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ScienceDirect
Tribology International 41 (2008) 556–563
TRIBOLOGY INTERNATIONAL
www.elsevier.com/locate/triboint

Effects of oil properties on spark-ignition gasoline engine friction

Martin Skjoedt, Ryan Butts, Dennis N. Assanis, Stanislav V. Bohac*

Mechanical Engineering, University of Michigan, Ann Arbor, MI 48109, USA

Received 29 January 2007; received in revised form 13 November 2007; accepted 9 December 2007
Available online 22 January 2008

Abstract

The effects of base oil, friction modifier (FM) and viscosity grade on firing engine friction are investigated in an automotive gasoline engine. Unique aspects of the study are (1) viscosity grade is maintained when synthetic and conventional base oils are compared, (2) the influence of engine operating condition on the effectiveness of base oil, FM and viscosity grade in reducing engine friction is considered, and (3) friction-relevant design details of the test engine are discussed. Results show that replacing conventional oil with synthetic oil of the same viscosity grade reduces friction, especially at high boundary friction conditions. Molybdenum dithiocarbamate (MoDTC), and to a lesser extent organic FM, also reduce friction, especially at high boundary friction conditions. Furthermore, using 5W-20 oil causes less friction than 5W-30 and 10W-40 oil at both high and low boundary friction conditions. Results are expected to hold true for engines with similar friction-relevant designs.

Keywords: Conventional and synthetic base oil; MoDTC and organic friction modifier additives; Viscosity grade; Engine friction

1. Introduction and literature review

Friction in internal combustion (IC) engines continues to receive substantial interest because despite significant improvements in engine design and oil formulation, mechanical friction continues to cause considerable fuel economy, performance and emissions degradation. For example, when the passenger car gasoline engine used in this study is operated a typical drive-cycle operating point of 2000 rpm and 2 bar brake mean effective pressure (BMEP) with manufacturer-recommended oil, 24% of indicated work (i.e., work performed on the pistons) is lost to mechanical friction. An engine friction reduction of 10%, if applied to all US passenger cars, would result in a fuel savings of 3.4 billion gallons in 2007.

This study investigates how three aspects of oil formulation—base oil, friction modifiers (FMs) and viscosity grade—affect friction in a production engine. Friction-relevant design details of the engine are provided, which is necessary to put the results into context and to allow the data to be used for engine friction modeling efforts [1]. Great care is taken to obtain repeatable engine friction measurements and the procedures used to obtain friction data are carefully described. An error analysis is also included. A detailed tribology analysis and engine durability, however, are not within the scope of this study.

1.1. Effect of base oil

The performance of engine oil is largely determined by the base oil used in its formulation. In the United States, the American Petroleum Institute (API) uses composition and properties to categorize base oils into five groups [2]. Since 1999, Group III, IV and V oils may be marketed as synthetic oils while Group I and II oils are considered conventional oils [3,4]; this study uses the same convention.

Kratzer et al. [5] and Miller et al. [6] are among the first to publish studies on synthetic oils produced on a commercial scale for passenger car engines. Although numerous advantages are discussed, engine friction is not addressed by these studies. Friction is addressed in later studies by Hetrick et al. [7], Barton et al. [8], Benda et al. [9] and Kelly et al. [10]; but for every study, the synthetic and conventional oils had different viscosity grades, making it impossible to differentiate base oil and viscosity effects.

*Corresponding author. Tel.: +1 734 936 0431; fax: +1 734 764 4256.
E-mail address: sbohac@umich.edu (S.V. Bohac).

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doi:10.1016/j.triboint.2007.12.001

These and other studies have clearly and independently demonstrated several advantages of synthetic oils. However, the claim of reduced friction and improved fuel economy, often cited in recent literature, is imprecise and unsubstantiated because comparisons are between synthetic oil with lower viscosity and conventional oil with higher viscosity. This comparison does not identify whether the improved fuel economy arises from lower viscosity or from improved lubricating properties of synthetic oil, i.e., base oil formulation and viscosity are confounded in the experiments. To answer the question of whether synthetic oil, by itself, reduces engine friction, this study examines the effect of base oil on engine friction using oils of the same viscosity grade.

1.2. Effect of friction modifier

Friction modifiers are additives designed to reduce boundary friction. Molybdenum dithiocarbamate (MoDTC) is a commonly used organometallic FM that works by bonding flakes of molybdenum disulfate (MoS_2) onto surface asperities, thereby reducing boundary friction. Stearic acid ($C_{18}H_{36}O_2$) is an example of an organic (ashless) FM. Organic FMs are believed to work by weakly bonding themselves to metal surfaces, thereby forming a lubricating surface film.

Black et al. [11] illustrate the benefits molybdenum FM on cam-follower wear but do not address friction. Grene and Risdon [12] report that molybdenum FM improves gasoline engine fuel economy by 3–5%, but engine design details are not given and the test engines were only tested at full load where boundary friction is maximized. More recently, Tseregounis and McMillan [13], Tseregounis et al. [14] and Hoshino et al. [15] measured fuel economy improvement (FEI) of molybdenum and organic FM on gasoline engines with different design details and under different operating conditions and found FEI to be in the range of 1–3%. Some information on engine design is provided by these authors, but results are only given in terms of FEI and not engine friction mean effective pressure (FMEP). FEI is important for the end user but typically provides less insight into the nature of engine friction because it effectively guarantees the conclusion that a larger FEI improvement occurs at low load conditions, simply because friction accounts for a larger relative loss at low loads. Noorman et al. [16] evaluated an FM of unspecified composition on gasoline engine friction at different speeds and loads and measured an FMEP reduction of 6–11%. This study is unique in that FMEP data are provided, not just FEI. Benvenutti et al. [17] ran a gasoline engine through different test cycles using 20W-50 oil without molybdenum FM and 10W-30 oil with molybdenum FM. Fuel economy was better for the 10W-30 oil with molybdenum FM, but since both oil viscosity and FM were changed, it is impossible to determine how much of the improvement was caused by the FM.

Since FM reduces boundary friction and the ratio of boundary friction to hydrodynamic friction varies with engine operating condition and engine design, the benefits of FM depend on engine operating condition and engine design. High load, high temperature, low speed operating conditions tend to increase boundary friction. Sliding contact valve trains, high-tension piston rings and substandard lubrication systems are design features that also increase boundary friction. Only a few published studies, however, address these variables. In this study, friction-relevant engine details are carefully described and the effects of the FM on friction are evaluated at two operating conditions—one with a higher level of boundary friction and the other with a lower level of boundary friction.

1.3. Effect of viscosity grade

Viscosity is a fundamental property of engine oil. If the oil is too thin (i.e., low viscosity), oil film thickness between components is reduced enough to cause asperity contact, resulting in mixed or boundary friction. If the oil is too thick (i.e., high viscosity), hydrodynamic friction coefficient is unnecessarily increased; thick oil also takes longer to pump through the engine following a startup, causing more boundary friction and wear. Optimum viscosity depends on engine design. Engines with minimal boundary friction benefit from relatively thinner oils because lower viscosity reduces the hydrodynamic friction coefficient. These engines are often called "low friction engines" and usually employ roller follower valve trains, carefully designed piston ring/wall characteristics and lubrication systems. Engines with more boundary friction benefit from relatively thicker oils because the reduction in boundary friction more than offsets the increase in hydrodynamic friction coefficient. These engines often utilize sliding contact valve trains and have piston ring/wall characteristics that allow more asperity contact. Optimum viscosity also depends on how the engine is operated. Engines operating under low speed, high load or in hot climates typically require thicker oil.

Benvenutti et al. [17] ran a gasoline engine using 20W-50 oil without molybdenum FM and 10W-30 oil with molybdenum FM. Fuel economy was better with the 10W-30 oil with molybdenum FM, but since both oil viscosity and FM were changed, it is impossible to determine if the improvement resulted from lower viscosity. Hoshino et al. [15] tested a gasoline engine and found that fuel economy was maximized with 5W-20 oil and deteriorated with higher or lower viscosity. The effect of operating condition was not investigated. Tseregounis and McMillan [13] found that switching from 20W-50 to 5W-20 oil improved gasoline engine fuel economy by 4%. They also did not determine how operating condition affects fuel economy. Tseregounis et al. [14] tested oils ranging in viscosity from 0W-10 to 10W-40 in four gasoline engines with different design details. This is a rare study that