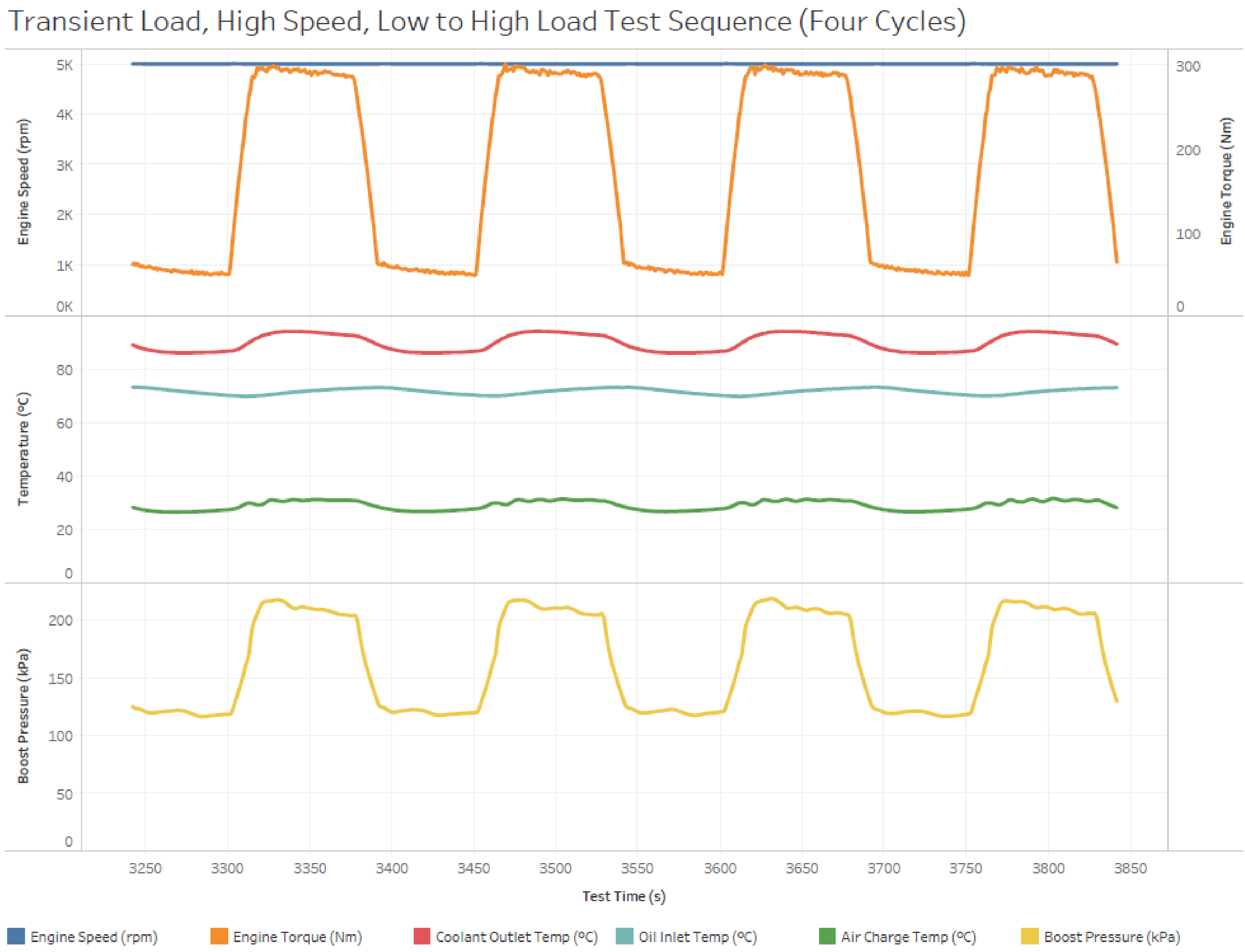
| Test Description | Oil |
|---|---|
| Hot Temp Stop-Start 4hr | Oil B |
| *Oil Change to Oil A* | |
| Hot Temp Stop-Start 4hr | Oil A |
| Trans Speed High Load (115C Oil Temp) | Oil A |
| Baseline Steady State Mid Speed | Oil A |
| *Oil Change to Oil B* | |
| Trans Speed High Load (115C Oil Temp) | Oil B |
| WOT 3500 | Oil B |
| *Oil Change to Oil A* | |
| WOT 3500 | Oil A |
| Trailer Tow (115C oil Temp) | Oil A |
| Baseline Steady State Mid Speed | Oil A |
| *Oil Change to Oil B* | |
| Trailer Tow (115C oil Temp) | Oil B |
| Stop-Start Very Cold | Oil B |
| *Oil Change to Oil A* | |
| Stop-Start Very Cold | Oil A |
| WOT 5000 Cold | Oil A |
| Baseline Steady State Mid Speed | Oil A |
| *Oil Change to Oil B* | |
| WOT 5000 Cold | Oil B |

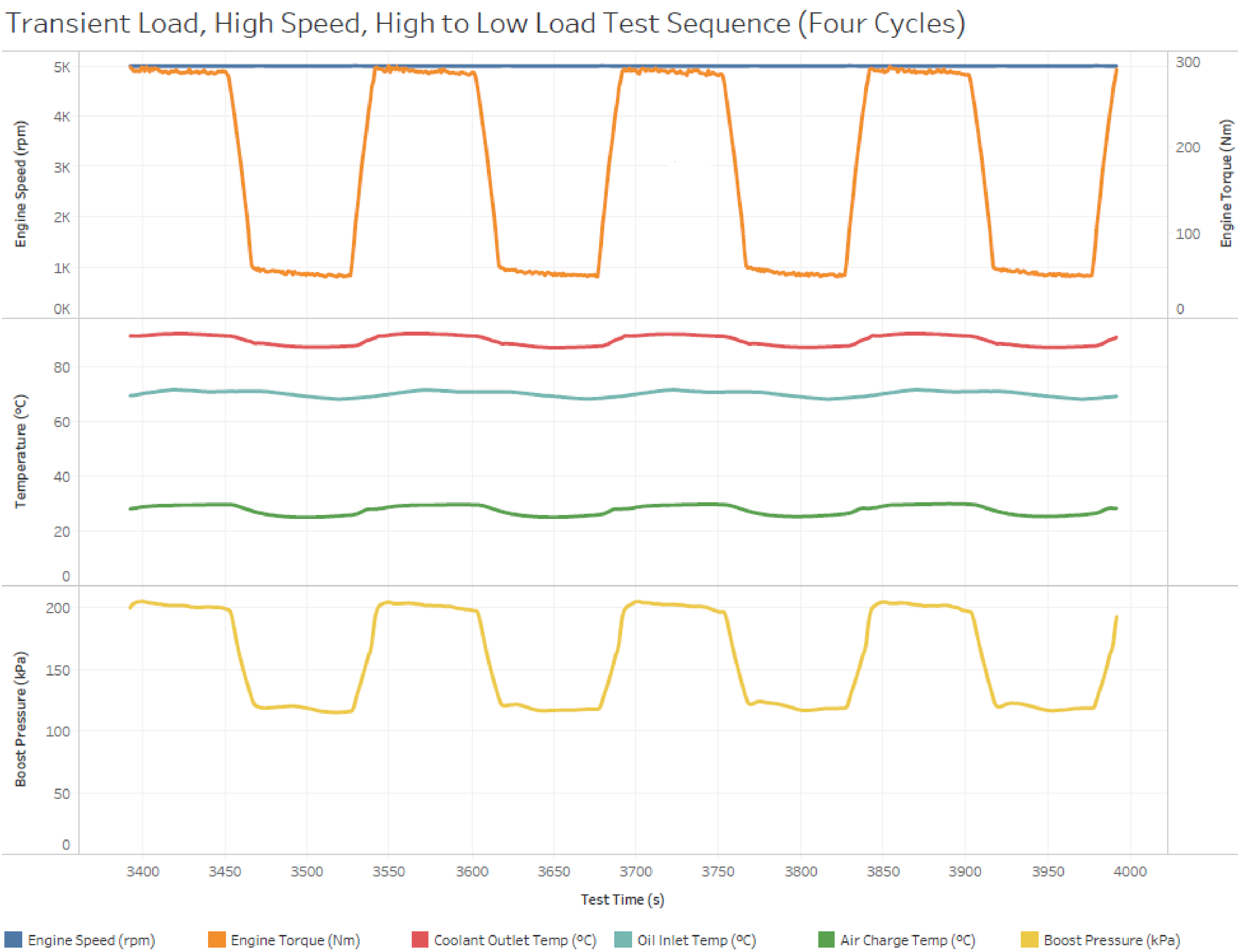


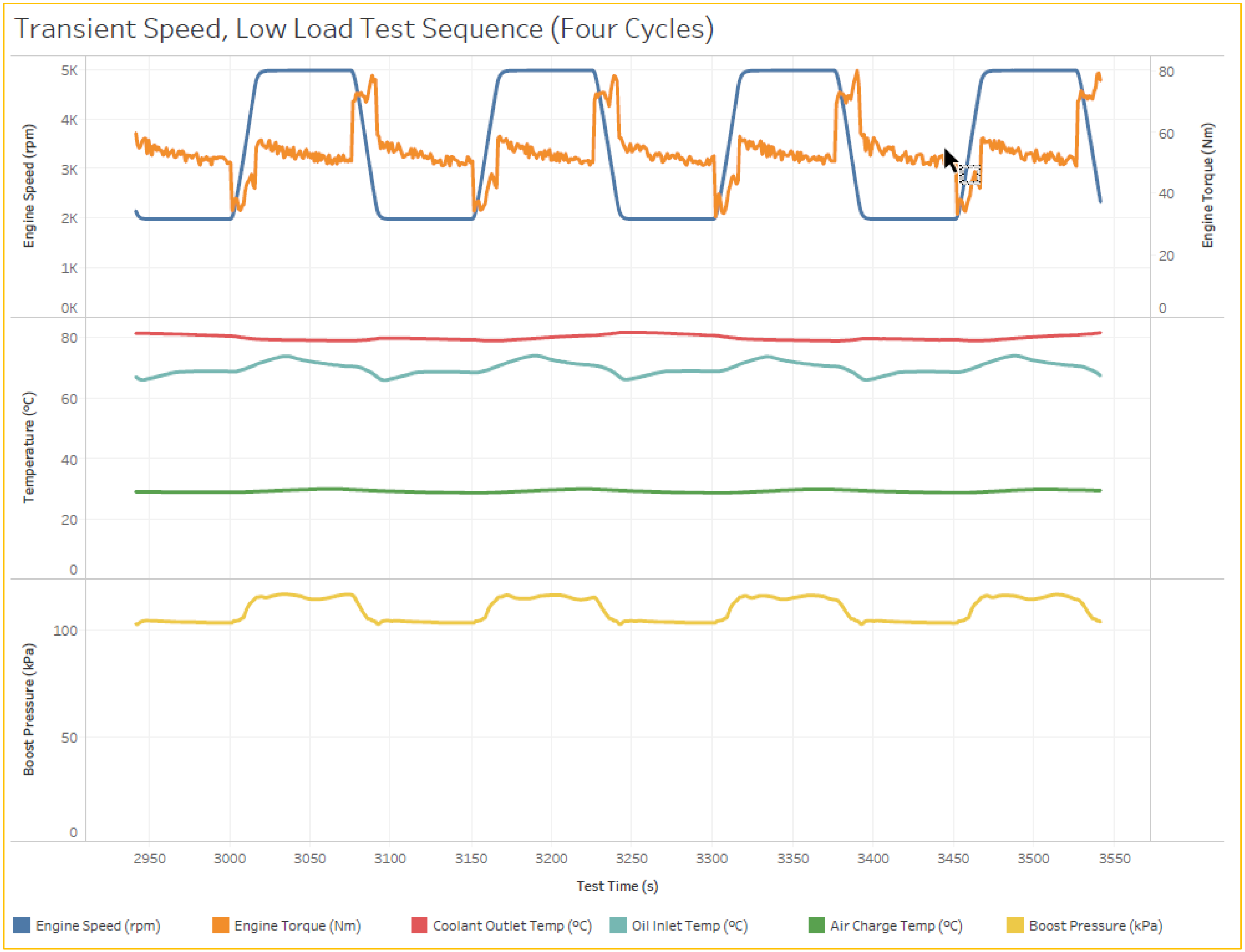
Cold Start Test Sequence
Engine Speed (rpm)
3K
2K
1K
0K
Engine Torque (Nm)
300
200
100
0
Temperature (ºC)
60
40
20
0
Boost Pressure (kPa)
200
150
100
50
0
-10
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
Test Time (s)
Engine Speed (rpm)
Engine Torque (Nm)
Coolant Outlet Temp (ºC)
Oil Inlet Temp (ºC)
Air Charge Temp (ºC)
Boost Pressure (kPa)

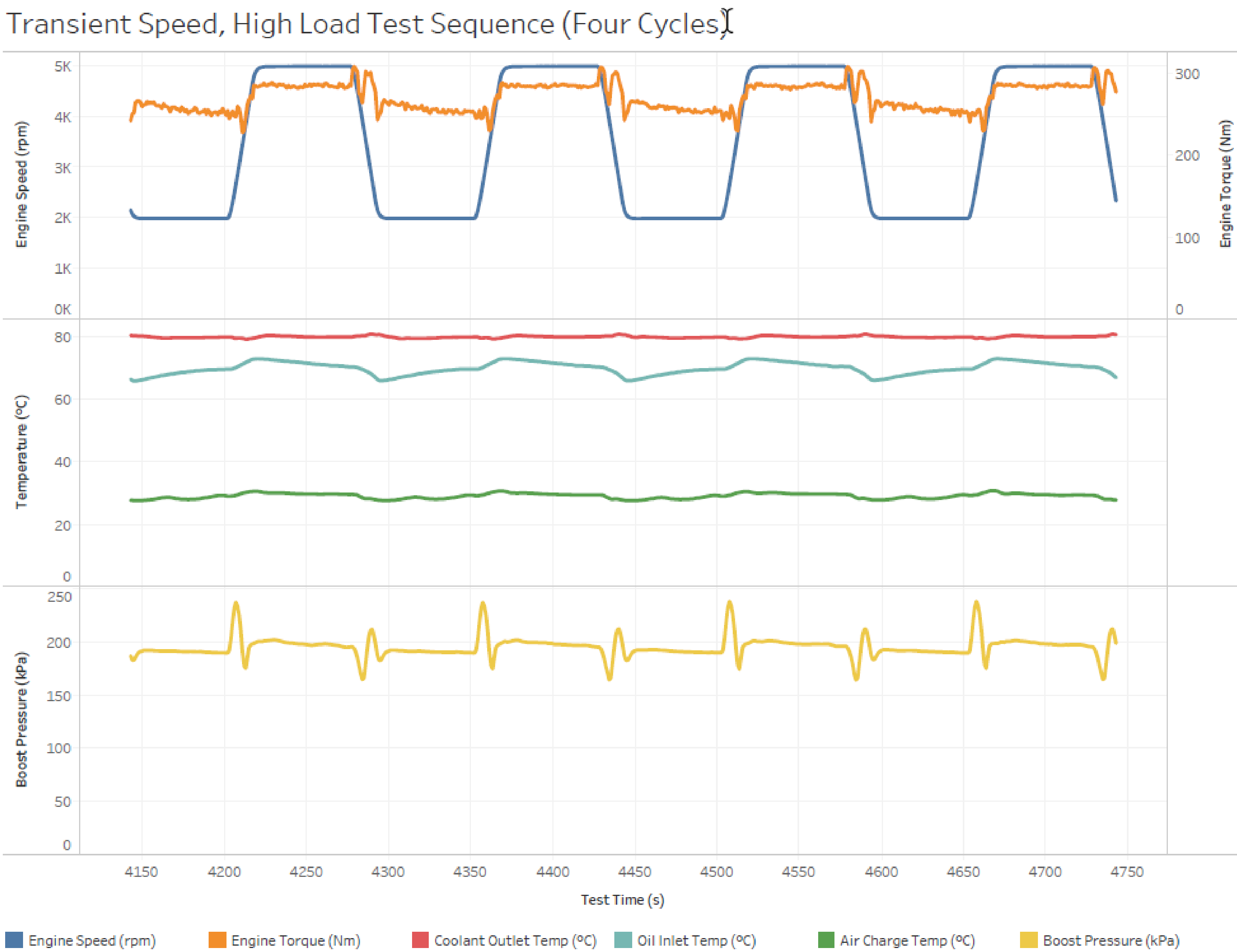

Start/Stop Test Sequence (Four Cycles)
Engine Speed (rpm)
3K
2K
1K
0K
300
200
100
0
Engine Torque (Nm)
Temperature (ºC)
80
60
40
20
0
Boost Pressure (kPa)
200
100
0
1240
1260
1280
1300
1320
1340
1360
1380
1400
1420
1440
1460
1480
1500
1520
1540
1560
1580
1600
1620
1640
Test Time (s)
Engine Speed (rpm)
Engine Torque (Nm)
Coolant Outlet Temp (ºC)
Oil Inlet Temp (ºC)
Air Charge Temp (ºC)
Boost Pressure (kPa)

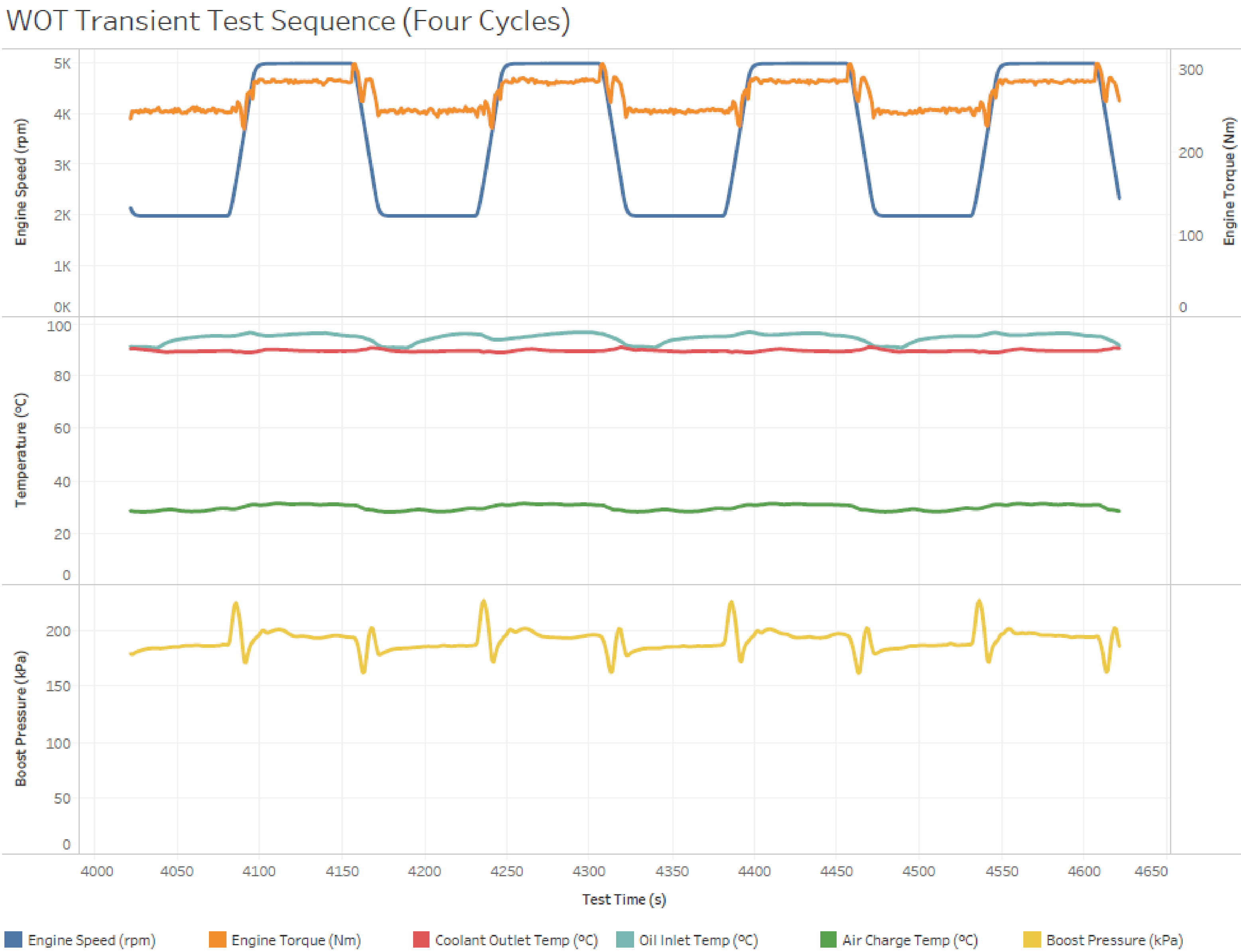

Transient Load, Low Speed, Low to High Load Test Sequence (Four Cycles)
Engine Speed (rpm)
Engine Torque (Nm)
Temperature (ºC)
Boost Pressure (kPa)
Test Time (s)
Engine Speed (rpm)
Engine Torque (Nm)
Coolant Outlet Temp (ºC)
Oil Inlet Temp (ºC)
Air Charge Temp (ºC)
Boost Pressure (kPa)


Transient Load, High Speed, Low to High Load Test Sequence (Four Cycles)
Engine Speed (rpm)
5K
4K
3K
2K
1K
0K
Engine Torque (Nm)
300
200
100
0
Temperature (ºC)
80
60
40
20
0
Boost Pressure (kPa)
200
150
100
50
0
3250
3300
3350
3400
3450
3500
3550
3600
3650
3700
3750
3800
3850
Test Time (s)
Engine Speed (rpm)
Engine Torque (Nm)
Coolant Outlet Temp (ºC)
Oil Inlet Temp (ºC)
Air Charge Temp (ºC)
Boost Pressure (kPa)

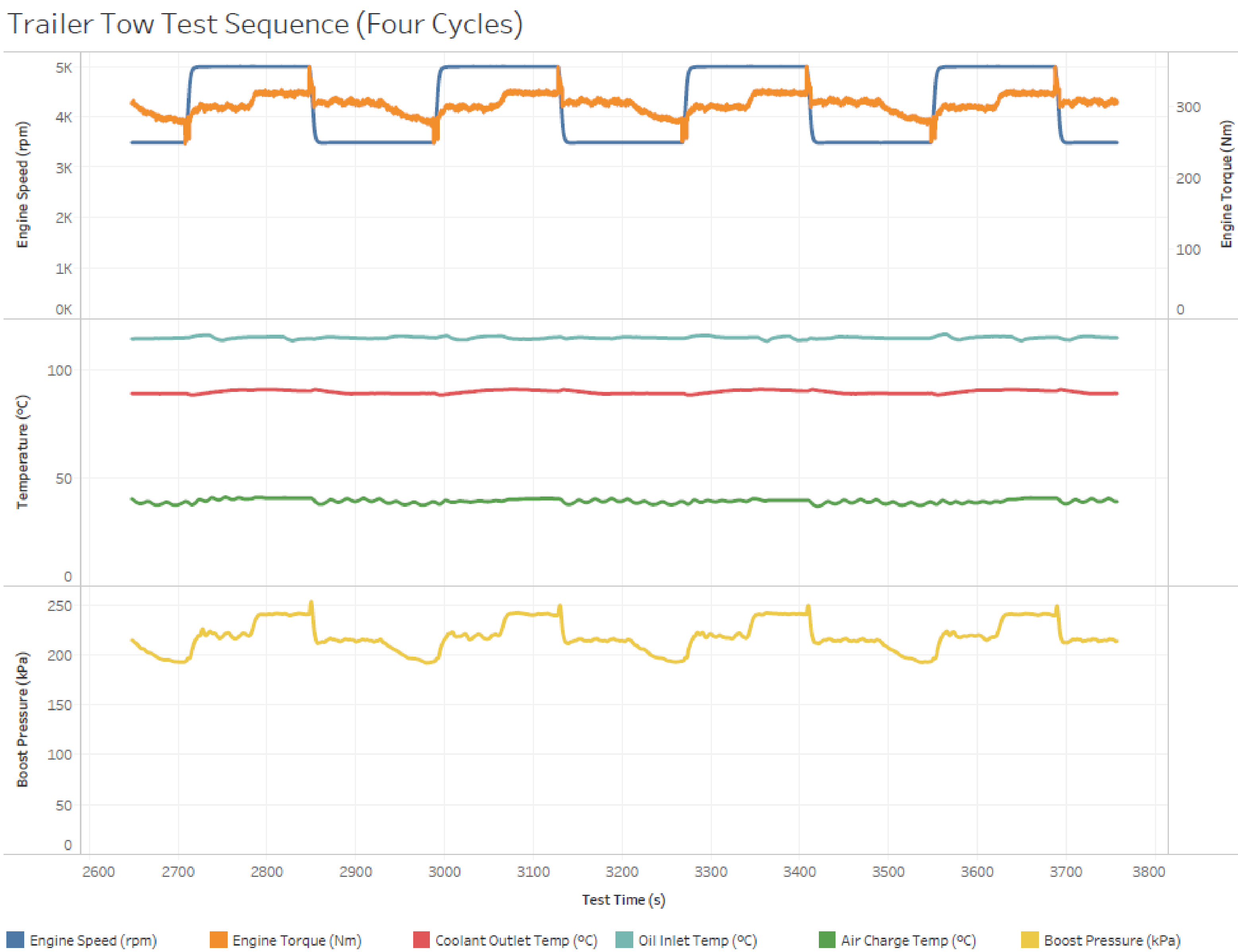

Transient Load, High Speed, High to Low Load Test Sequence (Four Cycles)
Engine Speed (rpm)
Engine Torque (Nm)
Temperature (°C)
Boost Pressure (kPa)
Test Time (s)
5K
4K
3K
2K
1K
0K
300
200
100
0
80
60
40
20
0
200
150
100
50
0
3400
3450
3500
3550
3600
3650
3700
3750
3800
3850
3900
3950
4000
Engine Speed (rpm)
Engine Torque (Nm)
Coolant Outlet Temp (°C)
Oil Inlet Temp (°C)
Air Charge Temp (°C)
Boost Pressure (kPa)


Transient Speed, Low Load Test Sequence (Four Cycles)
Engine Speed (rpm)
5K
4K
3K
2K
1K
0K
80
60
40
20
0
Engine Torque (Nm)
Temperature (ºC)
80
60
40
20
0
Boost Pressure (kPa)
100
50
0
2950
3000
3050
3100
3150
3200
3250
3300
3350
3400
3450
3500
3550
Test Time (s)
Engine Speed (rpm)
Engine Torque (Nm)
Coolant Outlet Temp (ºC)
Oil Inlet Temp (ºC)
Air Charge Temp (ºC)
Boost Pressure (kPa)

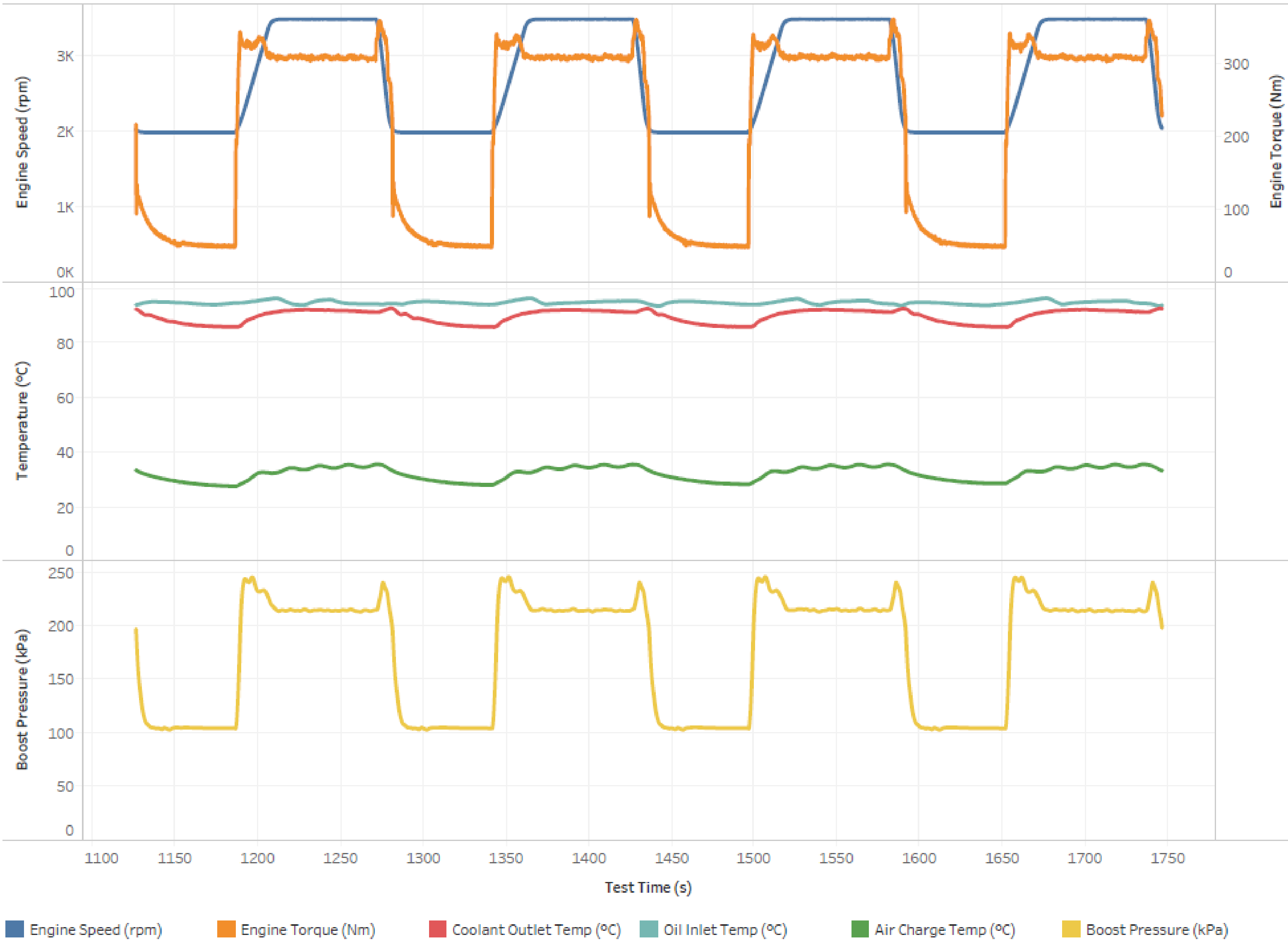

Transient Speed, High Load Test Sequence (Four Cycles)
Engine Speed (rpm)
Engine Torque (Nm)
Temperature (ºC)
Boost Pressure (kPa)
Test Time (s)
5K
4K
3K
2K
1K
0K
300
200
100
0
80
60
40
20
0
250
200
150
100
50
0
4150
4200
4250
4300
4350
4400
4450
4500
4550
4600
4650
4700
4750
Engine Speed (rpm)
Engine Torque (Nm)
Coolant Outlet Temp (ºC)
Oil Inlet Temp (ºC)
Air Charge Temp (ºC)
Boost Pressure (kPa)

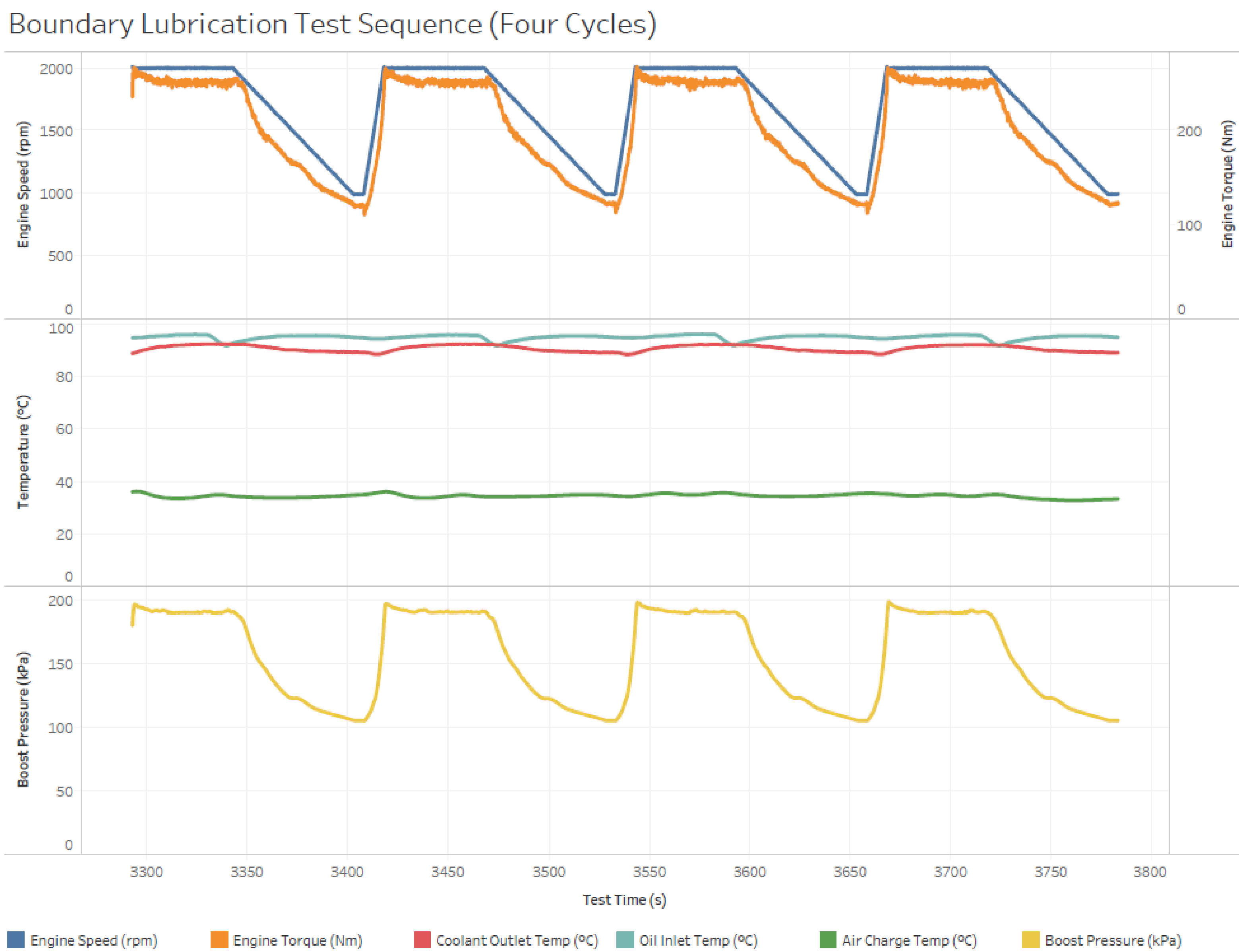


WOT Transient Test Sequence (Four Cycles)
Engine Speed (rpm)
5K
4K
3K
2K
1K
0K
Engine Torque (Nm)
300
200
100
0
Temperature (ºC)
100
80
60
40
20
0
Boost Pressure (kPa)
200
150
100
50
0
4000
4050
4100
4150
4200
4250
4300
4350
4400
4450
4500
4550
4600
4650
Test Time (s)
Engine Speed (rpm)
Engine Torque (Nm)
Coolant Outlet Temp (ºC)
Oil Inlet Temp (ºC)
Air Charge Temp (ºC)
Boost Pressure (kPa)


Trailer Tow Test Sequence (Four Cycles)
Engine Speed (rpm)
Engine Torque (Nm)
Temperature (ºC)
Boost Pressure (kPa)
Test Time (s)
5K
4K
3K
2K
1K
0K
300
200
100
0
100
50
0
250
200
150
100
50
0
2600
2700
2800
2900
3000
3100
3200
3300
3400
3500
3600
3700
3800
Engine Speed (rpm)
Engine Torque (Nm)
Coolant Outlet Temp (ºC)
Oil Inlet Temp (ºC)
Air Charge Temp (ºC)
Boost Pressure (kPa)

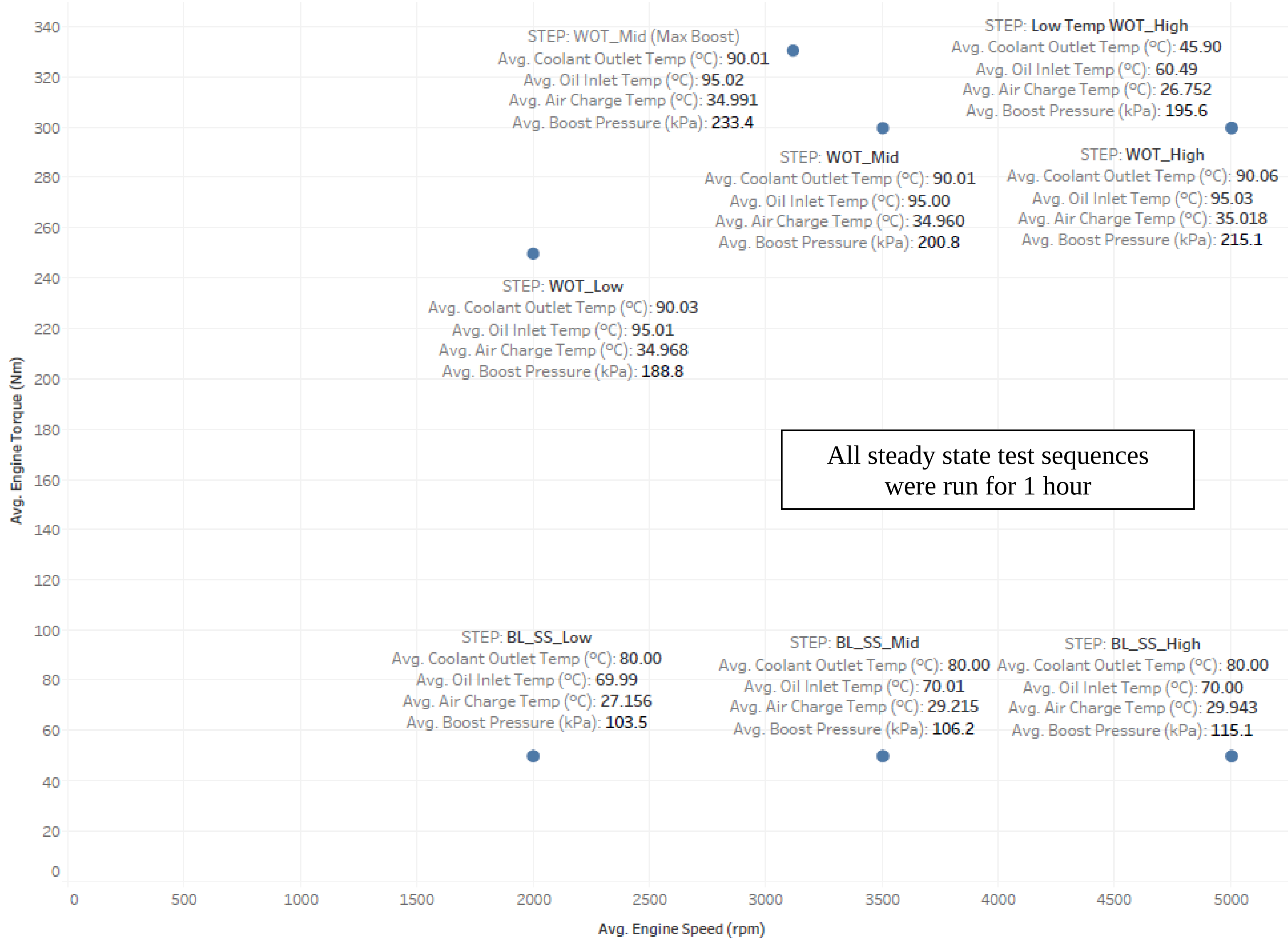
Turbo Transient Test Sequence (Four Cycles)

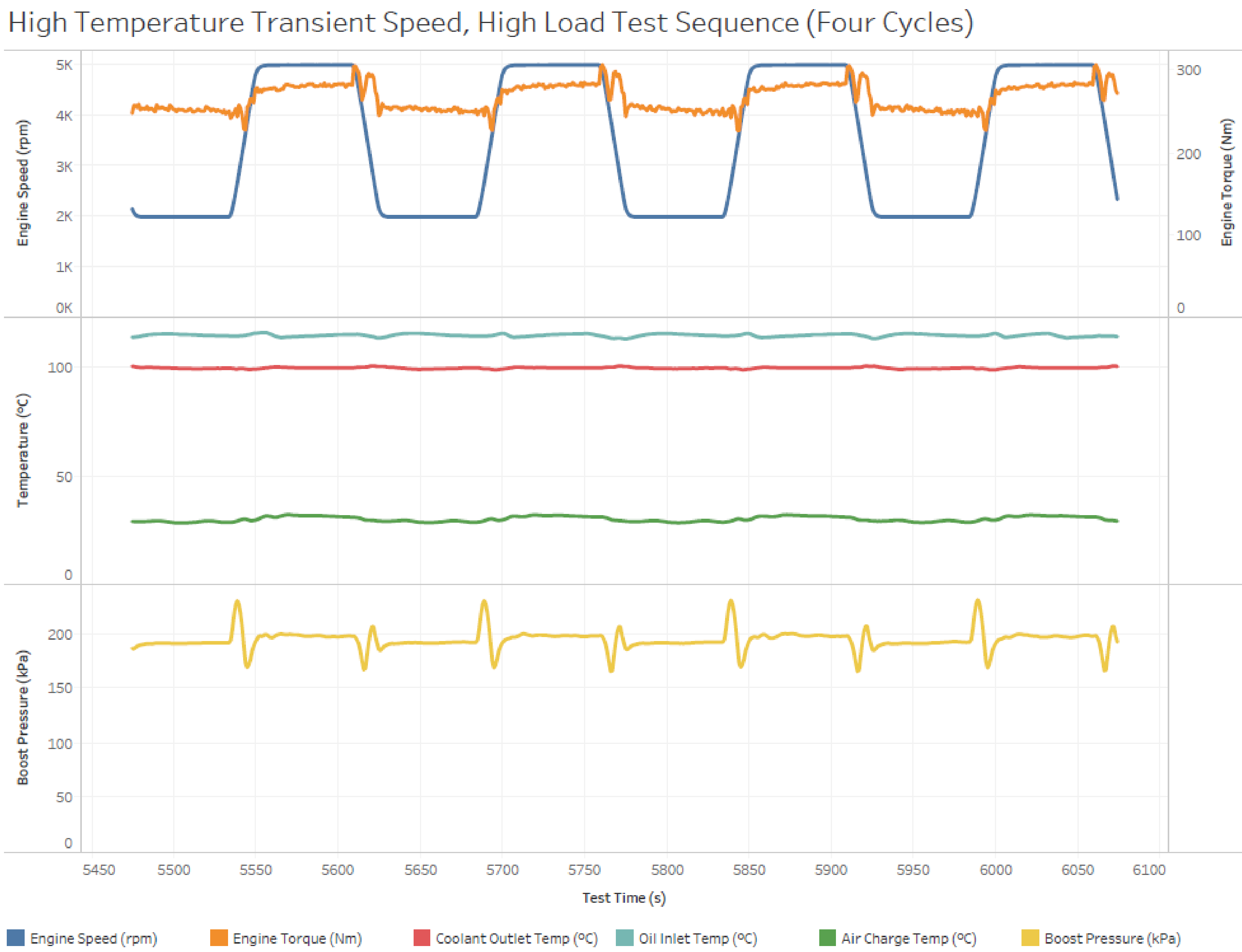


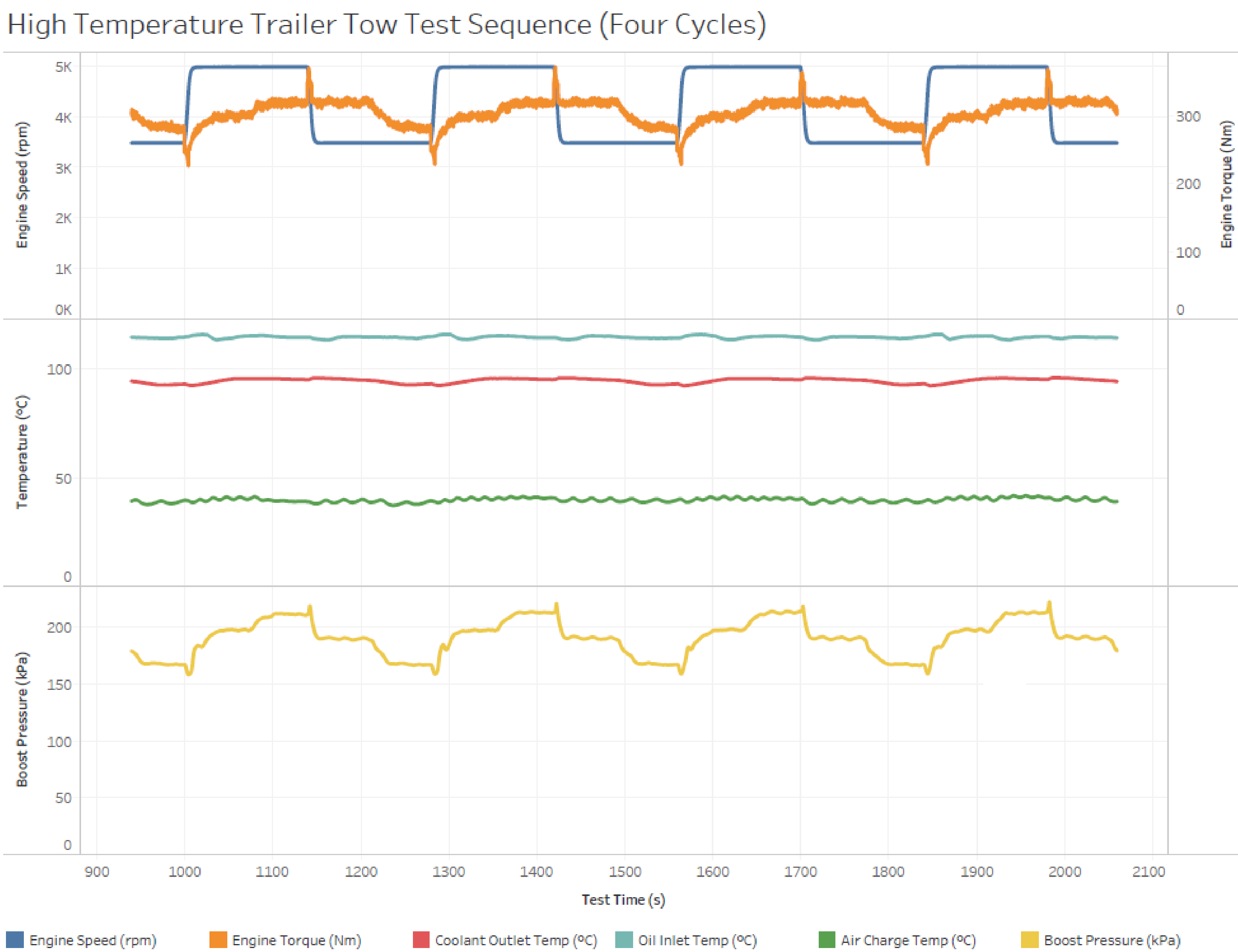


Boundary Lubrication Test Sequence (Four Cycles)
Engine Speed (rpm)
Engine Torque (Nm)
Temperature (ºC)
Boost Pressure (kPa)
Test Time (s)
2000
1500
1000
500
0
200
100
0
100
80
60
40
20
0
200
150
100
50
0
3300
3350
3400
3450
3500
3550
3600
3650
3700
3750
3800
Engine Speed (rpm)
Engine Torque (Nm)
Coolant Outlet Temp (ºC)
Oil Inlet Temp (ºC)
Air Charge Temp (ºC)
Boost Pressure (kPa)

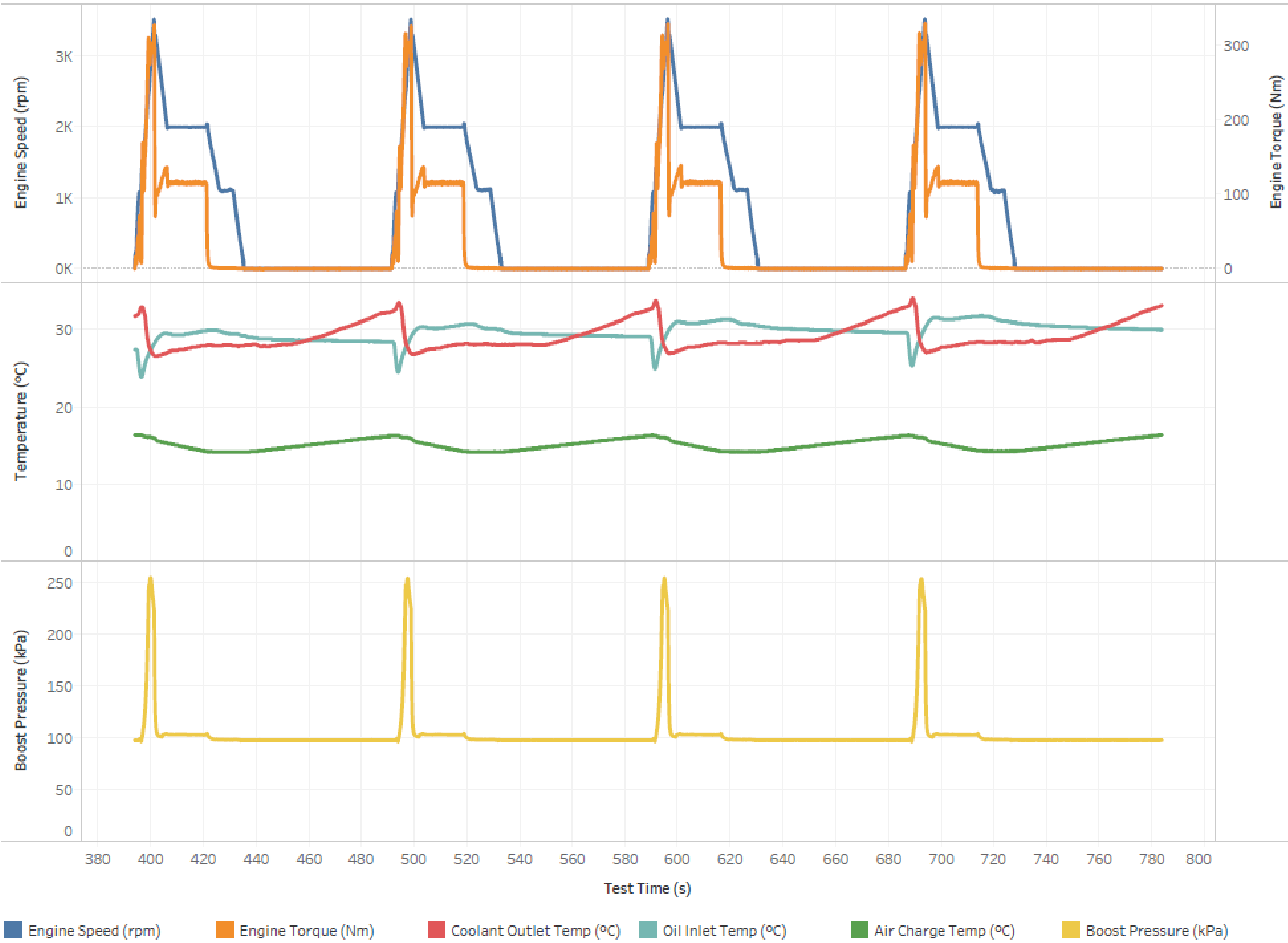
Steady State Test Sequences Summary




High Temperature Transient Speed, High Load Test Sequence (Four Cycles)
Engine Speed (rpm)
5K
4K
3K
2K
1K
0K
Engine Torque (Nm)
300
200
100
0
Temperature (ºC)
100
50
0
Boost Pressure (kPa)
200
150
100
50
0
5450
5500
5550
5600
5650
5700
5750
5800
5850
5900
5950
6000
6050
6100
Test Time (s)
Engine Speed (rpm)
Engine Torque (Nm)
Coolant Outlet Temp (ºC)
Oil Inlet Temp (ºC)
Air Charge Temp (ºC)
Boost Pressure (kPa)


High Temperature Trailer Tow Test Sequence (Four Cycles)
Engine Speed (rpm)
5K
4K
3K
2K
1K
0K
Engine Torque (Nm)
300
200
100
0
Temperature (ºC)
100
50
0
Boost Pressure (kPa)
200
150
100
50
0
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
Test Time (s)
Engine Speed (rpm)
Engine Torque (Nm)
Coolant Outlet Temp (ºC)
Oil Inlet Temp (ºC)
Air Charge Temp (ºC)
Boost Pressure (kPa)

Low Temperature Start/Stop Test Sequence (Four Cycles)



# APPENDIX D

# Engine Testing Results

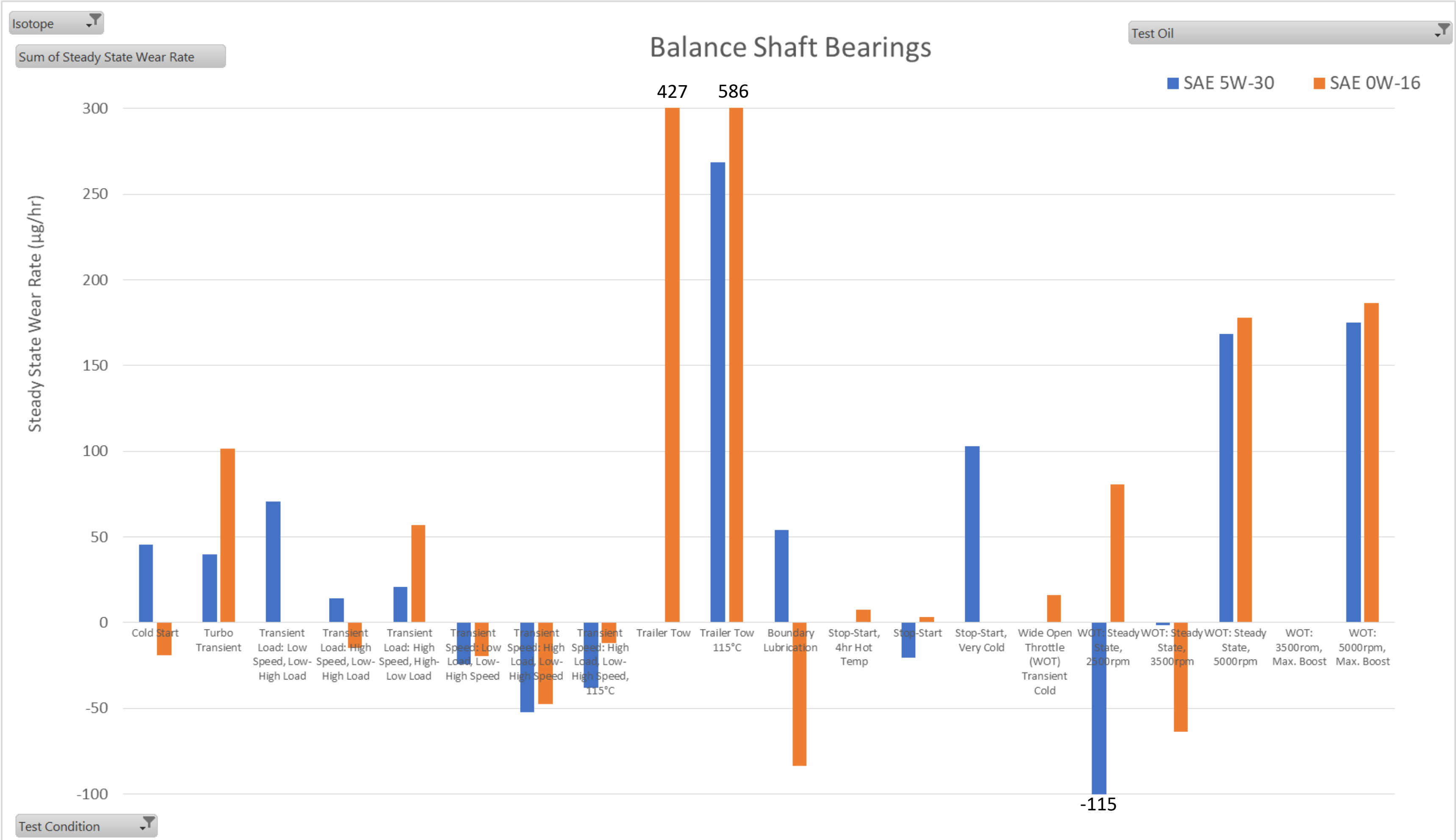



**Figure D1. Balance Shaft Bearings for Complete Test Matrix in Chronological Testing Order**

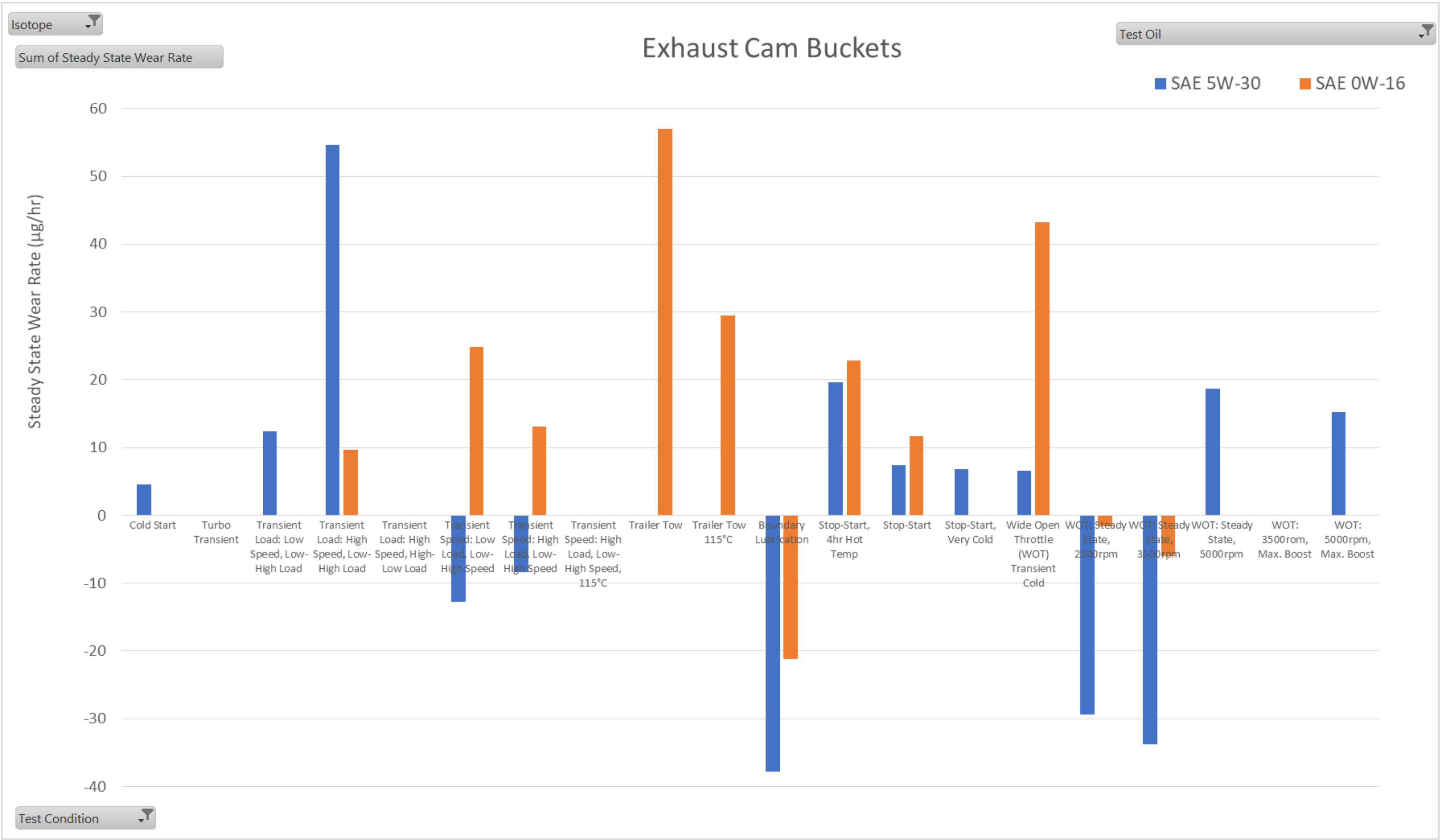



**Figure D2. Exhaust Cam Buckets Wear Summary for Complete Test Matrix in Chronological Testing Order**

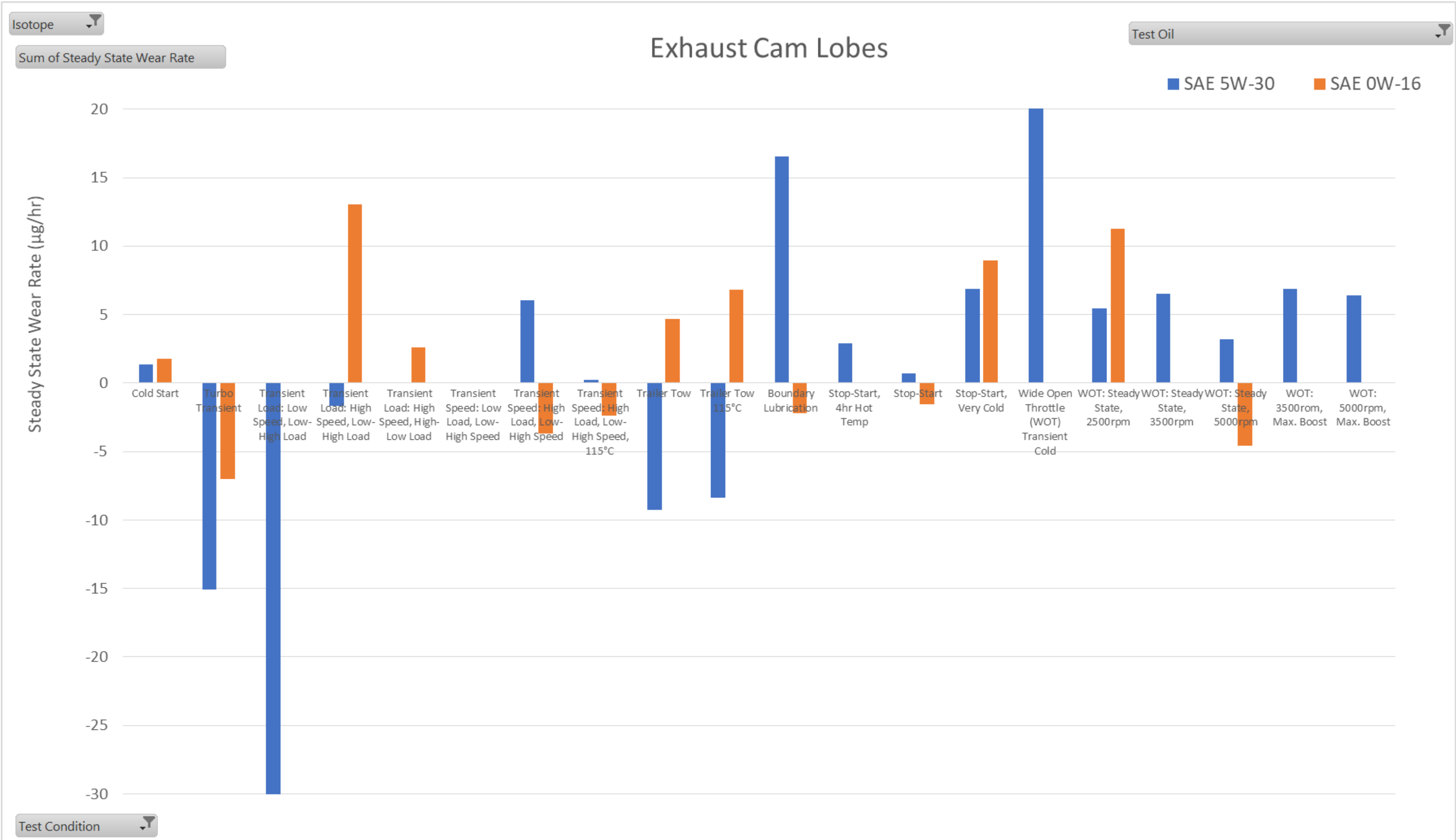



**Figure D3. Exhaust Cam Lobes Summary for Complete Test Matrix in Chronological Testing Order**

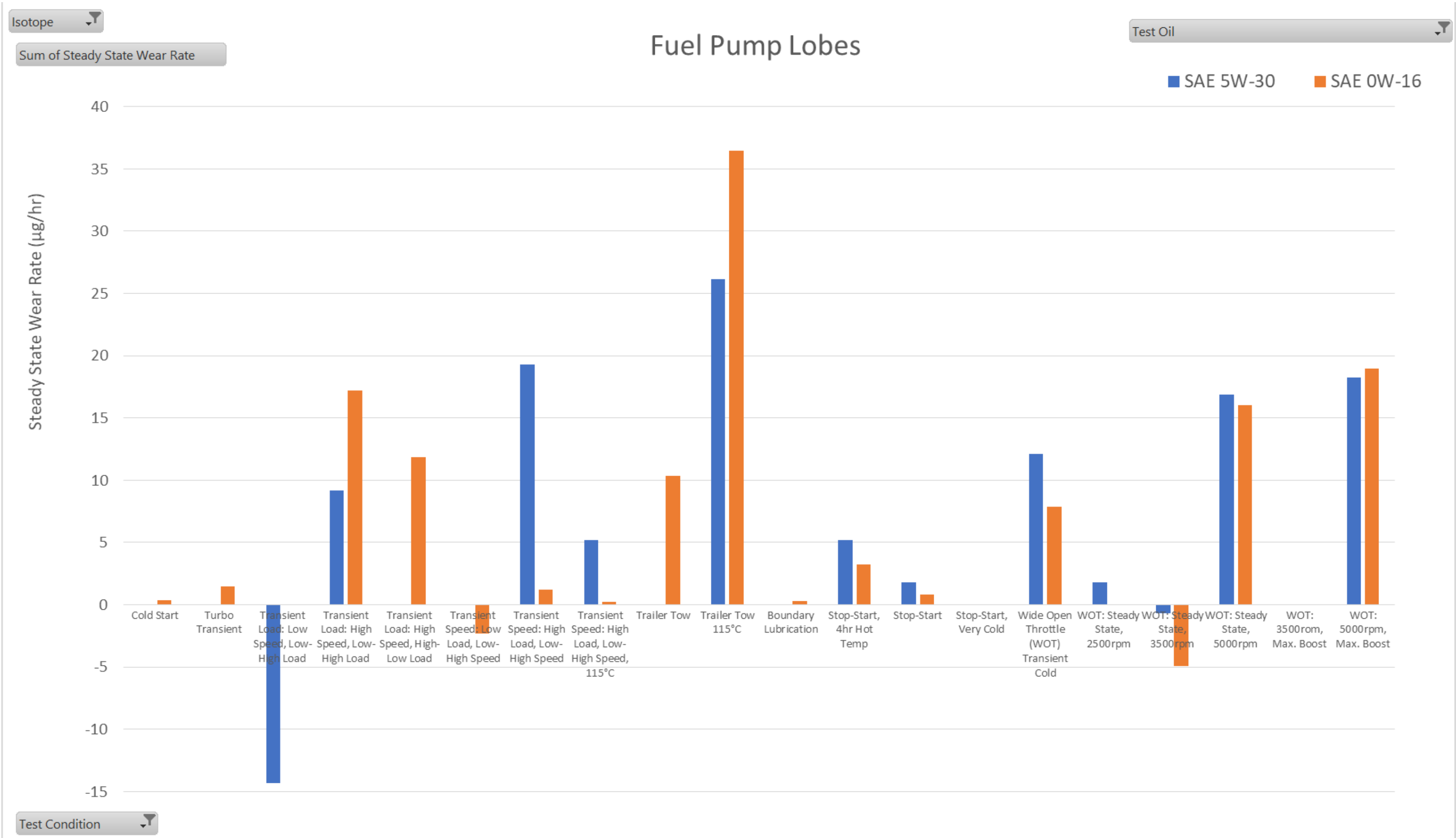



**Figure D4. Fuel Pump Lobes Summary for Complete Test Matrix in Chronological Testing Order**

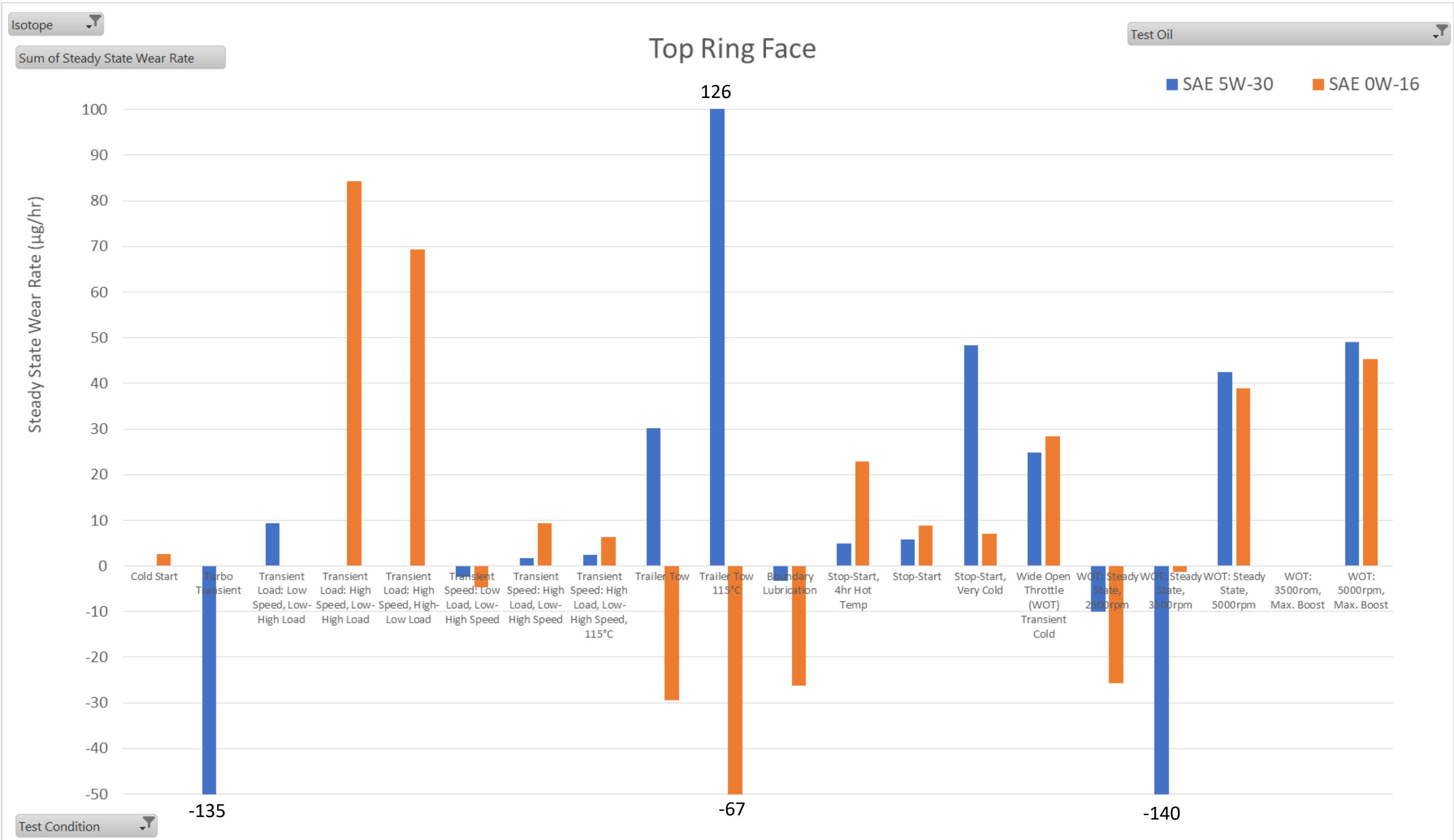



**Figure D5. Top Ring Face Wear Summary for Complete Test Matrix in Chronological Testing Order**

In a number of the tests, negative wear rates were recorded. This is not an unusual occurrence when using RATT® to measure real time wear of components. It is usual for this to occur in test conditions where the radioactive wear particles are lost at a faster rate than they are created. In almost all these circumstances it is reasonable to assume that the wear rates must be low, because if they are not, an increase in wear particles would be detected. These negative values and zero values have all been displayed as zeros in the graphs in the main report

# APPENDIX E

# Elemental Mass Concentrations for Engine Parts

| | Percent Mass Concentration by Element, % | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Na | Mg | Al | Si | V | P | K | S | Ca | Ti | Cr | Mn | Fe | Co | Ni | Nb | Mo | W | Cu | Sn | Zn | Pb |
| Wrist Pin Base metal | | | 0.3 | 0.46 | | | | | | | 0.54 | 0.55 | 98.14 | | | | | | | | | |
| Wrist Pin Surface Coating | | 1.47 | 1.13 | 3.2 | | 1.5 | | 2.86 | 1.92 | | 4.68 | 3.04 | 78.81 | | | | | | 0.27 | | | |
| Piston Skirt Base metal | | 1.26 | 68.96 | 24.22 | | | | | | | | 0.22 | 0.62 | | 1.86 | | | | 2.87 | | | |
| Cylinder Liner Base metal | | | 0.19 | 3.43 | | 0.23 | | | | | 0.12 | 0.72 | 94.22 | | 0.33 | | 0.76 | | | | | |
| Main Bearing Base metal | | | 0.37 | 0.25 | | | | | | | | 0.27 | 99.1 | | | | | | | | | |
| Main Bearing Coating Layer | | | 89.35 | 5 | 0.22 | | | | | | | 0.21 | 0.26 | | | | | | 0.73 | 4.23 | | |
| Main Bearing Thrust Surface | | | 0.29 | 0.23 | | | | | | | | 0.29 | 99.18 | | | | | | | | | |
| Wrist Pin Bushing Base metal | | | 0.35 | 0.22 | | | | | | | | 0.67 | 98.75 | | | | | | | | | |
| Wrist Pin Bushing ID Layer | | | 0.28 | 0.22 | | | | | | | | | | | | | | | 94.58 | 4.92 | | |
| Rod Bearing ID Layer | | | 89.11 | 5.2 | 0.21 | | | | | | | | | | | | | | 1.1 | 4.38 | | |
| Rod Bearing Base Material | | | 0.62 | 0.66 | | | | | | | | 0.34 | 98.37 | | | | | | | | | |
| Top Ring Base metal | | | | 2.17 | | | | | | | 0.61 | 0.65 | 96.57 | | | | | | | | | |
| Top Ring Contact Surface | | | 0.57 | 0.42 | | | | | | | 98.35 | | 0.66 | | | | | | | | | |
| 2nd Ring Base Metal | | | | 0.55 | | | | | | | 0.07 | 0.74 | 98.64 | | | | | | | | | |
| Oil Ring Spacer | | | 0.23 | 0.94 | 0.1 | | | | | | 17.86 | 1.02 | 69.52 | | 9.59 | | 0.36 | | 0.38 | | | |
| Oil Ring Side Rails | | | 0.26 | 0.63 | 0.05 | | | | | | 18.06 | 0.24 | 78.99 | | 0.2 | | 1.57 | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | |
| Turbine Wheel | | | 9.43 | 0.19 | | | | | | 1.04 | 12.51 | | 0.61 | | 67.47 | 3.18 | 4.69 | 0.88 | | | | |
| Turbocharger Compressor Wheel | | 0.62 | .81.03 | 16.72 | | | | | | 0.12 | | | 0.21 | | | | | | 1.3 | | | |
| Turbine Shaft | | | 0.36 | 0.82 | | | | | | | 1.01 | 0.71 | 96.45 | | 0.18 | | 0.47 | | | | | |
| Turbo Journal Bearing | | | 1.93 | 1.19 | | | | | | | | 2.05 | 0.48 | | | | | | 56.52 | | 36.69 | 1.14 |
| Turbo Thrust Bearing | | | | 0.3 | | | | | | | | | | | | | | | 64.46 | | 35.24 | |
| | | | | | | | | | | | | | | | | | | | | | | |
| Valve Bucket | | | 0.32 | 0.3 | | | | | | | 0.77 | 0.95 | 97.66 | | | | | | | | | |
| Valve Guide | | 0.48 | | 1.02 | | 0.69 | | | | | | 0.17 | 93.59 | | | | | | 4.05 | | | |
| Valve Spring | | | | 2.43 | | | | | | | 0.59 | 0.63 | 96.34 | | | | | | | | | |
| Valve Keeper | | | | 0.26 | | | | | | | 0.09 | 0.31 | 99.33 | | | | | | | | | |
| Intake Valve Seat | | 0.44 | 0.49 | 0.78 | 0.07 | | | | | | 2.1 | 0.55 | 83.79 | 8.29 | 1.31 | | 2.08 | | 0.09 | | | |
| Intake Valve Stem | | | 0.31 | 2.4 | 0.04 | | | | | | 8.09 | 0.34 | 88.52 | | 0.31 | | | | | | | |
| Intake Valve Face | | | | 1.33 | | | | | | | 7.63 | 0.31 | 90.5 | | 0.23 | | | | | | | |
| Exhaust Valve Face | | | | | 0.11 | | | | | | 22.27 | 8.7 | 58.46 | | 3.69 | 3.58 | | 3.18 | | | | |
| Exhaust Valve Stem | | | | 3.99 | | | | | | | 8.72 | 0.43 | 86.63 | | 0.23 | | | | | | | |
| Exhaust Valve Seat | | | 0.4 | 0.32 | | | | | | | | 0.47 | 91.4 | | | | 0.78 | | 6.63 | | | |
| | | | | | | | | | | | | | | | | | | | | | | |
| Timing Chain Link | | | 0.18 | 0.62 | | | | | | | 0.1 | 0.71 | 98.39 | | | | | | | | | |
| Timing Chain Gear | | | | 0.54 | | | | | | | 1.09 | 0.82 | 97.55 | | | | | | | | | |
| Timing Chain Pin | | | 1.85 | 0.58 | | | | | | | 1.34 | 0.51 | 94.95 | | 0.18 | | 0.59 | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | |
| Camshaft Bearing Base Metal | | | 0.33 | 0.25 | | | | | | | | 0.21 | 99.21 | | | | | | | | | |
| Camshaft Bearing Babbitt | | | 88.23 | 5.53 | 0.21 | | | | | | | | 0.3 | | | | | | 0.73 | 4.93 | | |
| Camshaft Lobe | | | | 1.92 | | | | | | | 0.12 | 0.69 | 96.92 | | | | 0.34 | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | |
| Oil Pump Gear | | | 0.17 | 0.3 | | | | | | | 0.05 | 0.51 | 96.36 | | | | 0.63 | | 1.97 | | | |
| Oil Pump Shaft | | | 0.28 | 0.32 | | | | | | | | 0.85 | 97.59 | | | | 0.96 | | | | | |
| Oil Pump Bearing | | 0.68 | 82.77 | 13.38 | | | | | | | | 0.16 | 0.8 | | | | | | 1.29 | | 0.91 | |
| | | | | | | | | | | | | | | | | | | | | | | |
| Balance Shaft Bearing Base Metal | | | 0.42 | 0.3 | | | | | | | | 0.22 | 99.07 | | | | | | | | | |
| Balance Shaft Bearing Babbit | | | 81.62 | 9.92 | 0.2 | | | | | | | 0.12 | 1.23 | | | | 0.16 | | 0.72 | 6.04 | | |
| Balance Shaft Gear | | | 0.29 | 0.66 | | | | | | | 0.83 | 0.72 | 96.53 | | 0.26 | | 0.69 | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | |
| Block | | 0.51 | 81.45 | 14.45 | | | | | | 0.15 | | 0.31 | 0.46 | | | | | | 2.2 | | 0.46 | |
| Crankshaft (from Counterweight) | | | 0.26 | 2.75 | | | | | | | | 0.66 | 95.26 | | | | | | 1.06 | | | |
| Cylinder Head | | 0.72 | 82.3 | 12.97 | | | | | | 0.18 | | 0.36 | 0.58 | | | | | | 2.49 | | 0.41 | |
| | | | | | | | | | | | | | | | | | | | | | | |
| Mahle Piston Surface | 2.78 | 0.53 | 54.87 | 28.5 | | 9.36 | 0.16 | | 1.63 | | | | 0.31 | | 0.95 | | | | 1.18 | | | |
| Mahle Piston Base Metal | | 1.56 | 75.55 | 21.39 | | | | | | | | | 0.2 | | 0.63 | | | | 0.68 | | | |

# APPENDIX F

# Ford 8hr Run-in

**Eight Hour Break-In.** Run as follows:

| Stage No. | Time per Stage Hr:Min | Total Time Hr:Min | Engine Speed Setpoint rpm | BMEP Setpoint bar (psi)-lb/ft |
|---|---|---|---|---|
| 1 | 0:12 | 0:12 | Idle | Min. Load ^ |
| 2 | 0:18 | 0:30 | Idle | Min. Load ^ |
| 3 | 0:30 | 1:00 | 1500 | 2.5-28.2 lb/ft |
| 4 | 0:30 | 1:30 | 2000 | 4.5-52.8 |
| 5 | 0:30 | 2:00 | 2500 | 7.0-82.1 |
| 6 | 0:30 | 2:30 | 3000 | 8.5-99.7 |
| Optional: Shut down engine to drain oil and remove oil filter. Replace drain plug with drain valve. Install new oil and new oil filter. If specified, install bottles in the pushover and pullover sides of the crankcase ventilation system. | | | | |
| 7 | 0:15 | 2:45 | 3000 | Full Load * |
| 8 | 3:00 | 5:45 | 3000 | Full Load * |
| 9 | 0:15 | 6:00 | 2000 | 4.5-52.8 |
| 10 | 0:15 | 6:15 | 3250 | Full Load * |
| 11 | 0:15 | 6:30 | 3500 | Full Load * |
| 12 | 0:15 | 6:45 | 3750 | Full Load * |
| 13 | 0:15 | 7:00 | 4000 | Full Load * |
| 14 | 0:15 | 7:15 | 4250 ** | Full Load * |
| 15 | 0:15 | 7:30 | 4500 ** | Full Load * |
| 16 | 0:15 | 7:45 | 4750 ** | Full Load * |
| 17 | 0:15 | 8:00 | 5000 ** | Full Load * |

^ "Min. Load" is defined as the greater value of either: 47 ± 7 N-m (35 ± 5 ft-lbs) engine load or the load required to maintain zero crankcase pressure.

* For boosted applications, "full load" points are set to zero boost, meaning intake manifold pressure equal to barometric pressure.

** DO NOT EXCEED MAXIMUM RATED ENGINE SPEED DURING BREAK-IN. If this setpoint speed exceeds the maximum rated engine speed, run at maximum rated speed instead.

For this project, this 8hr run-in was repeated until 67hrs of run-in was achieved.