Paper Number

Contribution of Oil Traction to Diesel Engine Cam Galling

Mandeep Saini and Frances E. Lockwood
The Valvoline Company

Jerry C. Wang and Carl F. Musolff
Cummins, Inc.

ABSTRACT

Heavy Duty diesel engines typically use roller followers in contact with the cam to reduce friction and accommodate high Hertzian stresses. When the rolling contact slips into sliding, cam galling can occur that may lead to major cam failures. Oil traction has been identified as a possible source to cause slipping. In this study, oil traction was first measured in a Mini Traction Machine (MTM). The results were then validated by a series of engine tests to show that the measured oil traction correlated with the occurrence of cam galling. Finally, the MTM was used to evaluate various engine oil formulations. It is concluded that some advanced base oils, if not properly compensated by the additive package, exhibit dangerously low oil traction. Oil traction needs to be part of the oil formulation considerations.

INTRODUCTION

Heavy-duty diesel engines use camshaft rotation to control the timing of valve and injector events. Figure 1 shows a typical valve train assembly in relation to the camshaft. As the cam rotates, the interfacial friction causes the cam follower roller to rotate while lifting the push tubes to activate the valve or the injector. The profile of the lobe dictates the timing of such events[1].

The friction between the cam lobe and the follower comes from the normal loading due to the combined cylinder pressure and the valve spring force. A rolling contact is necessary to minimize friction and sustain the high Hertzian stresses in modern engines. However, the normal load varies rapidly from maximum to almost no load as the camshaft rotates through the tip of the profile under high speed. Under certain conditions of rapidly changing loads and high temperature, sliding can occur in the rolling contact. The design of the lobe profile requires the cam and the followers to sustain repeated high loading while minimizing slipping for the longevity of the system[2].

Many other factors can contribute to the slipping at the camshaft- follower interface. For example, the corrosion of the bronze pin may increase the friction of the pin-follower interface to cause the roller to "stick"[3]. The focus of this paper is to study if the lubricating oil can affect the contact friction to cause slipping.

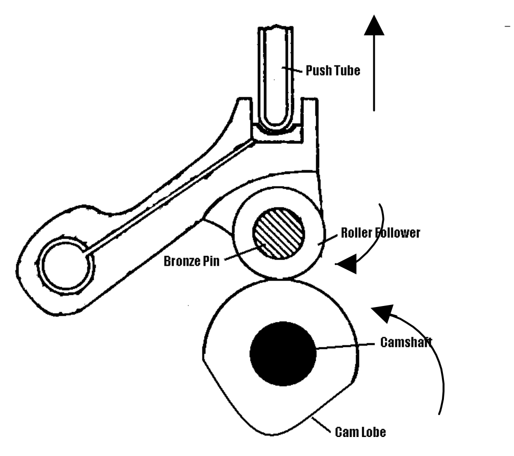
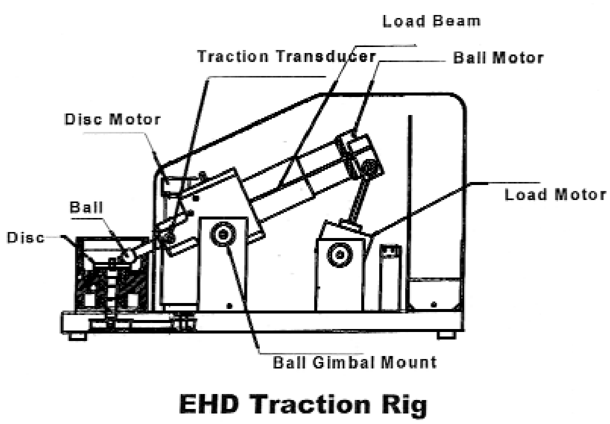


Figure 1 A typical setup of the camshaft and the valve train assembly. The arrows indicate the direction of motion.

EXPERIMENTAL DESIGN

Oil Traction Measurement – The cam and roller follower contact is designed to operate under elasto-hydrodynamic condition if a pure rolling contact is realized. The friction of the lubricated contact is the driving force for roller rotation. The oil traction is assumed to be related to the friction measured when a cam-and-follower contact is lubricated by the oil. However, it is very difficult to measure an actual contact reliably. In order to provide a consistent measurement of the traction coefficient, and to make the measurement easily applicable to future studies, a Mini Traction

Machine (MTM)[4] is selected to simulate such a contact and provide traction coefficient measurement. The test contact is formed between a polished ¾ inch ball and a 46-mm diameter disc, each independently driven to produce a sliding/rolling contact. To perform a test, a small sample of fluid is placed in the test reservoir and the system steps through a series of loads, speeds, slide/roll ratios and temperatures following a custom program predefined by the operator.



A Sliding to Rolling Ratio (SRR) of 50% is selected as a standard slipping condition. The oil temperature is set at 120^0C, and the contact pressure is 1.1 GPa. The friction is measured from 0 to 2000 cm/s with the same SRR, load, and temperature.

Engine Test Condition – Galling is defined as material transfer as a result of two surfaces coming into direct contact after penetrating through the lubricating film. Typically, the roller material transfers to the cam surface. Once the surfaces encounter galling, the load carrying capacity of the system is greatly reduced. The breakdown progresses to spalling caused by high contact fatigue stress. Continued running eventually causes the lobe to disintegrate, with accompanying engine malfunction. Early stage galling can be visually distinguished with a trained eye. This is normally confirmed later under an electronic microscope. A typical galling phenomenon is shown in Figure 3.

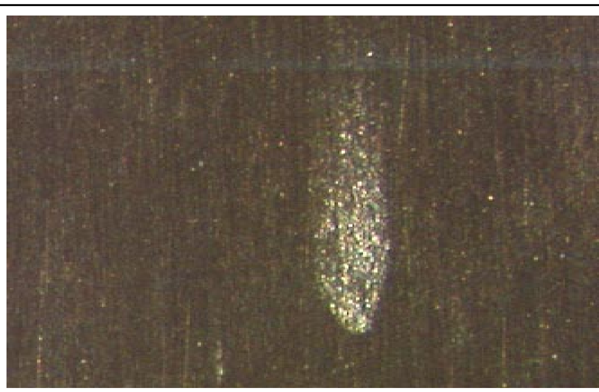


Figure 3 A galled cam lobe

Cummins has developed a cam galling test to create a visually verifiable galling situation with an N14 STC heavy duty diesel engine in a relatively short period of time. This is accomplished by subjecting the engine to repeated fast acceleration and deceleration under high loads. The operating condition is illustrated in Figure 4. A visual inspection of the cam is performed every 50 hours without removing the cam from the engine. If there is no galling, the test resumes for another 50 hours. The test continues until the verifiable galling, sometimes on multiple lobes, occurs. To further accelerate the test, the surface finish, surface profiling, and follower pin material are selected to give the most severe combination based on past design experiences. Under this situation, a gall on the injector lobe is usually produced after 250-500 hours of testing if a commercial heavy-duty diesel engine lubricant (HDEO) is used. Note that production cams and cam followers will not fail in 500 hours of testing. The test is designed as a flush and run test. That is, after each 50 hours of operation, only the cam and cam followers are replaced, if necessary. There is no rebuild of the engine until a whole sequence of tests has been completed.

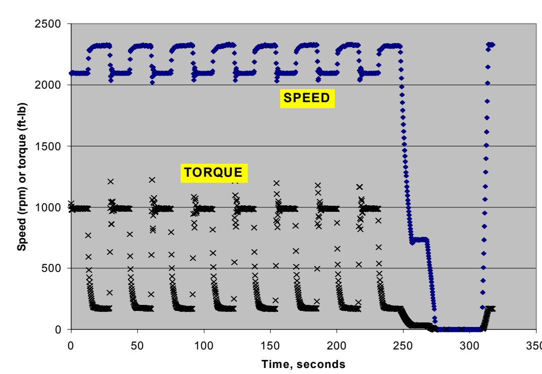


Figure 4 The N14 5-minute-15-second cam test cycle

Test Oil Selection – A series of oils with different base oils and viscosity grades have been selected for this study. The HDEO is used as the baseline case, and all other test oils have the same additive package. Table 1 shows the different test oils. The tests were at a 120^0C, rolling velocity of 2000cm/s and a Hertzian pressure of 1.1 Gpa.

Table 1 Test Oils

Oil Name	**Viscosity Grade**	**Base Oil**	**Trac. Coef. (10%SRR)**
HDEO	15W40	Group II	0.02
HTO	15W40	Group I	0.04
LTO	5W30	Synthetic	0.00625
HTO1	5W30	Synthetic	0.016

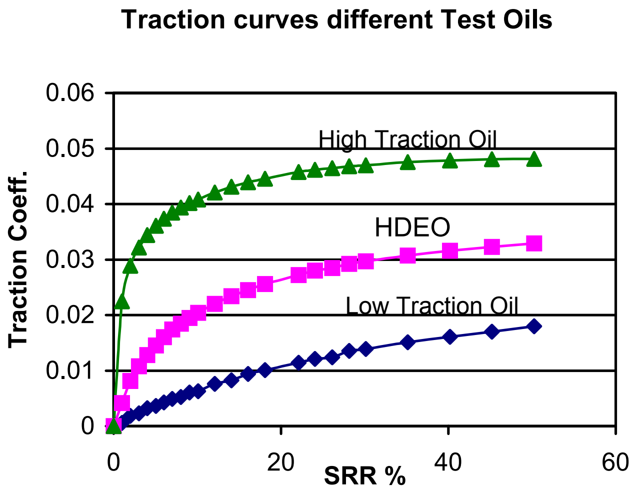


Figure 5 Traction curves for test oils.

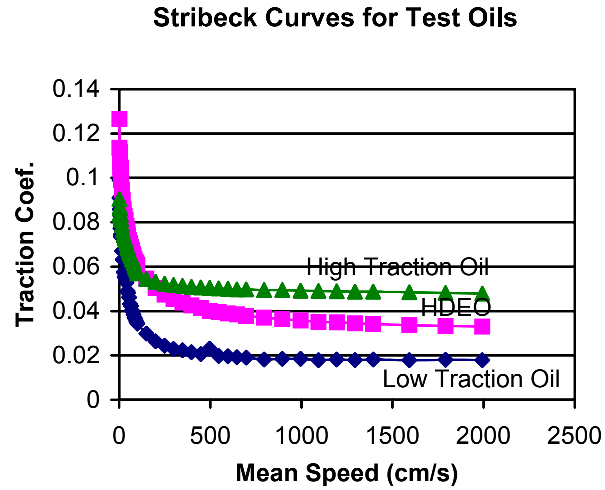


Figure 6 Traction coefficient of LTO and HTO vs. Premium Blue at 50% SRR

RESULTS

The first step of the program is to formulate a Low Traction Oil (LTO). The traction coefficient for the various formulations is measured using the MTM device. By changing the base oils, a High Traction oil (HTO) and a LTO have been formulated to show a 50% increase or decrease in oil traction coefficient relative to the base line HDEO (Figure 6). LTO is then used in engine tests to establish the correlation between the measured traction and the propensity to induce galling in an engine.

Two side-by-side tests have been run at two separate facilities. The test results are summarized in Table 2. Table 2 is structured in the way that the first row indicates the number of the cam used in the engine designated as "engine A". A different number means a new cam has been installed after the inspection. The second row indicates the inspection results of engine A. The same applies to "engine B" in rows 3 and 4.

For "engine A", galling was found at the end of each of the three 50-hour tests in a row. A new cam and cam follower assembly were installed after each inspection. This indicates that the use of LTO has repeatedly caused galling much quicker than the base line oil (250-500 hours). After the third test, production cam and cam follower assembly were installed. The test continued for 600 hours without finding any galling during interim visual inspections. While the production parts tolerated LTO better, 600 hours is not long enough to warrant trouble free operations. To make sure that the test has not drifted mild during the process, a fifth cam (non-production, same as cam #1 to #3) was installed. Galling was observed in 50 hours, showing the stand remains valid.

A similar sequence of testing was done with "engine B" at a different facility to make sure this test is repeatable. Again, three cams failed in sequence during the first 50 hours. They are followed by 600 hours of successful run with the production hardware. After going back to the special test hardware, the second set of cam (#6b) produced gall in 100 hours, thus validated the second test series.

Table 2 N14 LTO cam galling test summary

cam #	1 a*	2 a*	3 a*	4 a	4 a	4 a	4 a	4 a	4 a	4 a	4 a	4 a	4 a	4 a	4 a	5 a*			
test A	X	X	X	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	X			
cam #	1 b*	2 b*	3 b*	4 b	4 b	4 b	4 b	4 b	4 b	4 b	4 b	4 b	4 b	4 b	4 b	5 b*	5 b*	6 b*	6 b*
test B	X	X	X	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	X

"X" indicates galling by visual inspection.
"ok" indicates no galling.
"*" indicates the use of special cams and cam followers to increase test severity. All others are production cams and cam followers.

Based on these two series of engine tests, it is clear that LTO greatly accelerates galling in the N14 cam-galling test. It also establishes the correlation between the measured traction coefficient in MTM with the cam galling phenomena in engines.

The LTO was formulated as a 5W30 with the intention to produce a more severe lubrication condition (thinner oil film). It is desirable to know if the accelerated failure simply results from decreasing the oil viscosity, or if oil traction actually plays a role. A third series of engine tests was performed to evaluate a 5W30 oil with high traction coefficient (HTO1). This engine was installed in yet a third test facility. The first test was performed using LTO to make sure the test stand was set up correctly. A gall was observed in 50 hours. Additional distress (but no additional galls) was observed at 100 hours. A new set of cam and cam follower was installed to run on HTO1. The test was run for 150 hours without verifiable galling (though some surface distress was observed). It is clear at this point that low oil traction contributes to the quick galling in the engine tests.

DISCUSSIONS

There are many factors affecting cam galling. As clearly demonstrated in this study, both hardware designs and lubricant properties contribute to this problem. While engine hardware should be designed to tolerate reasonably low traction oils as demonstrated by the production N14 cam and cam followers, it is possible that future oils may have a traction coefficient lower than what is typical.

Traction coefficient is a measure of the viscous dissipation or friction losses occurring in the EHD lubrication regime. For a given system, two factors, fluid viscosity and pressure-viscosity coefficient influence traction coefficient. If frictional heating is negligible, lower traction coefficient translates into lower film thickness which lowers the lambda ratio (ratio of film thickness to surface roughness). Under severe operating conditions of high load and high temperature this increases the chances of solid-solid interaction[5], leading to galling and eventual cam failure.

Additional MTM oil traction measurements were performed on various engine oil formulations to evaluate if realistic engine oil formulations can lead to extremely low oil traction. Figure 7 shows the oil traction of various engine oil base stocks as categorized by API[6]. These oils do not contain any additives. Note that Group III and Group IV base oils exhibit substantially reduced oil traction. The lower traction coefficient of the VHVI and synthetic base-stocks is directly related to their lower pressure-viscosity coefficient[7].

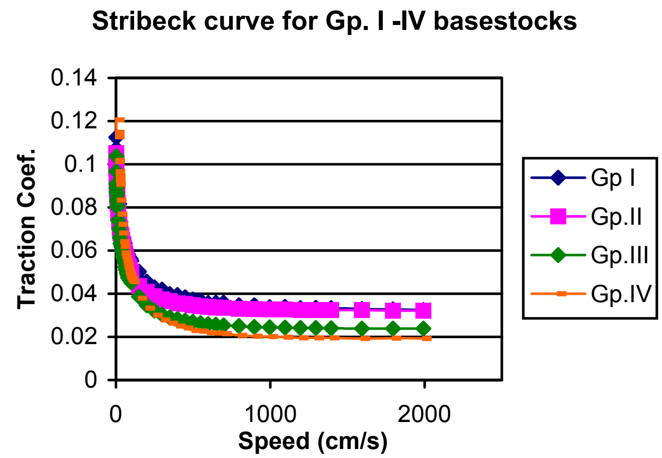
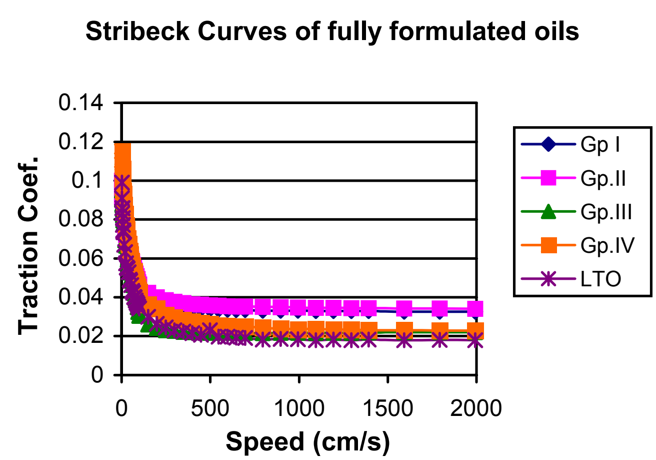


Figure 7 Traction coefficient of various base oils

While Group I and Group II base oils are prevailing in today's commercial market, Group III and Group IV base oils are gaining popularity as the basis for high performance, more expensive, engine oils. These high performance oils may inadvertently cause cam problems due to their very low traction coefficients. The rankings of Group III and Group IV reversed when all base oils are formulated with the same additive package as used in the HDEO (Figure 8). However, both are still very low, at a level similar to LTO.

Figure 8 Traction coefficient of various base oils



formulated with Premium Blue additives

As seen from Figures 7 and 8 the high pressure rheological properties of a fully formulated lubricant closely mirror those of the base-stocks. Therefore in formulating lubricants using VHVI or synthetic base-stocks care must be given to make sure that they provide sufficient film thickness to protect the surfaces under extreme conditions. This is possible as demonstrated by HTO1 in Table 1. HTO1 has the same viscosity as LTO, but shows a traction coefficient similar to the HDEO.

Conclusion

1. The high-pressure rheological properties of VHVI and synthetic base-stocks have to be carefully optimized in a fully formulated lubricant in order to minimize wear as demonstrated in the N14 engine cam wear test.

2. The traction coefficient, as measured by the Mini Traction Machine (MTM), is a meaningful indication of oil traction. The MTM oil traction correlates with the galling events in a designed N14 engine cam wear test.

ACKNOWLEDGMENTS

The authors would like to thank Mr. Andrie Buzinov for conducting the engine tests.

REFERENCES

1. Heywood, J. B., *Internal Combustion Engine Fundamentals*, 2nd ed., p. 220-5 (1993)
2. Ibid, p. 737-9
3. J. C. Wang and C. M. Cusano, “Development of A Bench Test to Detect Oils Corrosive to Engine Components”, SAE Paper 940790
4. PCS Instruments Inc., 5 Warple Mews, Warple Way, London W3 0RF, www.pcs-instruments.com
5. M. Smeeth, P.M. Cann and H.A. Spikes, “Measurements of Elastohydrodynamic Film Formation in Rolling Contacts at very High Pressures.”, Lubricants and Lubrication, D.Dawson et.al.(Editors), Elsevier Science B.V., pp. 497-502, (1995).
6. American Petroleum Institute, *Engine Oil Licensing and Certification System*, API 1509, 14th ed.(1996)
7. Hyun-Soo Hong and Scott Bair, “Film-Forming Tendencies of some Base Fluids and Viscosity Modifiers”, Journal of Synthetic Lubrication, 16-3, pp. 233-245 (1999).