Impact of Lubricants on Engine Friction and Durability

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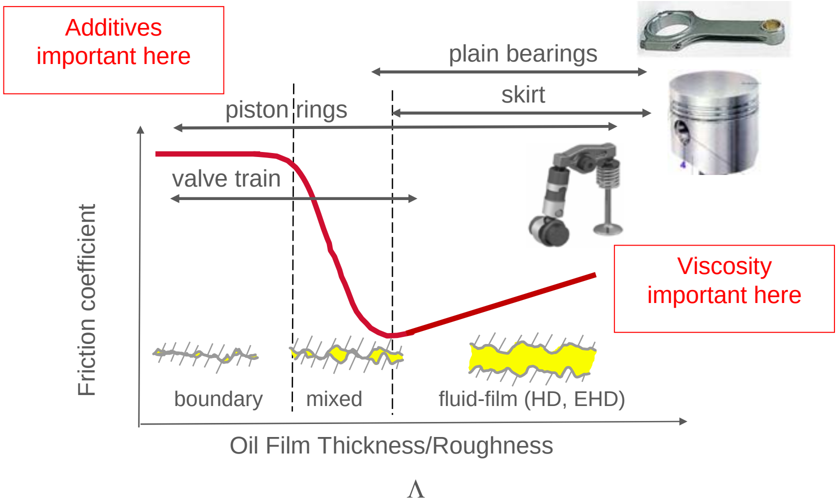
Tribology Days in Trollhättan, 8th-10th November 2011

Outline

- Introduction
- Energy efficiency/CO_2 reductions a key driver
- Impact of engine lubricants on engine friction
- Impact of gearbox/axle lubricants on transmission efficiency
- Typical data of lubricant impact on vehicle fuel consumption
- Impact of energy efficient lubricants on oil film thickness
    - Journal bearings
    - The piston assembly
    - The valve train
    - EHD contacts
- Final examples of lubricant impact on fuel consumption/durability
- Conclusions

Introduction

- The Stribeck curve

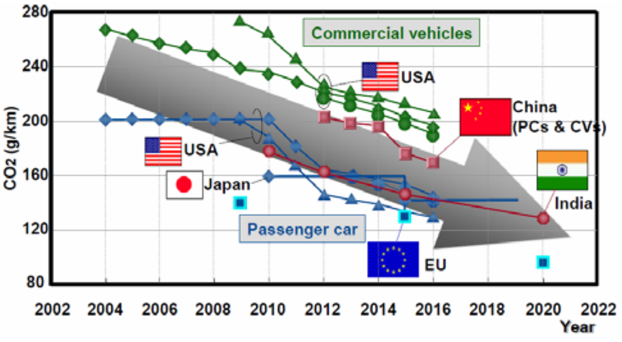


Additives important here

Viscosity important here

Energy Efficiency/CO_2 Reductions – Key Driver

- Many regions of the worldwide imposing fleet average CO_2 emission limits. In 2020, the EU is proposing a limit of 95 gCO_2/km (equivalent to 4.09 litres/100 km* for a gasoline car = 69.1 mpg)



* For gasoline cars, 1 litre/100 km = 23.2 g/km CO_2

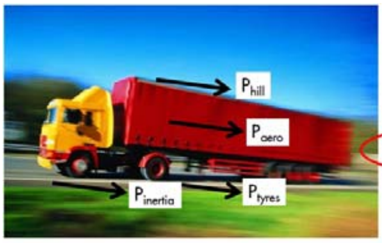
Energy Efficiency/CO$_2$ Reductions – Key Driver

- Typical current CO$_2$ emissions of various vehicles

2012 Target = 130g/Km
2020 target = 95g/km

Energy Efficiency/CO$_2$ Reductions – Key Driver

- Vehicle fuel consumption model
  - Moving to energy efficient lubricants can be a cost effective way of improving vehicle fuel consumption



$$\eta P_{\mathrm{fuel}} = \frac{P_{\mathrm{wheels}}}{\varepsilon} + P_{\mathrm{access}} + P_{\mathrm{friction}}$$

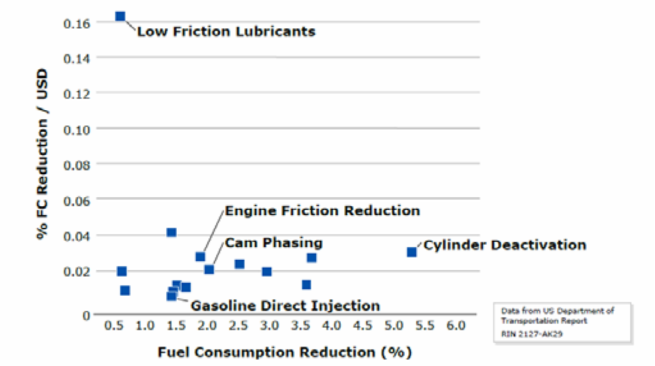
$$P_{\mathrm{wheels}} = \underbrace{C_R M g v}_{P_{\mathrm{tyres}}} + \underbrace{C_D \rho A v^3}_{P_{\mathrm{aero}}} + \underbrace{M a v}_{P_{\mathrm{inertia}}} + \underbrace{M g v \sin\theta}_{P_{\mathrm{hill}}}$$

P$_{friction}$ and ε can be directly affected by the choice of lubricants

P$_{fuel}$ = power required from fuel
P$_{wheels}$ = power required at wheels
P$_{access}$ = power of accessories
P$_{friction}$ = power to overcome engine friction
ε = transmission efficiency
η = engine thermal efficiency (approx 40%)
M = mass of truck
v = speed of truck
A = frontal area of truck
a = acceleration of truck
C$_R$ = coefficient of rolling resistance
C$_D$ = drag coefficient
θ= angle of any hill
ρ = air density

Impact of Engine Lubricants on Engine Friction

- Changing to energy efficient lubricants is a very cost effective way to influence vehicle fuel consumption
- No hardware changes needed on vehicle, can be implemented quickly



From *North American Fuel Economy Testing*, T. Miller, 15th Annual Fuels & Lubes Asia Conference

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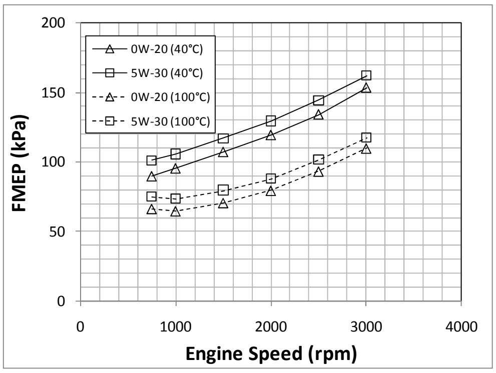
Impact of Engine Lubricants on Engine Friction

- FMEP measurements on motored gasoline engine for two different lubricants (SAE 5W-30 and SAE 0W-20) at 40°C and 100°C
- Clear reduction in engine friction when lubricant viscosity is reduced



	5W-30	0W-20
V_k40 (cSt)	68.85	43.36
V_k100 (cSt)	12.01	8.04

Δ(FMEP) ≈ 40-50 kPa when viscosity changes from 8 to 70 cSt

Impact of Gearbox/Axle Lubricants on Transmission Efficiency

- Shell's heavy duty driveline test rig in Hamburg can be used to independently measure energy losses from the engine, gearbox and axle of a heavy duty truck

Impact of Gearbox/Axle Lubricants on Transmission Efficiency

- The oils below were tested in an OM460LA diesel engine, a manual 16 speed ZF Astronic gearbox and a Mercedes Benz HL8 axle

"Mainstream" oils

	Engine Oil	Gear Oil	Axle Oil
CCS (mPa.s)	6,600 at -20°C	82,284 at -30°C	702,560 at -30°C
V_k40 (cSt)	105.1	66	145
V_k100 (cSt)	14.3	9.2	14.3
HTHS (mPa.s)	4.06	N/A	N/A

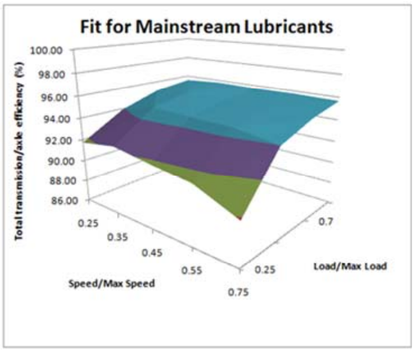
"Top tier" oils

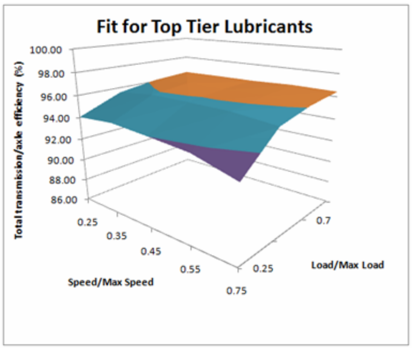
	Engine Oil	Gear Oil	Axle Oil
CCS (mPa.s)	5,638 at -30°C	36,500 at -40°C	13,500 at -40°C
V_k40 (cSt)	66.9	56	115
V_k100 (cSt)	12.13	9.1	15.2
HTHS (mPa.s)	3.37	N/A	N/A

References: "The Effect of Engine, Axle, and Transmission Lubricants on Heavy Duty Diesel Fuel Economy: Parts 1 and 2" (JSAE 20119224, JSAE 20119236) (Papers presented at SAE International Conference, Kyoto, Japan, Sept 2011)

Impact of Gearbox/Axle Lubricants on Transmission Efficiency

- Efficiency data for the oils summarised below



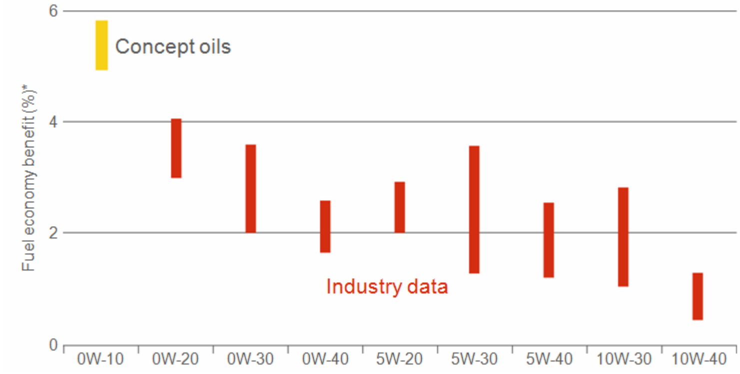


Clear, statistically significant,
improvement in driveline efficiency
seen for top tier lubricants

Ref: JSAE 20119236

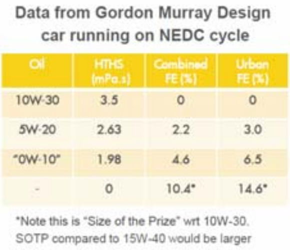
Impact of Lubricants on Fuel Consumption

- Graph below shows fuel consumption benefit (relative to a reference SAE 15W-40 lubricant) in an industry standard M111 engine test, which runs on the New European Driving Cycle – some portions of the test are run at low temperatures (20 and 33°C)



Impact of Lubricants on Fuel Consumption

- Recent work with “experimental” T.25 city car from Gordon Murray Design
- T.25 car is a 650 kg small car (3 seater) equipped with a 3 cylinder Mitsubishi 0.67 litre gasoline engine
- A Shell experimental “0W-10” oil gave combined FE benefit of 4.6% in European driving cycle (compared to an SAE 10W-30 engine oil)



Data from Gordon Murray Design car running on NEDC cycle

Oil	HTHS (mPa.s)	Combined FE (%)	Urban FE (%)
10W-30	3.5	0	0
5W-20	2.63	2.2	3.0
“0W-10”	1.98	4.6	6.5
-	0	10.4*	14.6*

*Note this is “Size of the Prize” wrt 10W-30. SOTP compared to 15W-40 would be larger

WINNING ROAD TRIALS

The T.25 won both its categories at the Royal Automobile Club’s inaugural Brighton to London Future Car Challenge. The petrol-powered T.25, on its first public outing, won awards as the most economic and environmentally friendly, small, passenger internal-combustion engine vehicle.

The lightweight T.25 achieved **96 mpg** (**2.9 L per 100 km**), despite not yet being fully optimised for fuel efficiency, and beat eight diesel-engine entrants. Using a sample of 16 small passenger cars, GMD calculates an average efficiency increase of 27% for a diesel model. Therefore, had the car been powered by a diesel engine, it could have recorded a staggering 131 mpg (2.2 L per 100 km).

96 mpg = 2.9 litres/100 km = 67.3 gCO_2/km

Impact of Lubricants on Fuel Consumption

- Data from heavy duty diesel truck field trials- 18 tonne Mercedes Benz Atego trucks used: Overall, 1.79% benefit seen at 99% confidence interval

Route Section	Road/Driving Type	Distance	Time - approximate
A to B	Motorway	16 Km	23 min
B to C	City	10 Km	16 min
C to D	Motorway	3.5 Km	3 min
D to E	3% gradient Hill Climb	1.8 Km	3 min
E to F	Motorway	4.1 Km	3.5 min
F to G	Highway	2.2 Km	2.5 min
G to H	Motorway	13.5 Km	9.5 min
H to I	Highway	8.5 Km	8 min
I to J	4% gradient Hill Climb	2.7 Km	2.5 min
J to K	Highway	21.2 Km	20.5 min
K to L	Motorway	19.5 Km	19 min
A to L (total)	Overall	96 Km	110.5 min

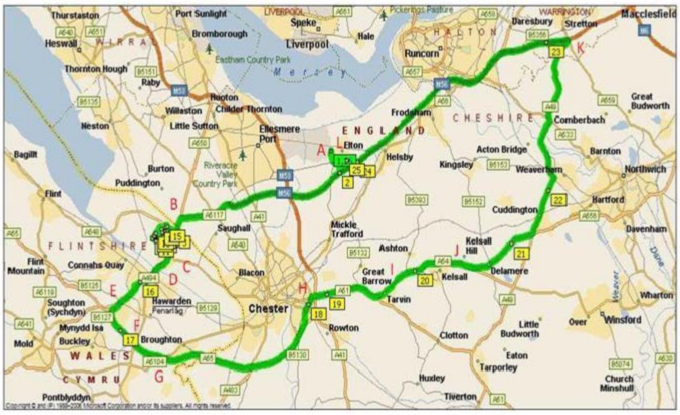
Mercedes Atego trucks
18000 kg

Road/Driving Type	Distance	Time - approximate
Overall	96 Km	110.5 min
Motorway	56.6 Km	58 min
Highway	31.9 Km	31 min
City	10 Km	16 min
Hill	4.5 Km	5.5 min

Ref: JSAE 20119224

Impact of Lubricants on Fuel Consumption

- Data from heavy duty diesel truck field trials- 18 tonne Mercedes Benz Atego trucks used: Overall, 1.79% benefit seen at 99% confidence interval



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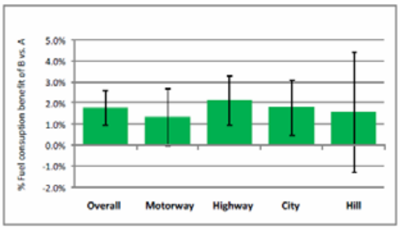
Ref: JSAE 20119224

Impact of Lubricants on Fuel Consumption

- Data from heavy duty diesel truck field trials- 18 tonne Mercedes Benz Atego trucks used: Overall, 1.79% benefit seen at 99% confidence interval

Road Type	FC for Lubes set A (L/100km)	FC for Lubes set B (L/100 km)	Benefit of Lubricants B vs. A		Statistical Data	
			L/100 km	%age	±95% Confidence of Benefit	Actual Sig.
Overall	26.77	26.30	0.47	1.79	0.82%	99%
Highway	23.40	23.09	0.31	1.33	1.35%	95%
A Road	24.58	24.06	0.52	2.13	1.17%	99%
City	32.80	32.21	0.59	1.80	1.33%	98%
Hill	60.87	59.89	0.98	1.61	2.87%	75%



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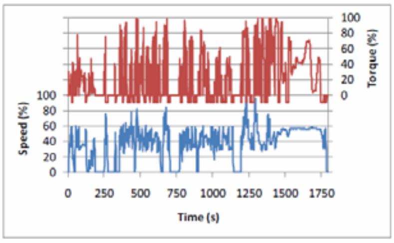
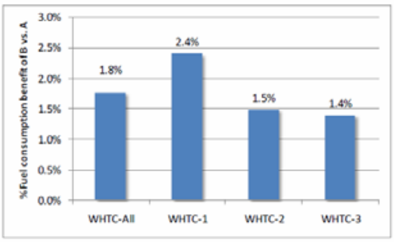
Ref: JSAE 20119224

Impact of Lubricants on Fuel Consumption

- Data from heavy duty driveline rig in Hamburg
- WHTC data: 1.8% overall benefit averaged over three WHTC cycles (with benefit of 2.4% for first (cold) WHTC cycle
- WHSC data: 1.1% overall improvement (at 99% confidence level) with max benefit of 3.1% at 25% load/75% speed condition

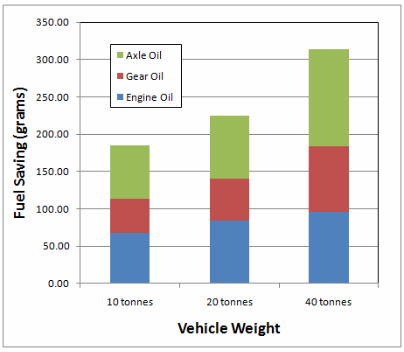


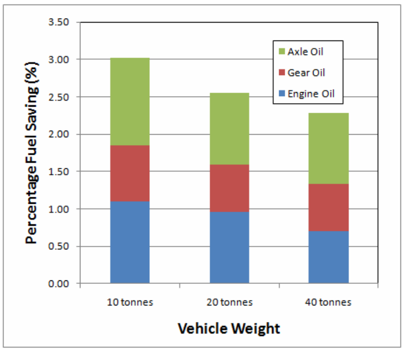


Ref: JSAE 20119224

Impact of Lubricants on Fuel Consumption

- Vehicle fuel consumption model predicted that a large portion of the fuel savings in the heavy duty diesel truck tests came from the gearbox and axle
- These predictions were carried out for the European Transient driving cycle





Ref: JSAE 20119236

Impact of Lubricants on Fuel Consumption

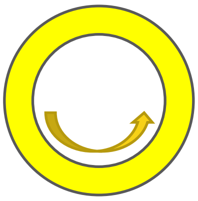
- There is a wealth of data to support the view that lower viscosity, friction modified lubricants help to improve a vehicle's fuel economy
- In terms of the Stribeck curve, this is because the oil film thickness separating the moving surfaces is getting smaller*

- What is the trade-off between lower friction and oil film thickness ?

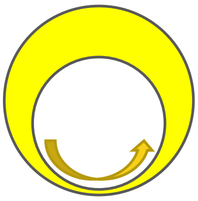
*Ref: D. Dowson, "Developments in Lubrication - The Thinning Film", J.Phys.D., 1992

Impact of Lubricants on Oil Film Thickness

- Journal Bearings



Low Load



High Load

Radius = R (m)
Width = L (m)
Angular speed = ω (rad/s)
Viscosity = η (Pa.s)
Radial clearance = c (m)
Load = W (N)
P = friction power loss (W)

Ref: R.I. Taylor, SAE 2002-01-3355

$$\boxed{h_{\min} \approx c}$$

$$\boxed{P = \frac{2\pi\eta\omega^2 LR^3}{c}}$$

$$\boxed{h_{\min} \approx \sqrt{\frac{\eta\omega RL^3}{4W}}}$$

$$\boxed{P = \frac{2\pi\eta^{0.75}\omega^{1.75}L^{0.25}R^{2.75}W^{0.25}}{c^{0.5}}}$$

Hydrodynamic lubrication: A lower viscosity oil would give lower friction

Impact of Lubricants on Oil Film Thickness

- Journal Bearings – more complex model that includes “squeeze” effects and lubricant shear thinning (but which still assumes “short” bearing)

$$\frac{\partial}{\partial y}\left(\frac{h^3}{\eta}\frac{\partial P}{\partial y}\right) \approx 6U\frac{\partial h}{\partial x} + 12\frac{\partial h}{\partial t}$$

$$h(x) = c(1+\varepsilon.\cos(x/R))$$

$$P(x,y) = \frac{6\eta}{h^3}\left(\frac{Uc\varepsilon}{2R}\sin\theta - c\frac{\partial\varepsilon}{\partial t}\cos\theta\right)\left(\frac{L^2}{4} - y^2\right)$$

$$W_1 = \frac{\eta L^3}{2c^2}\int_0^{\pi}\left(\frac{U\varepsilon.\sin\theta}{(1+\varepsilon.\cos\theta)^3} - \frac{2.\frac{\partial\varepsilon}{\partial t}.R.\cos\theta}{(1+\varepsilon.\cos\theta)^3}\right)\cos\theta.d\theta$$

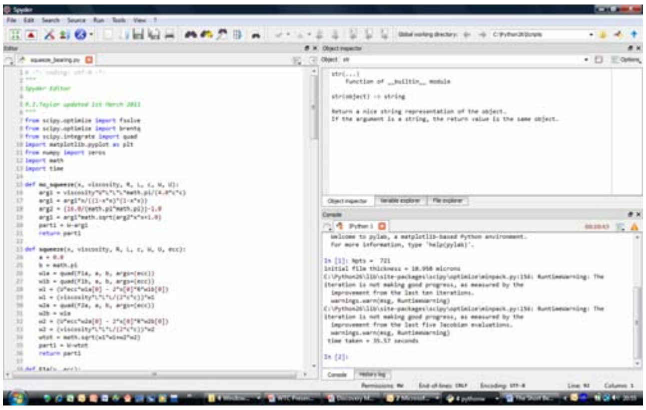
$$W_2 = \frac{\eta L^3}{2c^2}\int_0^{\pi}\left(\frac{U\varepsilon.\sin\theta}{(1+\varepsilon.\cos\theta)^3} - \frac{2.\frac{\partial\varepsilon}{\partial t}.R.\cos\theta}{(1+\varepsilon.\cos\theta)^3}\right)\sin\theta.d\theta$$

$$W = \sqrt{W_1^2 + W_2^2}$$

- Above equations are solved by guessing an initial value for ε and then solving for $\partial\varepsilon/\partial t$. The next value of ε is then: $\varepsilon_{i+1} = \varepsilon_i + (\partial\varepsilon/\partial t).\Delta t$
- This process is repeated for two load cycles to ensure convergence

Impact of Lubricants on Oil Film Thickness

- Journal Bearings – more complex model that includes “squeeze” effects and lubricant shear thinning
- Python(x,y) code for journal bearing only 150 lines of code



```
# -*- coding: utf-8 -*-
"""
Spyder Editor

R.I.Taylor updated 1st March 2011
"""
from scipy.optimize import fsolve
from scipy.optimize import brentq
from scipy.integrate import quad
import matplotlib.pyplot as plt
from numpy import zeros
import math
import time

def no_squeeze(x, viscosity, R, L, c, W, U):
    arg1 = viscosity*U*L*L*L*math.pi/(4.0*c*c)
    arg1 = arg1*x/((1-x*x)*(1-x*x))
    arg2 = (16.0/(math.pi*math.pi))-1.0
    arg1 = arg1*math.sqrt(arg2*x*x+1.0)
    part1 = W-arg1
    return part1

def squeeze(x, viscosity, R, L, c, W, U, ecc):
    a = 0.0
    b = math.pi
    w1a = quad(F1a, a, b, args=(ecc))
    w1b = quad(F1b, a, b, args=(ecc))
    w1 = (U*ecc*w1a[0] - 2*x[0]*R*w1b[0])
    w1 = (viscosity*L*L*L/(2*c*c))*w1
    w2a = quad(F2a, a, b, args=(ecc))
    w2b = w1a
    w2 = (U*ecc*w2a[0] - 2*x[0]*R*w2b[0])
    w2 = (viscosity*L*L*L/(2*c*c))*w2
    wtot = math.sqrt(w1*w1+w2*w2)
    part1 = W-wtot
    return part1

def F1a(x, ecc):
```

```
str(...)
    Function of __builtin__ module

str(object) -> string

Return a nice string representation of the object.
If the argument is a string, the return value is the same object.
```

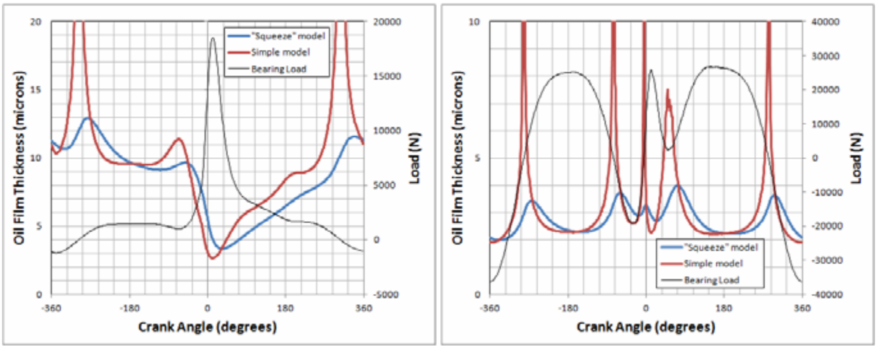
```
 Welcome to pylab, a matplotlib-based Python environment.
 For more information, type 'help(pylab)'.

In [1]: Npts =  721
Initial film thickness = 10.958 microns
C:\Python26\lib\site-packages\scipy\optimize\minpack.py:156: RuntimeWarning: The
iteration is not making good progress, as measured by the
 improvement from the last ten iterations.
 warnings.warn(msg, RuntimeWarning)
C:\Python26\lib\site-packages\scipy\optimize\minpack.py:156: RuntimeWarning: The
iteration is not making good progress, as measured by the
 improvement from the last five Jacobian evaluations.
 warnings.warn(msg, RuntimeWarning)
 time taken = 35.57 seconds

In [2]:
```

Impact of Lubricants on Oil Film Thickness

- Journal Bearings – more complex model that includes “squeeze” effects and lubricant shear thinning
- Comparison of oil film thicknesses calculated with more complex model and with simple model for two different loads



R = 25 mm, L = 20 mm, c = 30 µm, η = 10 mPa.s, ω = 2500 rpm

Impact of Lubricants on Oil Film Thickness

- Piston Assembly

- Lubricant viscosity = η
- Linear speed at any particular crank angle = U
- Load on back of piston ring = W

- Minimum oil film thickness = h_{min}
- Friction power loss = P (Watts)

$$h_{min} \propto \sqrt{\frac{\eta U}{W}}$$

$$P \propto \sqrt{\eta U^3 W}$$

Ref: Furuhama et al, JSAE Review, November 1984

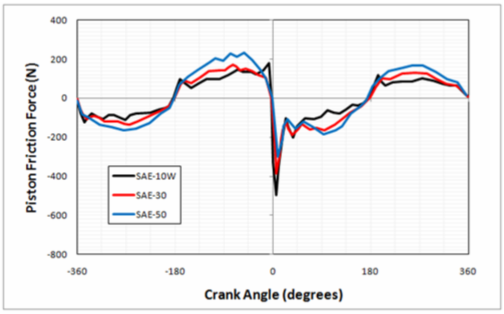
Hydrodynamic lubrication: A lower viscosity oil would give lower friction

Impact of Lubricant on Oil Film Thickness

- Piston assembly: Direct “floating liner” friction measurements show that around TDC firing oil film thickness is small enough for mixed/boundary lubrication to occur

$\text{FMEP} \propto \eta^{0.4}$

	FMEP (kPa)	Peak Force (N)
SAE-10W	37.9	490
SAE-30	51.0	380
SAE-50	64.5	300

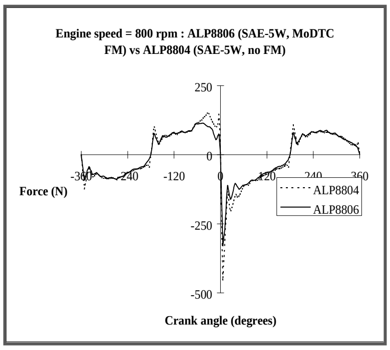


Predominantly hydrodynamic lubrication: A lower viscosity oil gives lower FMEP but more boundary friction at TDC firing

Ref: R.I. Taylor et al, International Tribology Conference, Yokohama, 1995

Impact of Lubricant on Oil Film Thickness

- Piston assembly: Friction modifiers in the lubricant can also influence piston assembly friction. Floating liner rig data below shows measured piston assembly friction for an SAE 5W oil at 800 rpm
- Largest impact of FMs around TDC firing position

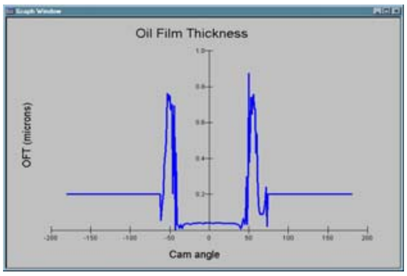


	P_f (kPa)	F_m (N)
SAE-5W : No FM	40.2	456
SAE-5W : Ester FM	39.7	422
SAE-5W : Amide FM	39.4	398
SAE-5W : Ester+Amide FM	38.2	364
SAE-5W : MoDTC FM	37.7	330

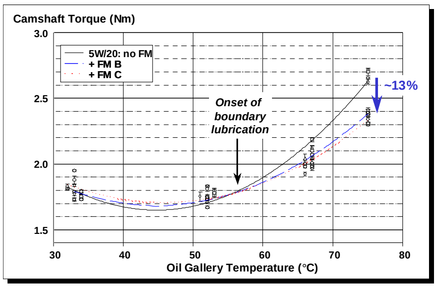
800 rpm, ¼ load, thin oil (5W)

Impact of Lubricant on Oil Film Thickness

- The Valve Train: Results below show friction torque measurements made by Shell on an M111 cylinder head rig
- Friction primarily determined by additives



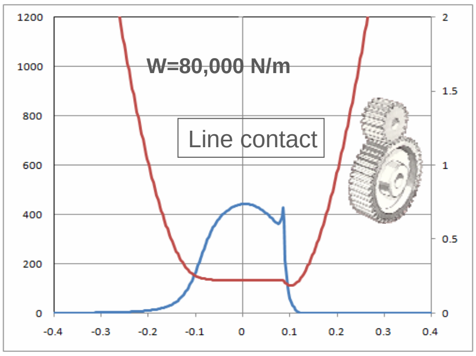
Predicted oil film thickness, Euro 2.0 litre engine, direct acting bucket tappet



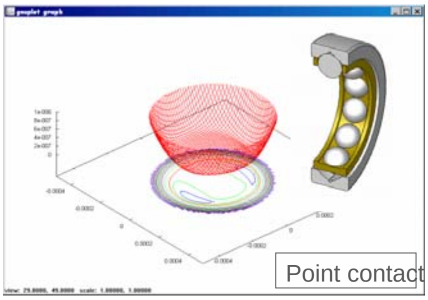
BOUNDARY LUBRICATION

Impact of Lubricants on Oil Film Thickness

- Elastohydrodynamic contacts (rolling element bearings, gears, …)
  - Under high pressures (> 200 MPa), even metal surfaces deform elastically, and the effect of pressure on lubricant viscosity becomes important
  - Lubricants with low pressure-viscosity coefficients (α value) such as PAO and Group III base oils will give lower oil film thicknesses



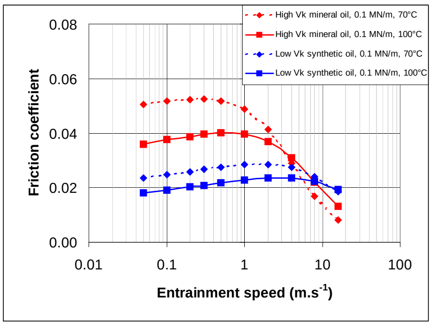
Line contact



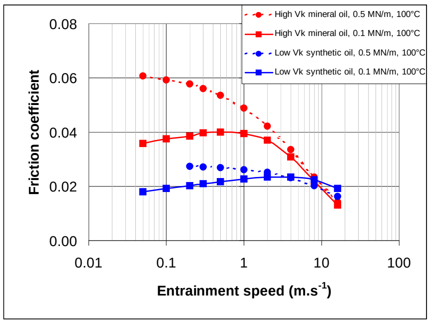
Point contact

Impact of Lubricants on Oil Film Thickness

- Elastohydrodynamic contacts (rolling element bearings, gears, …)
  - Predicted friction coefficient values shown below (from an EHD model which includes realistic lubricant rheology and thermal effects)
  - Results suggest synthetic based lubricants should give lower friction



Effect of temperature

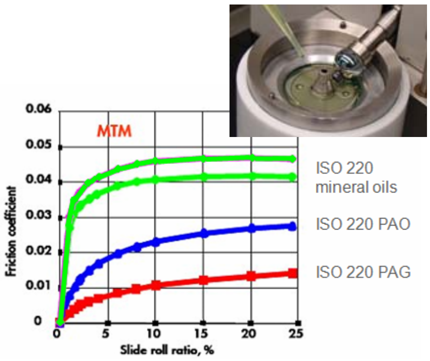


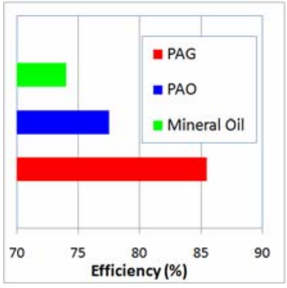
Effect of load

Ref: G.W. Roper et al, STLE Meeting Calgary, 2006

Impact of Lubricants on Oil Film Thickness

- Elastohydrodynamic contacts (rolling element bearings, gears, …)
  - Figures below show measured friction coefficient versus amount of sliding (%) from a PCS Instruments Mini-Traction Machine
  - These measured friction data correlate with worm gear efficiency (lower friction lubricants result in higher worm gear efficiency)

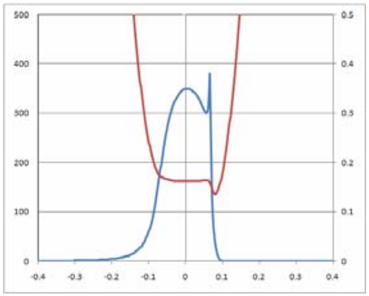




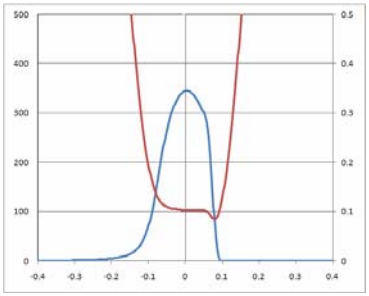
Radicon worm gear efficiency test at 100ºC

Impact of Lubricants on Oil Film Thickness

- Elastohydrodynamic contacts (rolling element bearings, gears, …)
  - Graphs below show effect of α on oil film thickness (red line) and pressure (blue line)
  - In this case, isothermal EHD line contact model used



α = 23.7 GPa^{-1}



α = 10.0 GPa^{-1}

Load/length = 5 x 10^4 N/m, Reduced radius = 0.0125 m, Entraining speed = 2 m/s, Reduced elastic modulus = 2 x 10^{11} Pa, Viscosity = 10 mPa.s

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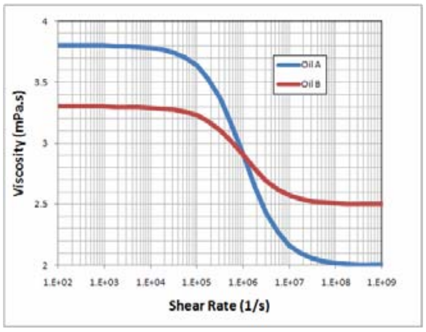
Key Lubricant Properties

- Key physical properties of an engine lubricant are:
  - Low pressure dynamic viscosity (at temperature of interest)
  - Kinematic viscosity of oils at 40°C and 100°C
  - High temperature high shear (HTHS) viscosity of lubricant
  - Cold Cranking Simulator (CCS) viscosity – a high shear measurement made at low temperatures (usually less than -25°C)
  - Pressure-viscosity coefficient of oil (in GPa^{-1}) - α
  - Viscosity Index (VI) of oil

Key Lubricant Properties – Example #1

- On basis of low shear viscosity – would expect Oil B to have better fuel economy
- On basis of HTHS we would expect oils to perform the same
- On basis of fully sheared viscosity would expect Oil A to be better
- In practice we would normally see better fuel economy from Oil A

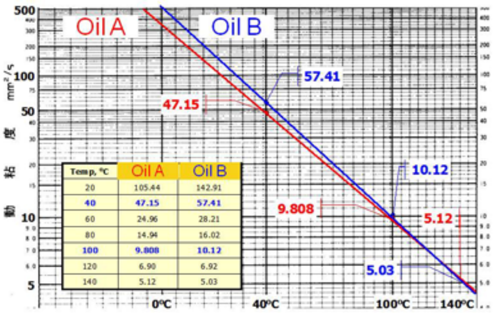


Key Lubricant Properties – Example #2

- High VI oils
  - At low temperatures, the high VI oil (Oil A) will give better fuel economy than Oil B. However above 140°C Oil A will give a higher oil film thickness than Oil B – therefore Oil A can give good fuel economy under most normal driving conditions, whilst giving higher oil film thickness under “extreme” conditions

Oil A: VI = 200

Oil B: VI = 165



Temp, °C	Oil A	Oil B
20	105.44	142.91
40	47.15	57.41
60	24.96	28.21
80	14.94	16.02
100	9.808	10.12
120	6.90	6.92
140	5.12	5.03

Conclusions

- Overview given of:
- Key drivers: Energy efficiency, CO_2 reduction
- Moving to energy efficient lubricants is cost effective compared to hardware modifications
- Direct engine measurements demonstrate that moving to lower viscosity engine lubricants results in lower engine friction
- Synthetic based gearbox and axle lubricants also shown to result in higher transmission efficiencies than mineral based oils
- These changes result in significant fuel consumption benefits with such oils
- However, oil film thicknesses will be smaller – care is needed to ensure lubricants also give adequate durability
- Lubricant properties can give insight into friction/fuel consumption provided the correct properties are used

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Many thanks for listening

Q & A

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