

Engine Oil Components Effects on Turbocharger Protection and the Relevance of the TEOST 33C Test for Gasoline Turbocharger Deposit Protection

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ABSTRACT

Countries from every region in the world have set aggressive fuel economy targets to reduce greenhouse gas emissions. To meet these requirements, automakers are using combinations of technologies throughout the vehicle drivetrain to improve efficiency. One of the most efficient types of gasoline engine technologies is the turbocharged gasoline direct injection (TGDI) engine. The market share of TGDI engines within North America and globally has been steadily increasing since 2008. TGDI engines can operate at higher temperature and under higher loads. As a result, original equipment manufacturers (OEMs) have introduced additional engine tests to regional and OEM engine oil specifications to ensure performance of TGDI engines is maintained. One such engine test, the General Motors turbocharger coking (GMTC) test (originally referred to as the GM Turbo Charger Deposit Test), evaluates the potential of engine oil to protect turbochargers from deposit build-up. In this paper, the authors discuss the impact of typical engine oil components on GMTC performance. Concern about turbocharger deposits is not a new phenomenon, however. In the early 1990s the TEOST 33C bench test was developed to simulate turbocharger coking, and early studies showed a correlation between TEOST 33C results and field issues. A comparison of the TEOST 33C bench test and the GMTC engine test revealed no such correlation between the two tests under the conditions studied. Due to this lack of correlation, a comparison of TEOST 33C response with turbocharger deposits generated during field operation was performed.

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INTRODUCTION

Countries from every region in the world set high standards in reducing greenhouse gas (CO₂) emissions and improving vehicle fuel efficiency. The enacted and proposed CO₂ emission targets of all four major industrialized regions, the United States, Europe, China, and Japan aim to significantly reduce regulated tailpipe CO₂ emissions. For example, the targeted reduction for the United States is 4.7% annually from 2012 to 2025 [1-2].

In order to meet these requirements, automakers are using combinations of technologies throughout the vehicle drivetrain to improve overall efficiency. Turbocharging is an effective means of increasing specific power output, thereby allowing downsizing for reduced weight and reduced friction [3]. Gasoline turbocharged vehicles were introduced into the United States in 1961 and they were primarily used in sport vehicles until 2010. Since 2010, several improvements in turbocharger materials, system design and electronic controls, as well as engine design changes such as direct fuel injection, have led to an increase in the market share of gasoline turbocharged vehicles in the United States of about 3% annually to 22% in 2016 [3, 4, 5]. The market share of gasoline turbocharged vehicles in other regions is generally higher than in the United States.

For example, European original equipment manufacturers (OEMs) were very quick to adopt turbochargers in passenger car engine designs; it is estimated that about two-thirds of the existing car parc in Europe is turbocharged. In 2017, turbocharged passenger vehicles will represent approximately 40% of all new light-duty vehicle sales globally, with the United States, India, and China leading the sales growth [5]. At present, the turbocharged gasoline direct injection (TGDI) engine is one of the most efficient types of gasoline engines. The top 10 automakers globally all produce downsized and turbocharged engines [3]. Downsized TGDI engines have the potential of creating a catastrophic spontaneous combustion phenomenon known as low speed pre-ignition (LSPI). OEMs, oil marketers, additive companies and others have invested significant resources in an effort to understand how to protect engines against damage caused by LSPI through engine design and operational control, as well as fuel and lubricant impacts [6, 7, 8, 9, 10]. In this paper, the authors focus on evaluating the role of engine oil in maintaining turbocharger performance.

Due to their interaction with hot exhaust gas, turbocharger housings, turbines, shafts, and bearings are exposed to high temperatures, as is the engine oil lubricating the turbocharger bearing. This may become especially true when the engine is shut off and there is no longer a

flow of oil to the bearings or coolant to the housing. While particular regions of the turbocharger may reach temperatures in excess of 500°C, the maximum temperature of the lubricant film, when measured 2 to 3 minutes after engine shut off, can reach about 260-316°C [11, 12, 13, 14]. Ribeiro et al. observed the maximum turbocharger bearing temperature was about 340°C 40 seconds after the engine was shut off [15-16]. Extended or repeated exposure to high temperatures can lead to oil degradation, deposit build-up in the turbocharger and possible bearing failure [11].

Over concern about deposit build-up within the turbocharger, and in response to turbocharger coking problems in the field, Florkowski and Selby developed the Thermo-Oxidation Engine Oil Simulation Test (TEOST) to simulate engine oil turbocharger coking. With a total run time of about 2 hours and cycling temperature range of 200 to 480°C, TEOST 33C later became an ASTM method D-6335. This test was introduced as part of the specifications ILSAC GF-2 and API SJ to demonstrate the ability to minimize and protect against turbocharger deposits. Using four reference oils in a vehicle or a dynamometer engine, final TEOST 33C test conditions were determined by correlating bench test response to field performance [12, 13, 14]. TEOST 33C requirements were removed from ILSAC GF-3 and API SL, but were re-instated in the ILSAC GF-5 and API SN specifications with a tightened limit of 30 mg total deposits, instead of 60 mg for ILSAC GF-2 and API SJ specifications.

General Motors (GM) Company and Intertek Automotive Research developed an engine test method using a 2012 GM Ecotec 1.4L turbocharged engine. The purpose was to evaluate the impact of engine oils on deposit formation in turbochargers under elevated temperature conditions [2]. The test method was finalized in 2014 and is referred to as the GM turbocharger coking test (GMTC) with GMW 17299 as its GM test code. It is included in the GM dexos1™ Gen 2 specification (GMW 17332).

In a previous paper [2], the authors discussed how dispersants and detergents impacted performance in the GMTC test. Viscosity modifier (VM) type, antioxidants (AO) level, and Molybdenum (Mo) component responses in this test will be further discussed here. In addition, correlation between the GMTC engine test and the TEOST 33C bench test, as well as an assessment of the relationship between engine oil field turbocharger deposits and TEOST 33C deposits will be discussed.

EXPERIMENTAL

GMTC Tests

Test Method

All GMTC tests of selected engine oils were conducted at an independent lab. In order to pass the GMTC test, an engine oil must be able to complete 2000 test cycles containing engine operation and soak stages, in which each cycle lasts 16 minutes, for a total of about

536 hours. During the test, if the boost pressure is less than 5 kPa for 10 seconds, then the test is considered a fail and the test is terminated. Among many parameters, the turbocharger coolant outside temperature (TCO Temp) at 3000 rpm was selected as a key parameter for the deposit severity level evaluation. The location of this measurement was designed for coolant passage, but is operated in a dry condition during this test. At 3000 rpm stage, parameters like engine speed, manifold absolute pressure (MAP), inlet air pressure, exhaust back pressure, humidity, pre-turbo inlet air temperature, intake manifold temperature, and equivalence ratio were controlled while there were many other non-controlled parameters like oil gallery temperature, oil sump temperature, turbo feed pipe temperature, coolant in temperature, coolant out temperature etc. Average TCO Temp of first 100 cycles (1-100 cycles) is used as a baseline which is typically at a temperature within 130-150°C. Following the same method, average TCO Temp of every 100 cycles until the end of test is calculated. Therefore, the percent TCO Temp increase against the baseline can be calculated. According to the GM dexos1™ Gen 2 specification, the pass/fail limit was set at a percent TCO Temp increase of less than 13% by comparing average TCO Temp at 1800 cycles (the average TCO temperature for cycles 1701 through 1800) to the baseline.

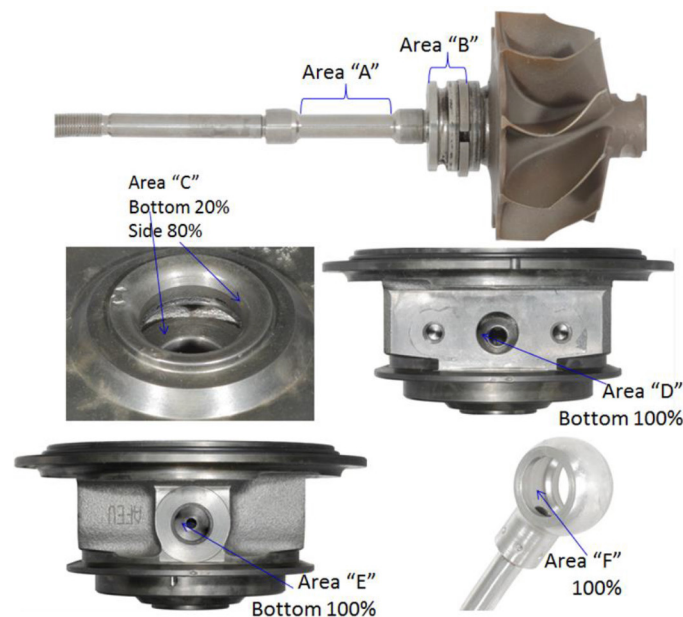


Figure 1. Six areas of GMTC end of test (EOT) merit ratings

In addition to evaluating the percent TCO Temp increase, at the end of the GMTC test an average merit rating of six areas of the turbocharger unit was reported. Figure 1 describes the six rated areas, which include two turbine shaft areas (A and B), the center housing turbine end hole (C), center housing turbine inlet hole (D), center housing turbine outlet hole (E), and inlet pipe (F). The rating method is an ASTM manual No. 20 non-rubbing carbon method. The parts used in Figure 1 were from a GMTC end of test but they were deeply cleaned in order to better illustrate the locations for ratings. Unlike many other engine tests, the end of test rating is report only, not a pass/fail parameter in this test.

Test Design for GMTC Test Response

Table 1. Test oil design and oil blend properties for GMTC test response study.

Oil	Detergent Inhibitor (DI) Package	Viscosity Modifier (VM)	KV100, cSt
Oil A	DI-A	VM-A: Star-type polymer, high shear stable	9.54
Oil B	DI-A	VM-B: OCP, mid-shear stable	10.68
Oil C	DI-B with 1X ^S AO and 1X* Mo	VM-C	10.85
Oil D	DI-B with 1/2 X AO and 1X Mo	VM-C	10.83
Oil E	DI-B with 1X AO and 9X Mo	VM-C	10.89

§: 1X AO stands for a typical antioxidant combination TR; *: 1X Mo stands for a typical Mo component TR; 9X Mo is at truly friction modifying level and much greater than 150 ppm Mo

The authors had previously [2] discussed the impact of detergent treat rate (TR), detergent type, and dispersant treat rate on deposit formation and test response on this test. In this paper, the study has been extended to evaluate the impacts of viscosity modifier type, AO treat rate, and Mo component treat rate. Test design and details of detergent inhibitor (DI) package, viscosity modifier, and kinematic viscosity at 100 °C (KV100) of the five fully formulated SAE 5W-30 test oils selected for the GMTC test response study are listed in Table 1. Same two-type antioxidant mixture system and same antioxidant ratio were used in oils C, D, and E but total treat rate of oil D was half of that of oil C or oil E. All five oils were blended using high quality Group III base oil slates, thereby minimizing the base stock impact. To investigate the impact of polymer introduced through the viscosity modifier, the performance of two finished fluids blended using either a high-level shear stable star-type polymer viscosity modifier or a mid-level shear stable olefin copolymer (OCP) viscosity modifier were evaluated. Oil A and Oil B were blended with identical DI packages, and viscosity modifier treat rates were calculated to deliver equivalent polymer loading.

Oxidation stability can be improved by modifying the antioxidant system and/or increasing the antioxidant treat rate. The effect of changing AO treat rate was determined by comparing the response of Oil C and Oil D. Mo components have long been implicated in an increase in turbocharger deposits as measured by the TEOST 33C bench test [17]. To assess any impact the Mo component may have on GMTC response, Oil E was blended with a significant increase (9X) in Mo level compared to Oil C.

Vehicle Tests

To compare engine oils in engine and turbocharger protection performance, two oils with very different Mo component treat rates (1X and about 7X which is at truly friction modifying level and much greater than 150 ppm) were selected to be tested under high temperature environmental conditions in taxi service vehicles, with three vehicles running on each oil. This test utilized 2012 Ford Explorers equipped with 2.0 Liter 4 cylinder turbocharged GDI engines in Las Vegas, Nevada. The vehicle test included both city and highway driving, with about 20-25% idle time. The fuel was not

controlled and from pump gas in Las Vegas Nevada area but the fuel quality can be considered equivalent to each test vehicle. The oil drain interval was about 16K km (10K miles) and test length was approximately 194K km (120K miles). Intermediate samples at about 8K km (5K miles) and drain samples at about 16K km (10K miles) were collected for used oil analysis. End of test engines were inspected including ratings for sludge. The turbocharger from one vehicle running on each oil was rated at the end of test for comparison purposes. The turbocharger from the Ford Explorer was physically different from the turbocharger in the GMTC test, but enough similarities exist to make meaningful comparisons. Locations within the Ford turbocharger were selected to closely approximate parts/locations rated in the GMTC test; the rating method used was ASTM manual No. 20 non-rubbing carbon method. The five areas of the Ford turbocharger selected to rate were: the compressor back plate - inner (center), oil deflector ring, bearing housing - turbine side, turbine shaft area A, and turbine shaft area B.

RESULTS AND DISCUSSION

GMTC Test Responses

Viscosity Modifier Type Impact

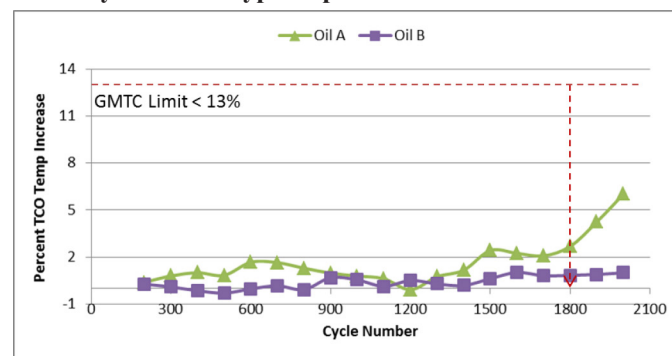


Figure 2. Viscosity modifier type impact on percent TCO Temp increase of GMTC test Oil A and Oil B

It is generally understood that viscosity modifier polymer loading has a negative impact on deposit tests. To evaluate whether polymer type has an impact on the formation of turbocharger deposits in the GMTC test, Oil A with a high-level shear stable star-type polymer viscosity modifier was compared to Oil B with a mid-level shear stable olefin copolymer viscosity modifier. Figure 2 illustrates the percent TCO Temp increase of Oil A and Oil B. Temperature increase in the TCO housing occurs when deposits form, causing an insulating effect and reducing oil flow. It is typical to observe very little change in percent TCO Temp increase within the first 1200 cycles or more because protection is maintained by the additive system. Once deposits begin to accumulate, heat transfer efficiency is reduced and oil flow through the passage becomes restricted. TCO Temp increase percentages of Oil B were almost flat until end of test while those of Oil A began increasing around 1700 cycles until end of test. Both oils passed the GMTC test as measured by percent TCO Temp increase at 1800 cycles; however, Oil B appeared to maintain performance beyond the point at which Oil A began to degrade.