Calculation of Friction in High Performance Engines

Ricardo Software European User Conference 2010

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Introduction

- Minimising friction in motorsport engines is vital because
  - power is required elsewhere…
  - high friction often means high wear
  - high friction leads to unnecessary heat generation and greater need for cooling
- Knowledge of friction level is required
  - to evaluate potential of alternative low friction designs, coatings etc
  - as input to performance simulation models
- Measurement of engine friction is
  - highly problematic, particularly at high engine speed
  - the results are often obtained too late to make key design changes
  - but measurements are useful for validation of calculation methods
- Analytical tools are beginning to reach required level of fidelity
  - but there are still some problems and mysteries…

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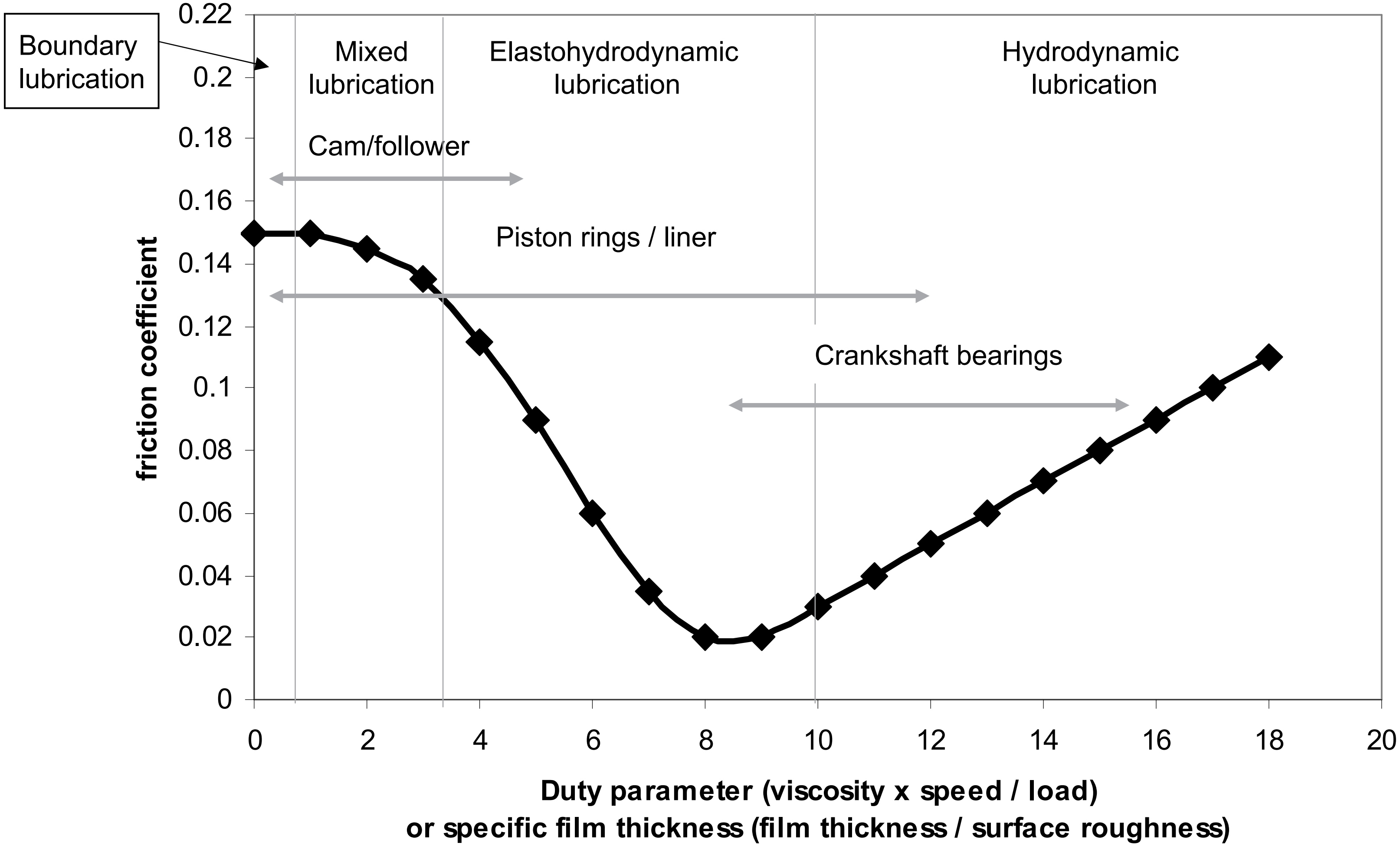
Which losses are included in “engine friction” ?

Definitely included	Optional	Definitely not included
Piston ring/liner friction Piston skirt/liner friction Small end bearing friction Big end bearing friction Main bearing friction Thrust bearing friction Valve train friction Camshaft bearing friction Timing drive friction Balancer bearing friction Seal friction Auxiliaries friction (oil pump, water pump, alternator, scavenge pumps etc)	Losses due to pumping of crankcase gas below pistons Windage losses in engine Oil churning losses in engine Power required to drive auxiliaries (oil pump, water pump, alternator) Transmission losses (gears, bearings, seals, windage, oil churning etc)	Pumping of gas above piston

Stribeck curve

- Friction coefficient at any lubricated contact depends on relative speed, normal load, oil viscosity, shape of contacting parts, roughness of contacting parts, temperature, materials of contacting parts etc



How to measure friction ?

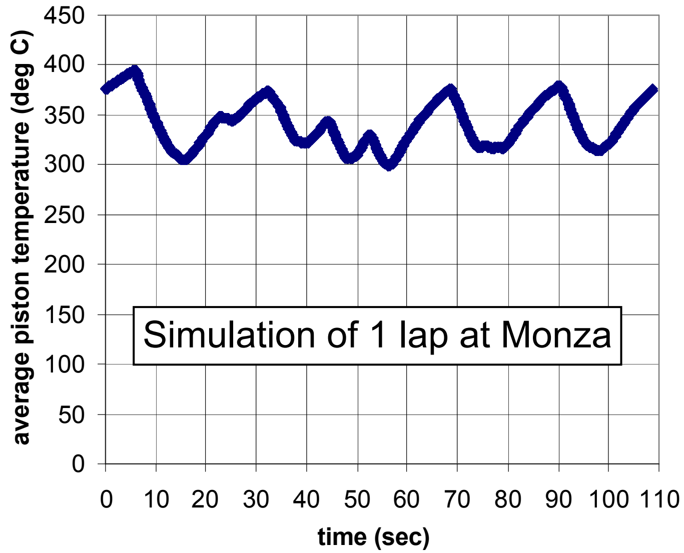
	Motored test	Fired test
Description	● Simply connect engine to motor ● Drive the engine without firing and measure the torque ● Need to control temperature of oil and water carefully ● Test can be extended by progressively stripping engine to give approximate breakdown in friction by subsystem	● Operate engine normally ● Measure cylinder pressure (with very good knowledge of TDC) and brake torque as accurately as possible ● Calculate FMEP from IMEP – BMEP ● Can extend test to make more detailed measurements
Issues	● When the whole engine is motored then pumping loss cannot be separated from friction by measurement ● No combustion so gas load due to compression only ● No way to account for increased local temperatures due to combustion	● FMEP is small compared to IMEP and BMEP so any measurement error is magnified ● Use of more intrusive instrumentation usually involved changes to components and this can affect durability

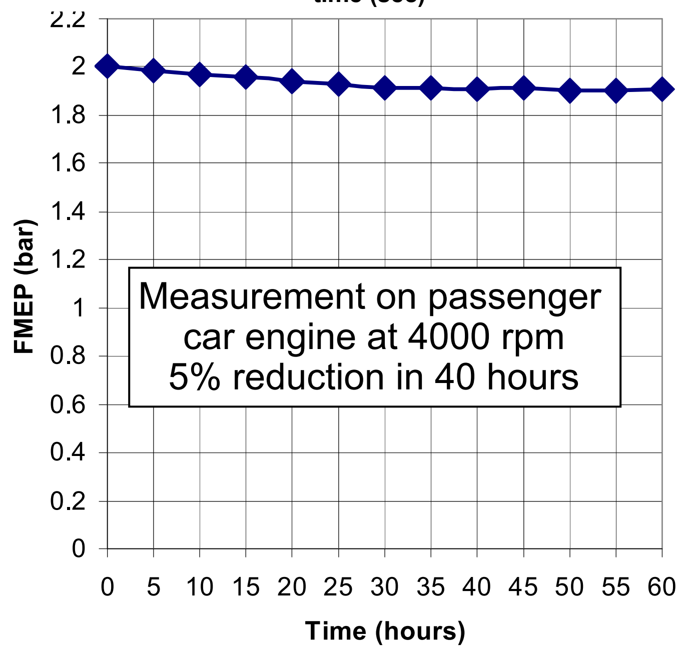
What kinds of calculation are performed ?

	Semi-empirical approach	Advanced CAE approach
Advantages	• Very quick to set up and run • Can potentially account for most sources of loss	• Potentially good accuracy for any contact if suitable model is available • Can account for differences in load, detailed component geometry, oil grade, temperature etc
Limitations	• Need lots of test data to develop tool • Accuracy depends of how similar engine is to those in database • Cannot accurately predict effect of detail design changes	• Potentially long set up times • Potentially long run times • Need different tools to analyse all contacts • Some losses are very difficult to model • Easy to lose sight of “big picture”

Some special problems of motorsport engines

- Friction testing usually calls for prolonged operation under stabilised conditions
  - Many motorsport engines cannot be operated under stabilised conditions at high speed/load
  - During a race the piston temperature varies significantly and can approach the limit at end of straights after ~15 seconds
  - If the engine is held at full load the piston temperature will rise significantly affecting clearances, local oil temperature and so piston friction before failure
- Motorsport engines are often not run-in properly before use
  - In typical passenger car engine friction reduces from initial value for at least 20-30 hours
  - Motorsport engines are sometimes used straight from new build so friction level is reducing all the time





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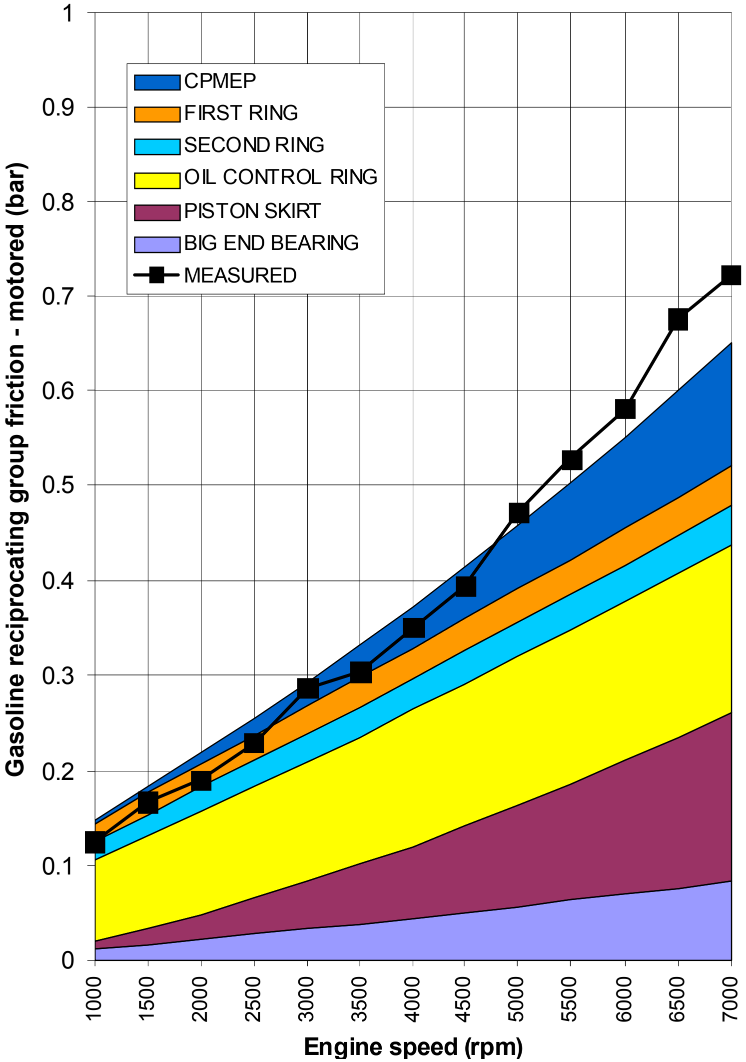
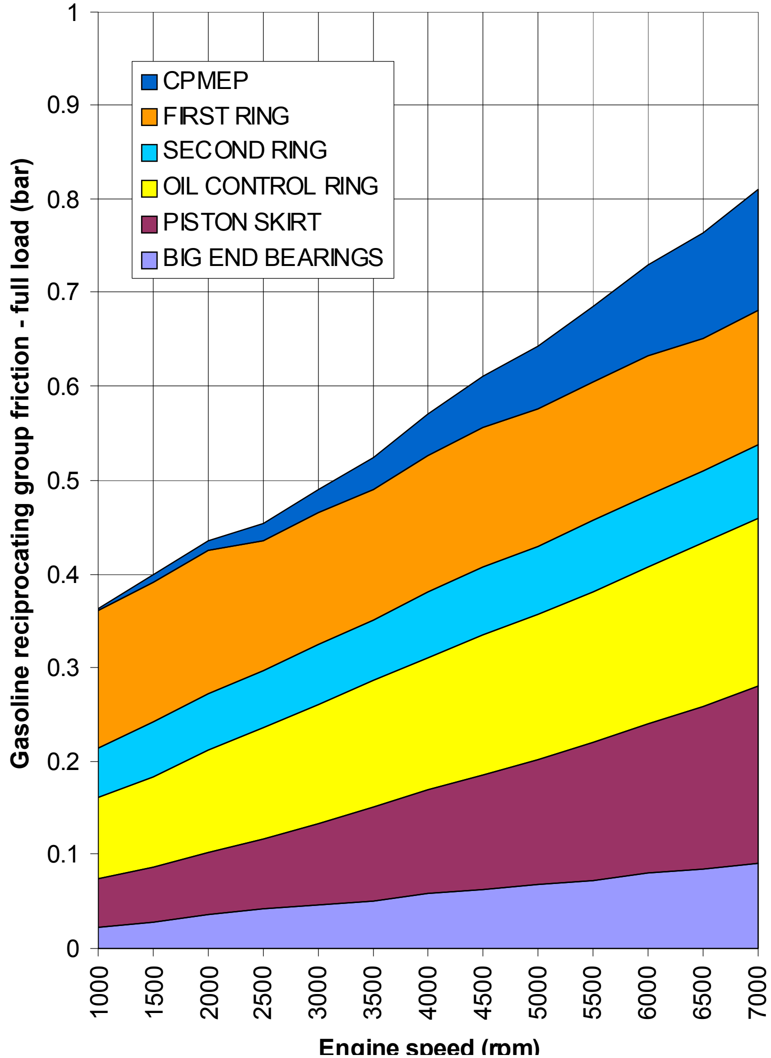
Semi-empirical models - FAST

- FAST (Friction Assessment Simulation Tool) is a semi-empirical engine friction prediction program used internally by Ricardo
- FAST predicts friction loss across the engine speed range for individual subsystems and for the whole engine
- FAST uses semi-empirical equations
  - Coefficients and exponents were developed by Ricardo to give improved agreement with the latest measured data obtained from motored teardown tests on modern passenger car engines and with other published measured data
  - New equations were developed for systems not covered by published sources
  - Latest version extended to enable prediction of friction under fired conditions
- FAST currently requires ~50 input values such as bore, stroke, bearing diameter, valve train type etc. to make a prediction of motored friction loss
  - All input values can be obtained easily from drawings or components
  - More detailed information such as cylinder pressure, piston mass, rod mass, ring tension etc. is required to calculate the increase in piston friction under fired engine conditions

Typical results for reciprocating group

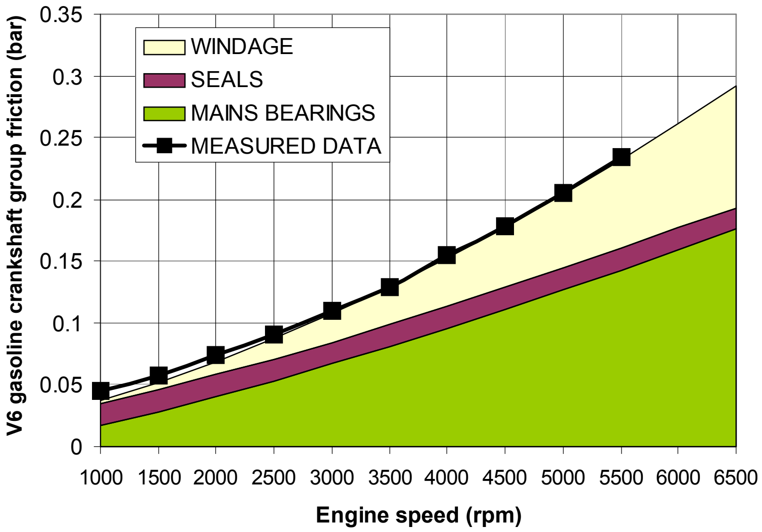
- Predictions under motored conditions compared with measured data from motored teardown test
- Prediction under full load conditions shows significant increase in friction at top piston ring and skirt

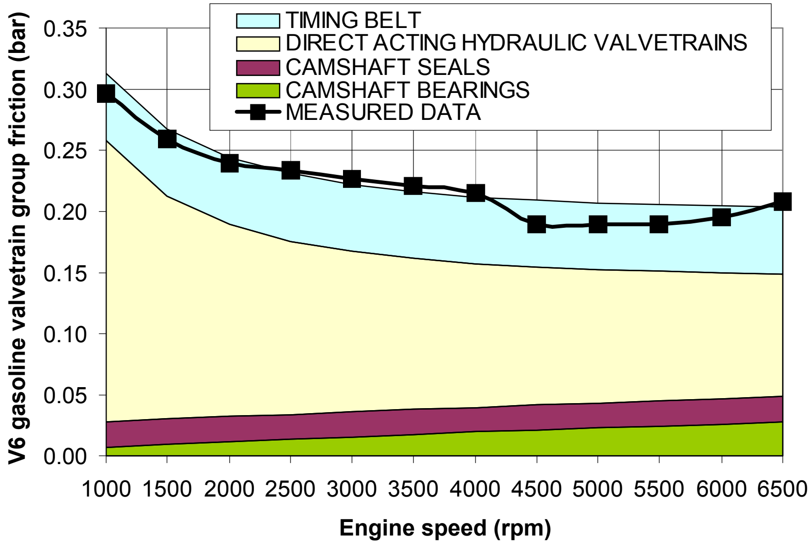


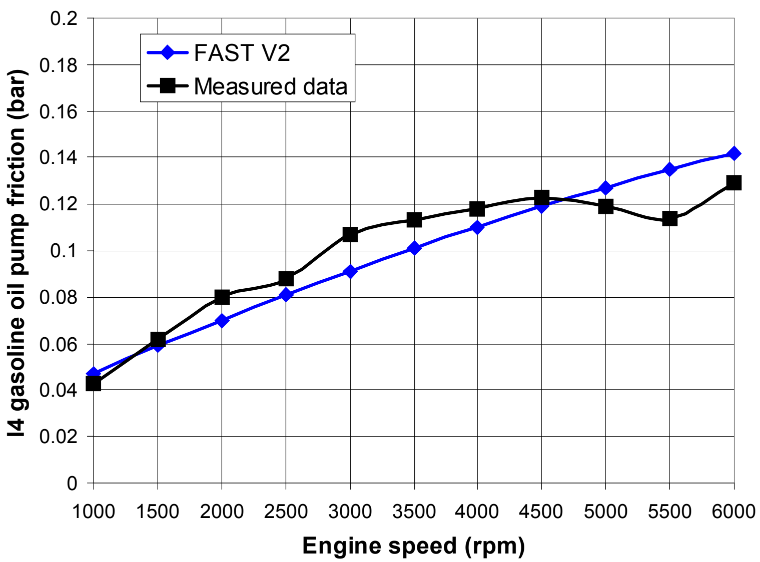


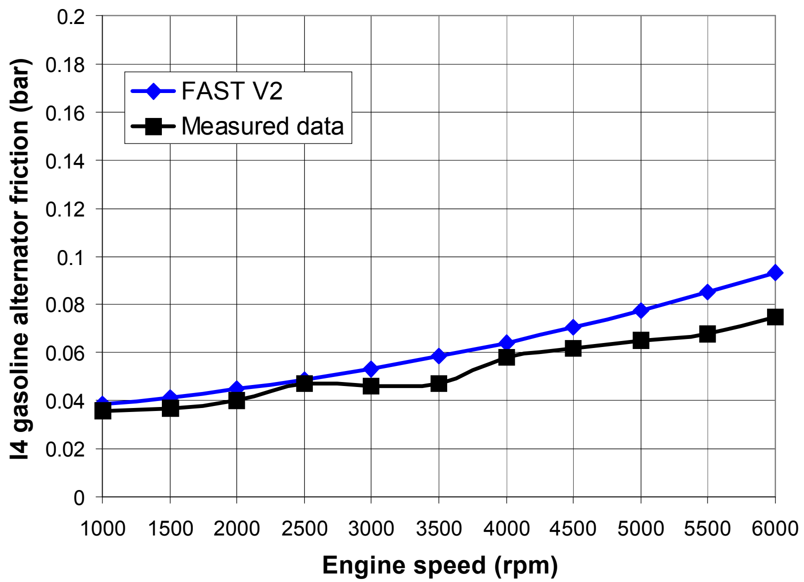
Typical results for other systems

- Results accurate to +/-20% for each subsystem and often much better than this



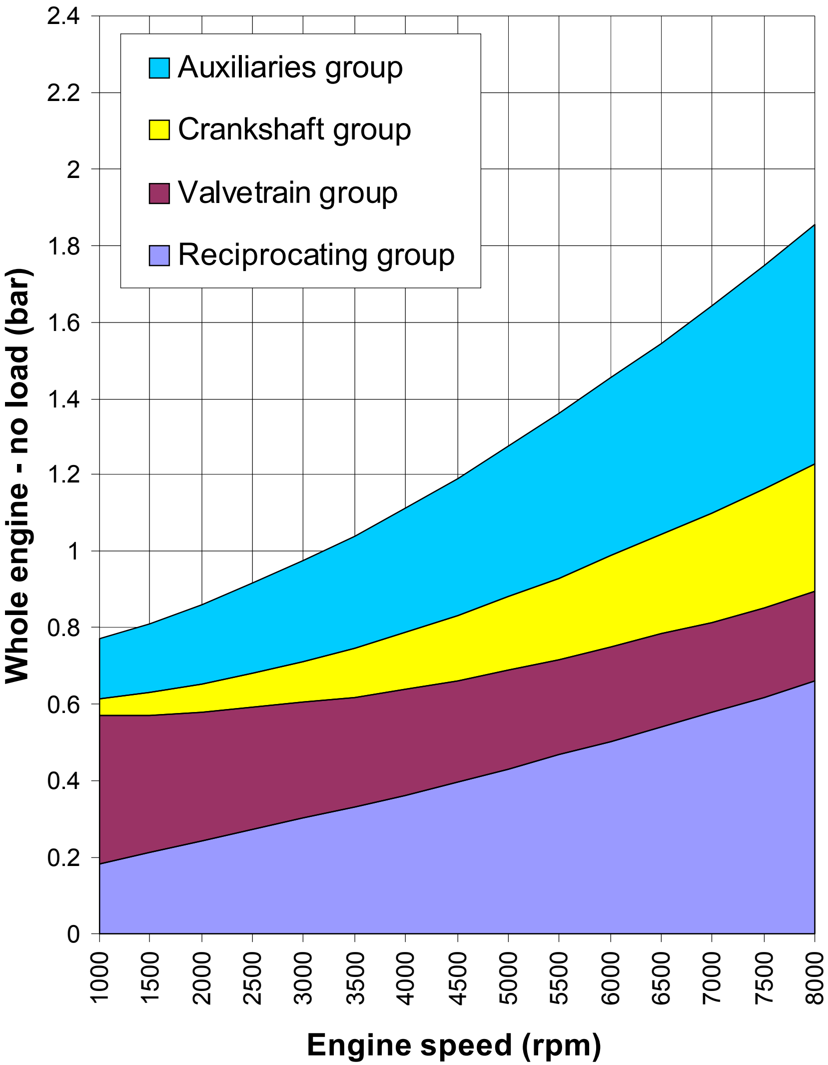


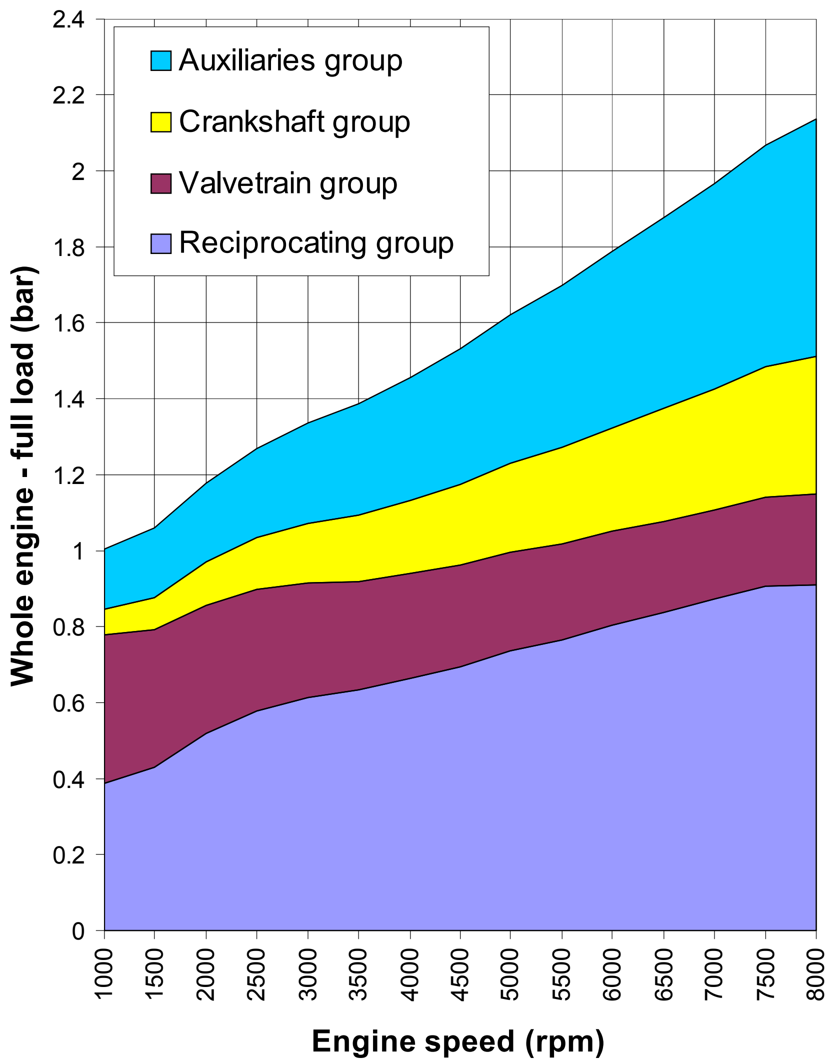




Typical results for high performance sports car engine

- For whole engine friction the results are generally accurate to within +/-10%
- FAST has not been validated for engines designed to rev higher than 8000 rpm





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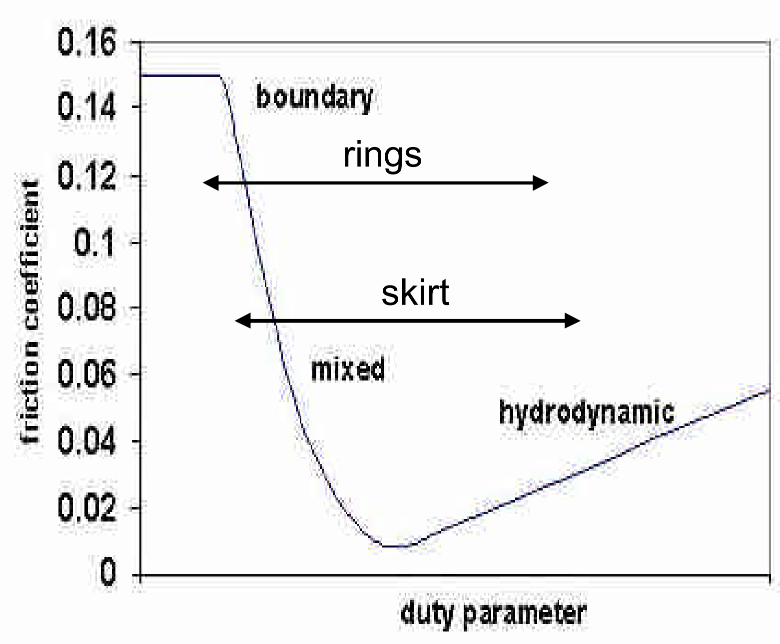
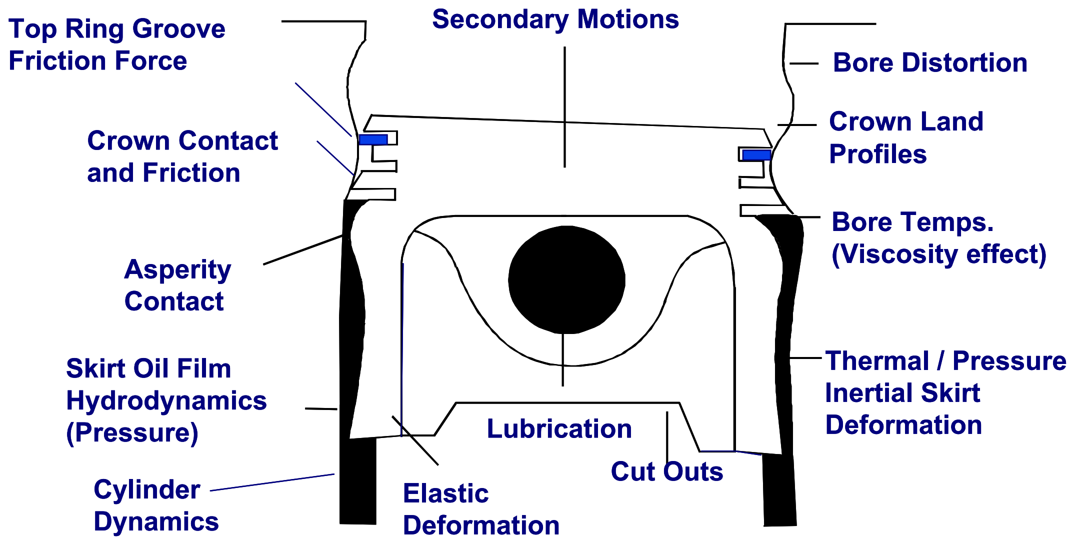
Piston assembly friction prediction

- Piston assembly friction
  - involves losses at many sliding interfaces
  - is very difficult to measure even if cost is not an issue
- Analysis can offer insights not possible by measurement
- Need for validated software but
  - Losses and rings and skirt are inter-related
  - Some key inputs are hard to determine
    - Temperature of surfaces and oil
    - Film thickness on liner
    - Worn surface shapes of skirt and rings
  - The lubrication regime, and so the effective friction coefficient, μ, can change dramatically during each half stroke
    - boundary at end of stroke (μ = ~0.1)
    - hydrodynamic at mid stroke (μ = ~0.005)

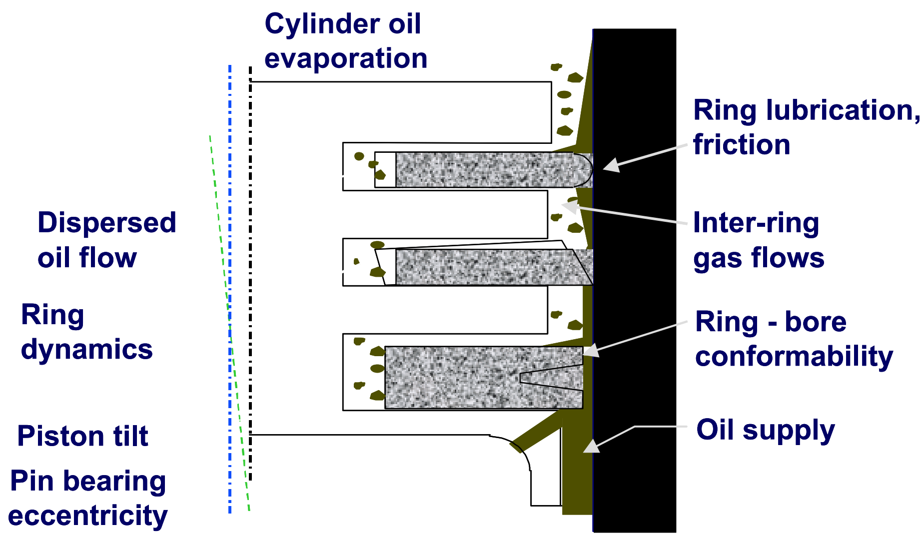


Ricardo Software - PISDYN and RINGPAK

- PISDYN can calculate
  - friction loss due to oil shearing effects and asperity contact
    - at skirt/liner contact
    - at small end bearing
  - piston secondary motion
  - wear loads

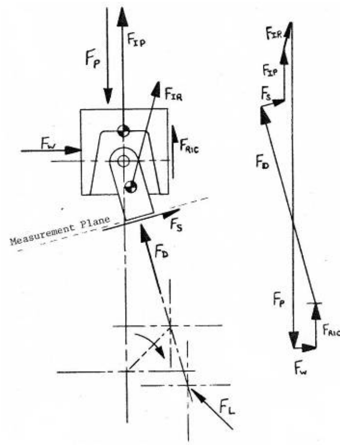


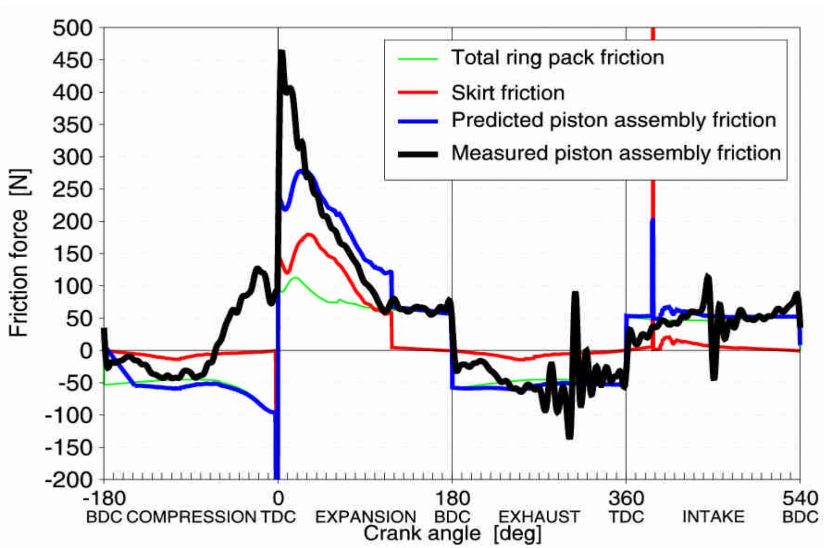
- RINGPAK can calculate
  - friction loss due to oil shearing effects and asperity contact
    - at each ring/liner contact
  - wear loads
  - oil consumption
  - blow-by and blow-back



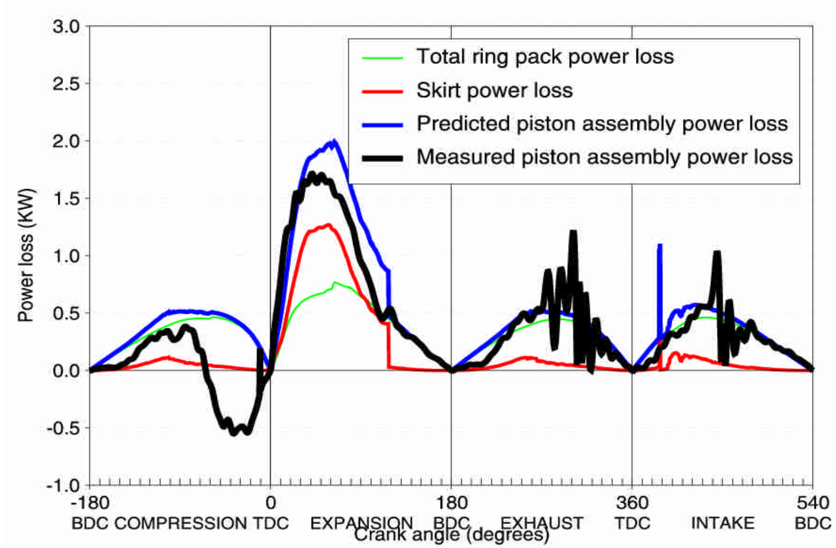
Model validation at low engine speed

- Predictions validated at low engine speed (up to 2500 rpm) using force difference method
- Measured cylinder pressure, connecting rod strain, crankshaft angular position, liner temperature, piston temperature etc.
- Piston friction force calculated from gas force, inertia force and rod force
- Future plans for validation at higher speed as part of ENCYCLOPAEDIC project



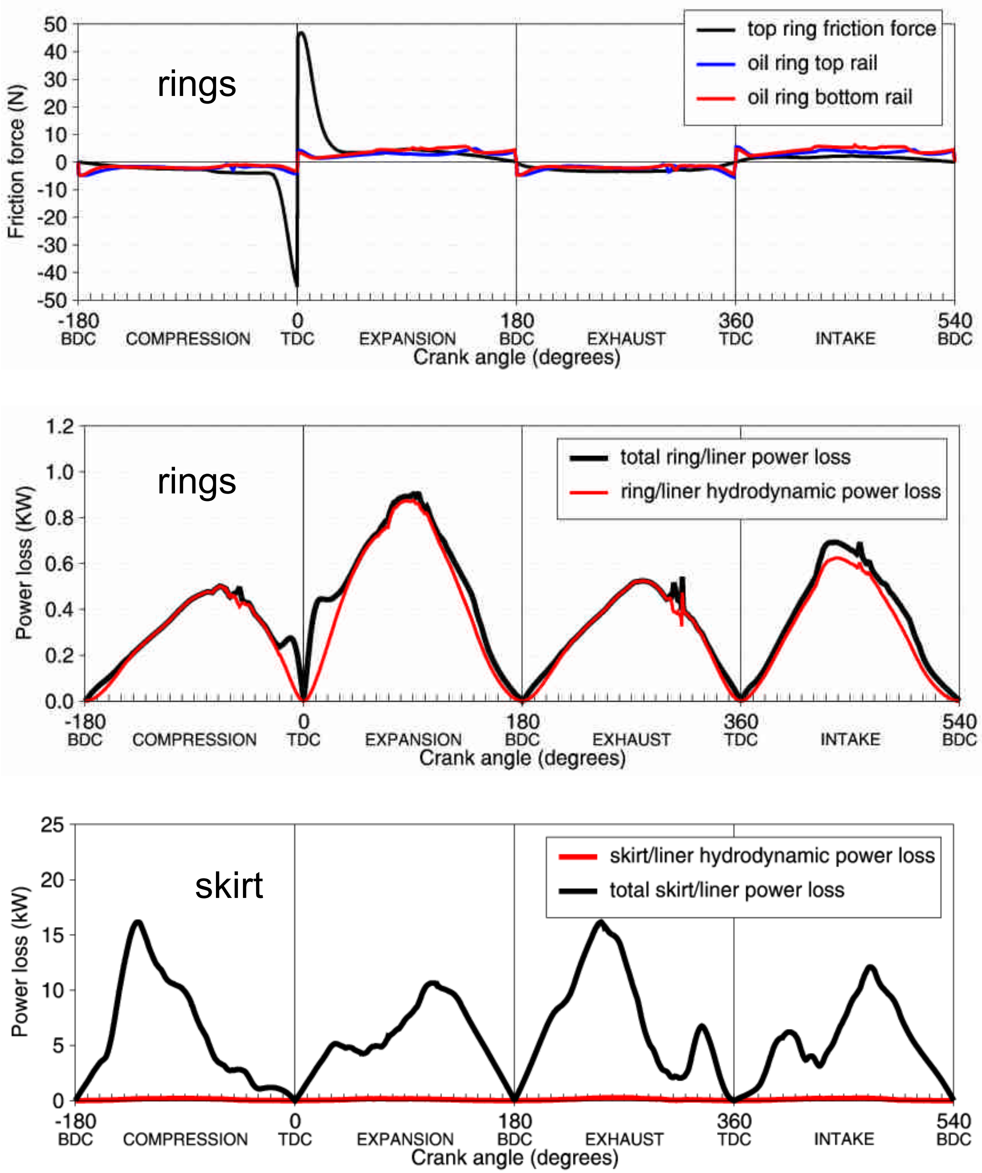


Results at 2000 rpm full load



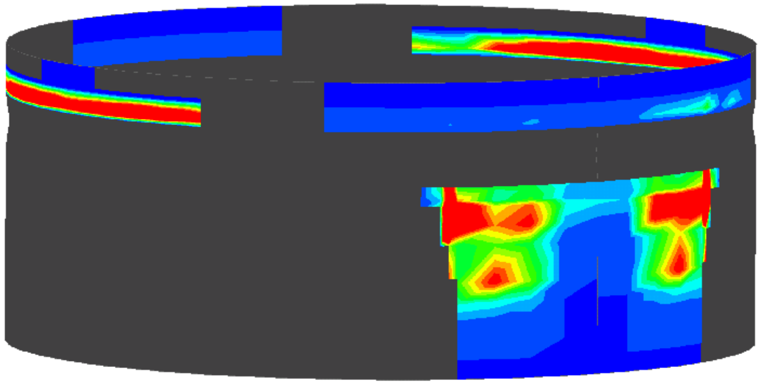
Experience at high speed

- Ricardo have used PISDYN and RINGPAK to calculate piston friction at very high engine speeds
  - Credible ring/liner friction results obtained from RINGPAK
  - But at high speed losses are dominated by piston/skirt asperity contact which is predicted to occur in each stroke even for a well-developed piston skirt profile
- Skirt/liner friction power loss shows strong sensitivity to
  - component temperature
    - governs clearance, component distortion, and local oil temperature
  - oil supply assumptions
  - component surface texture



High Speed Case Study

- Predicted result shows asperity contact pressure at 15000 rev/min



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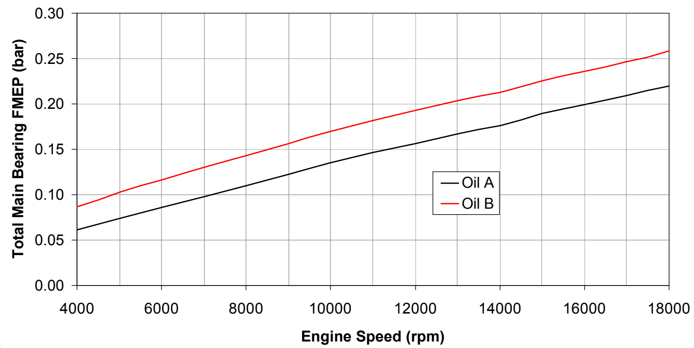
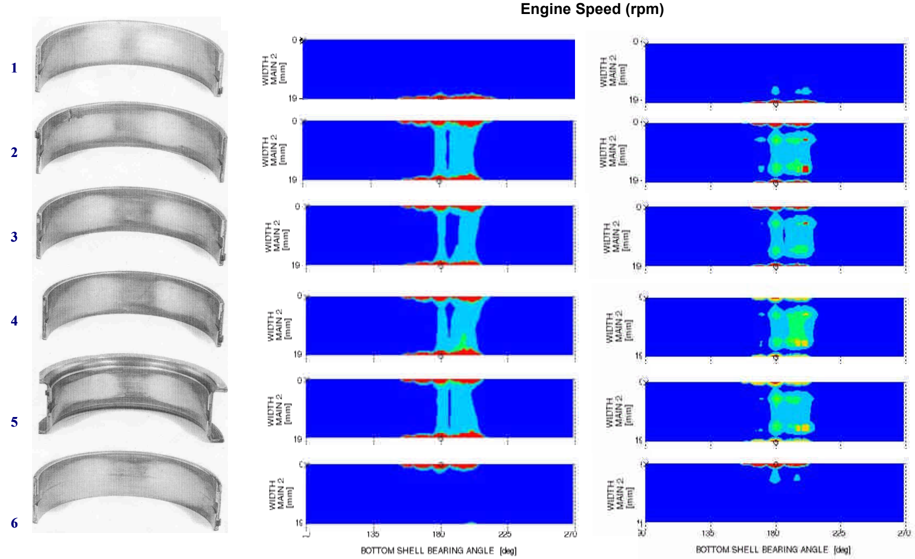
Fluid film bearing friction

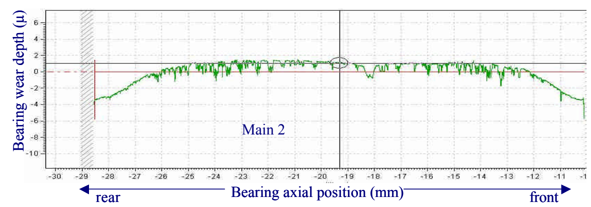
- Journal bearings normally operate in the hydrodynamic lubrication regime
- Losses are dominated by oil shearing effects
  - Relatively easy to quantify using simple bearing analysis methods
  - Can be used to study the effects of bearing dimensions, clearance, oil viscosity etc
- Surface contact (and so boundary or mixed lubrication) is possible during running-in process or if bearing is overloaded
  - Friction prediction is theoretically possible using elasto-hydrodynamic analysis with asperity contact model but
    - Measured worn axial bearing profiles and distorted shapes are needed for sensible results
    - so not very useful for design



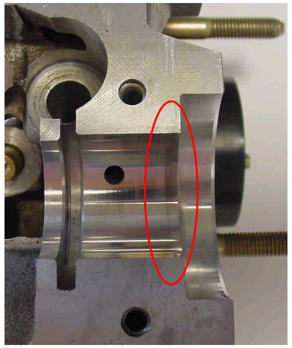


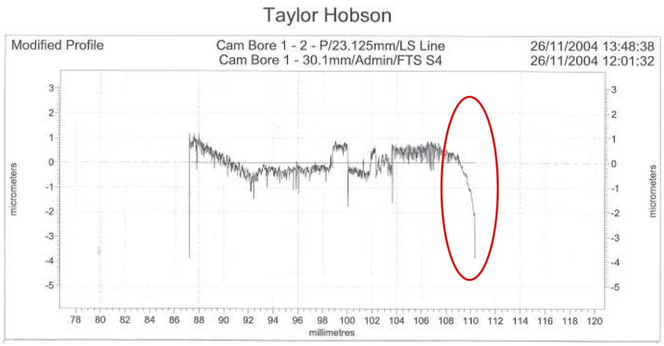
No axial profile

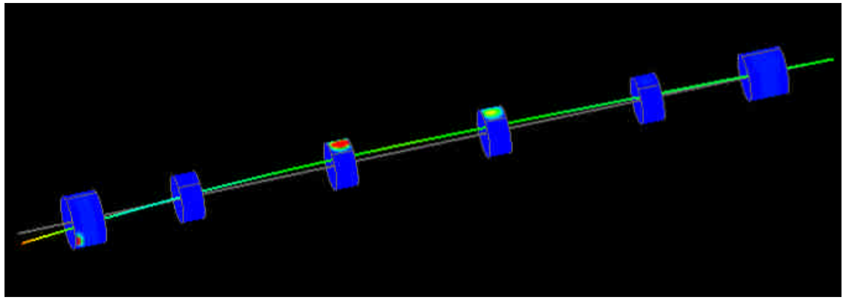
Axial profile



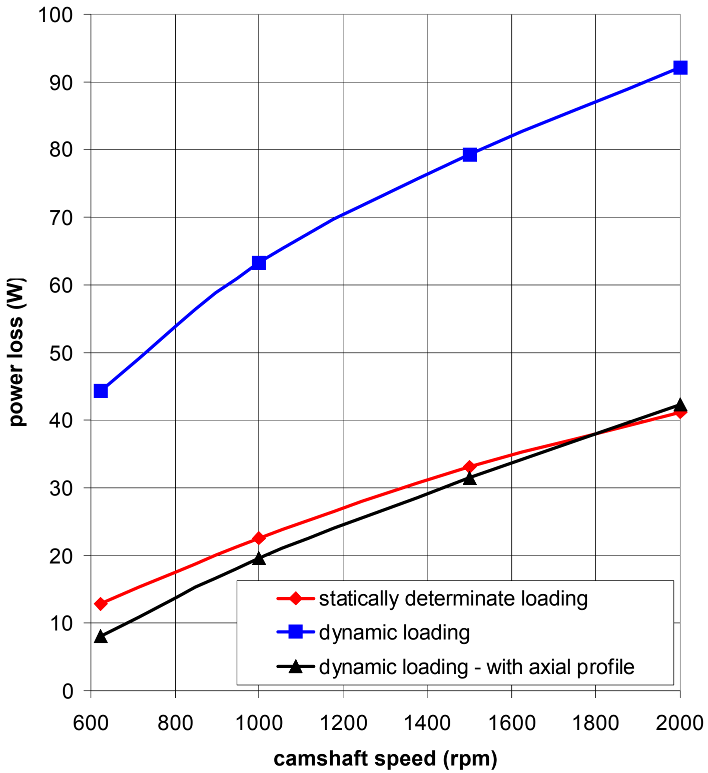
Camshaft bearing friction – effect of ENGDYN model level







- Front camshaft bearings often exhibit edge wear due to loads from the timing drive
  - This wear usually occurs during run-in period and then stabilises
- ENGDYN used to predict friction at camshaft bearings
  - Simple rigid model gives power loss due to oil shear effects
  - With flexible camshaft model edge contact leads to high friction loss
  - When worn profile is introduced friction loss is similar to results from simple model



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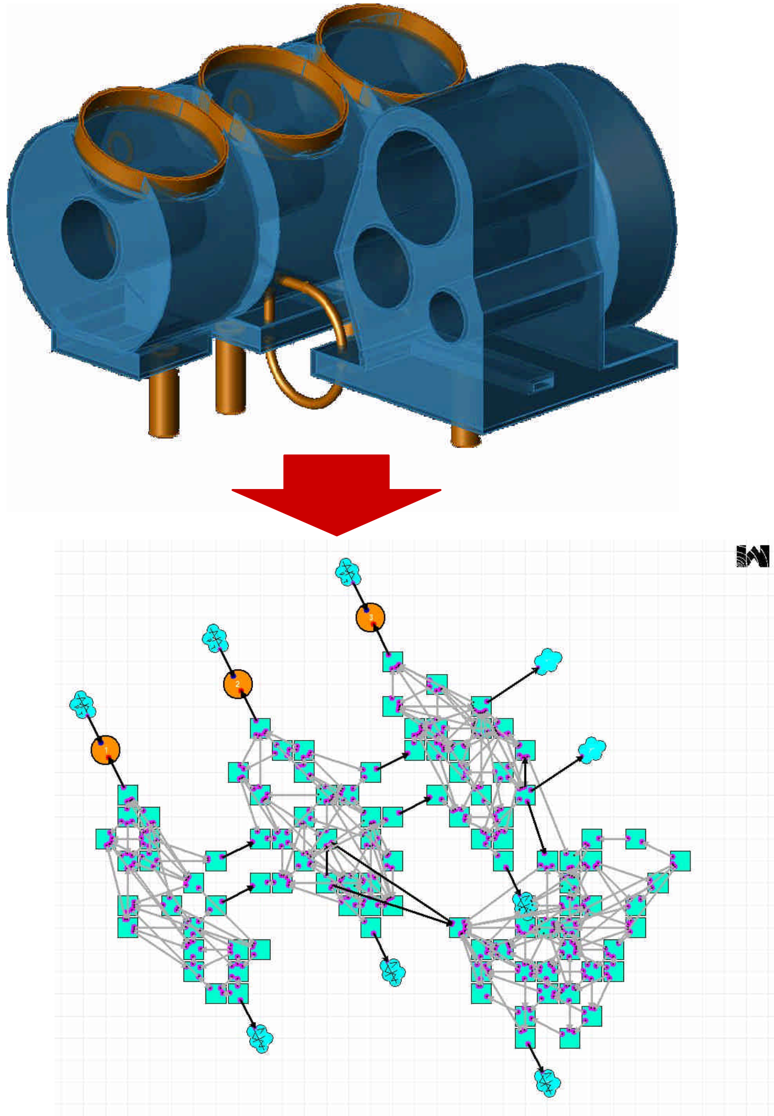
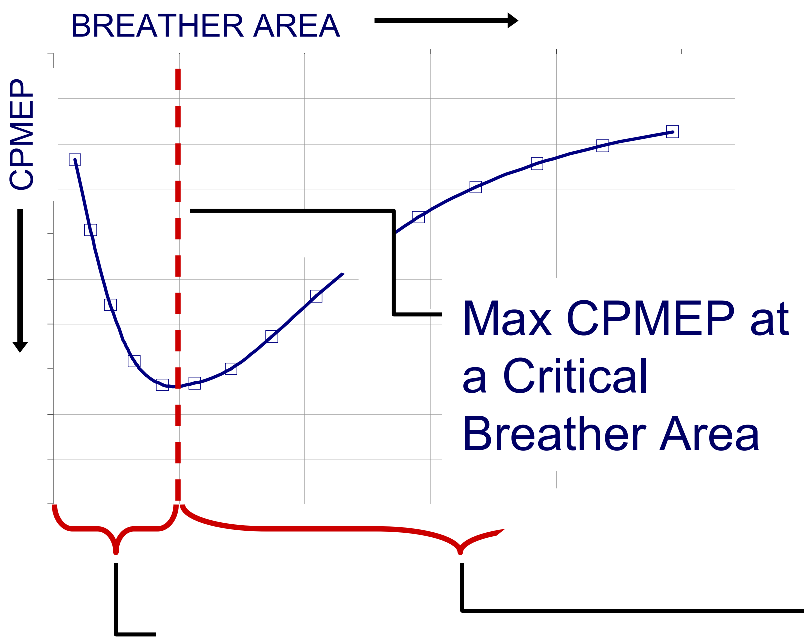
Crankcase pumping loss - WAVE

- Crank case pumping incurs a power loss
  - Power required to pump crankcase gas from one bay to the next as the pistons move up and down
  - This can be significant loss on high speed engines
    - so “dry sump” designs with scavenge pumps are often used to minimise this
- Ricardo and others have used 1D gas dynamics modelling software such as WAVE to predict crank case pumping loss with some success
  - Complex geometry of crank case from CAD and then automatically reduced to 1D network

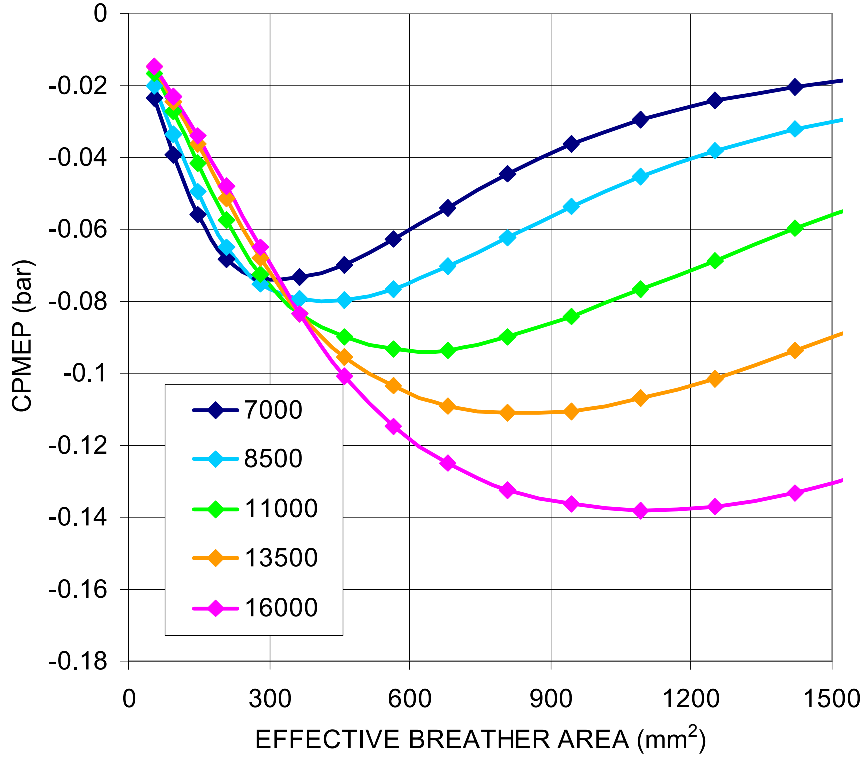


Crankcase pumping loss - WAVE



> Critical Breather Area

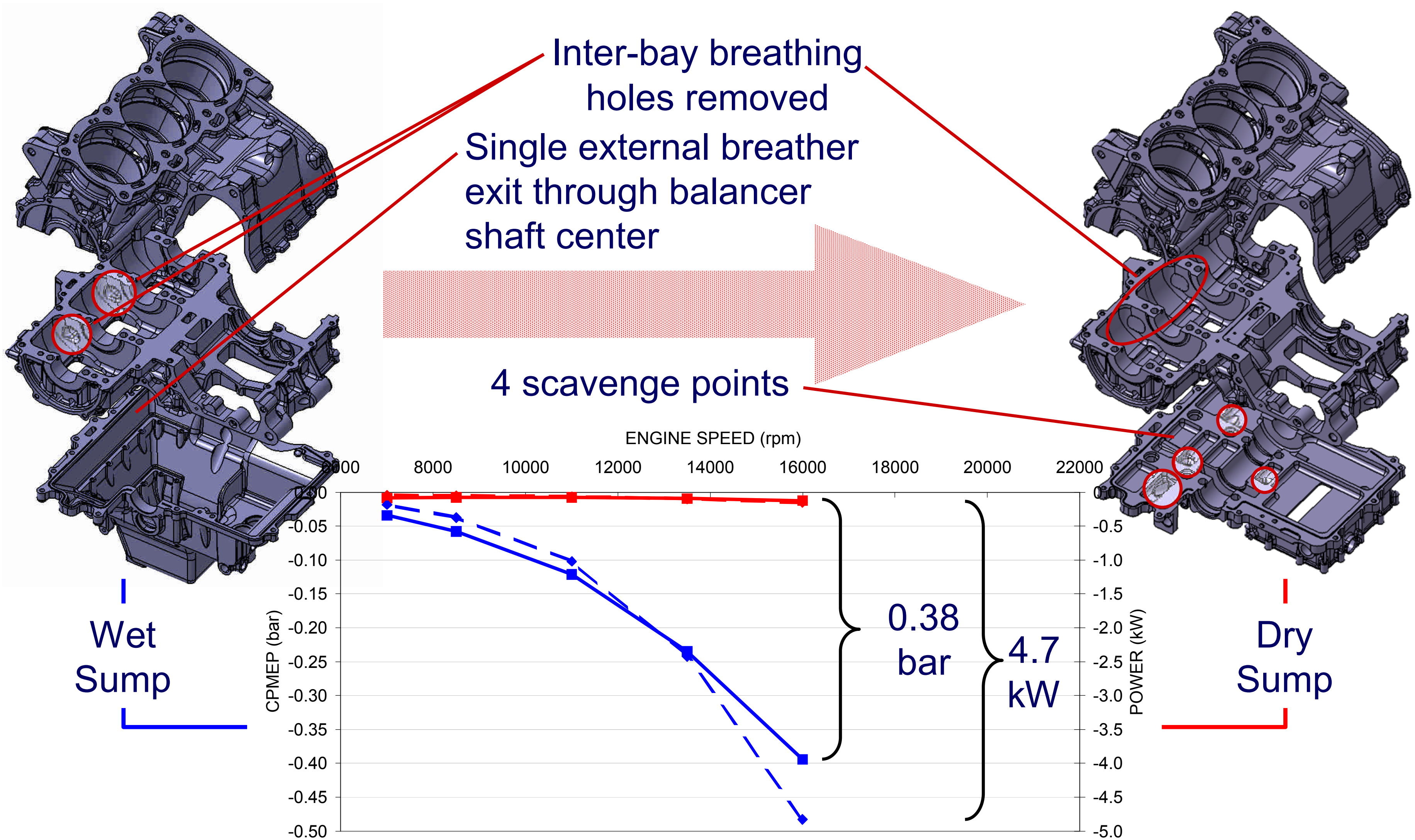
- Losses reduce with increase in area
- Reduced resistance to inter-bay flow exchange



< Critical Breather Area

- Losses increase with increase in area
- Increasing inter-bay flow exchange
- Reduced recovery of compression work

Crankcase pumping loss - WAVE



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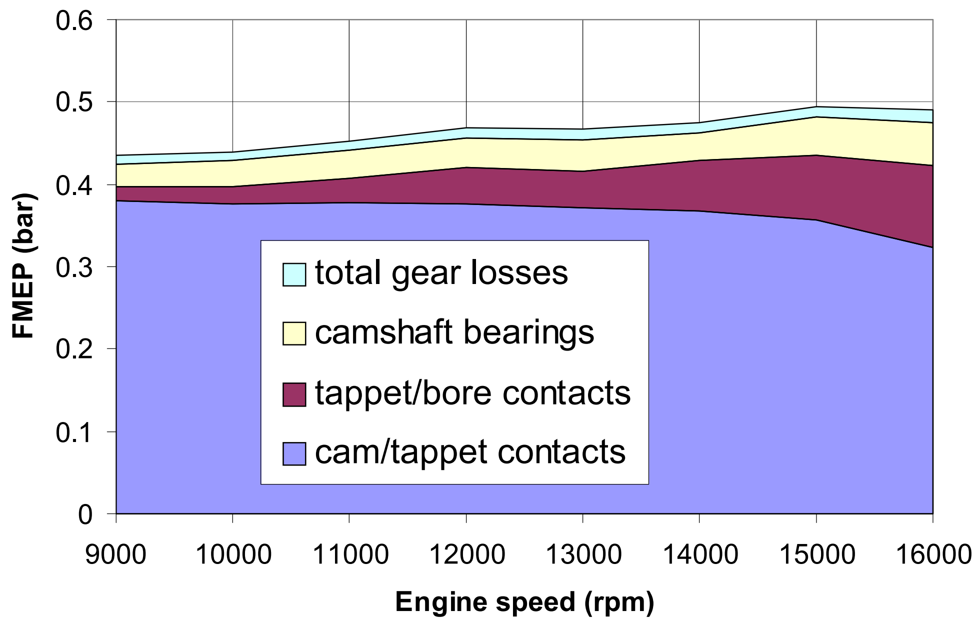
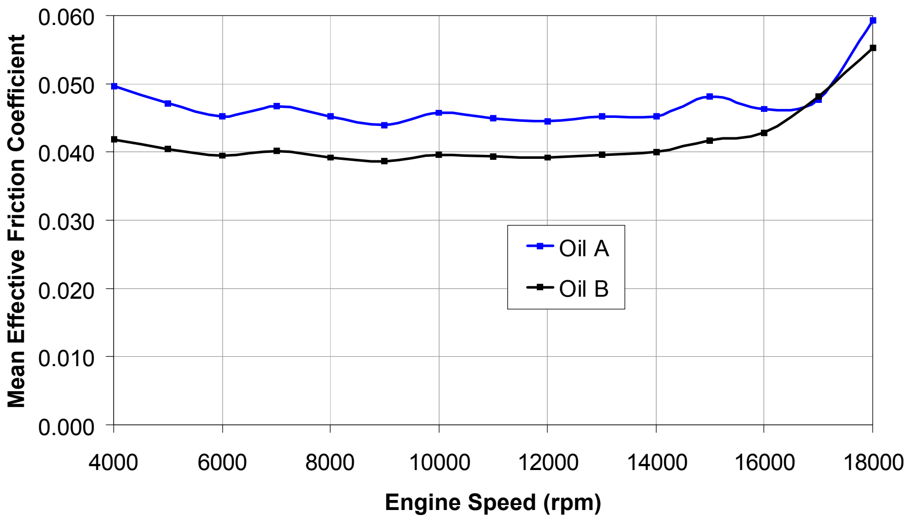
Valve train friction prediction

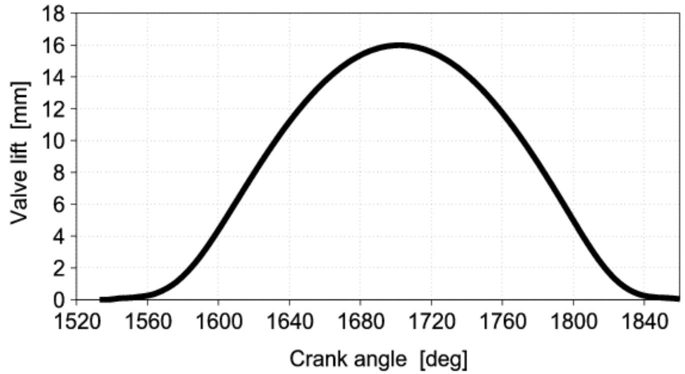
- At system level valve train friction is reasonably well-understood
  - The mean friction level of valve trains can be measured by driving the camshaft using an electric motor and measuring mean drive torque
- However
  - These system level measurements mask the fact that the detailed sources of loss are not very well understood
  - Especially since the measurements often include the timing drive as well as the valve train
- Motorsport engines nearly always have sliding contacts between cam and tappet to enable use of a lightweight follower and optimise high speed dynamics
  - Friction loss is dominated by losses at the these highly-loaded sliding contacts

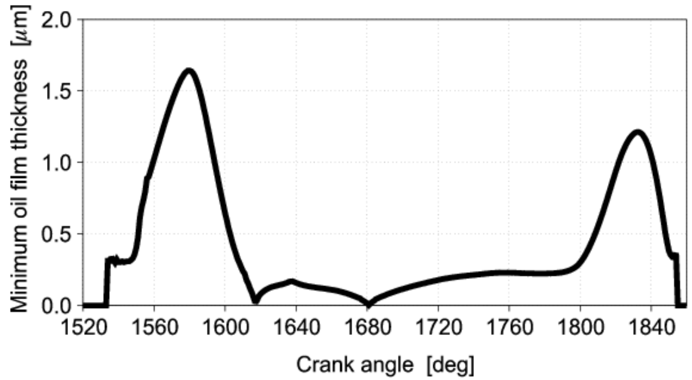


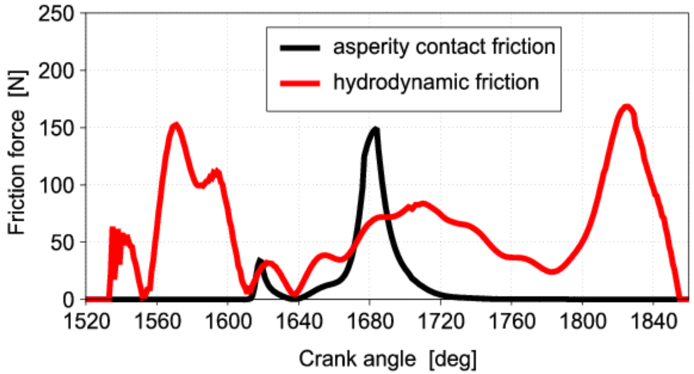
Cam/follower friction – sliding contact

- VALDYN can calculate friction power loss at sliding contacts between cam/tappet or cam/follower
  - Friction due to oil shear and asperity contact are calculated separately
  - Friction is therefore dependent on oil viscosity as well as surface texture
  - The model also considers
    - friction between tappet and cylinder
    - tappet rotation



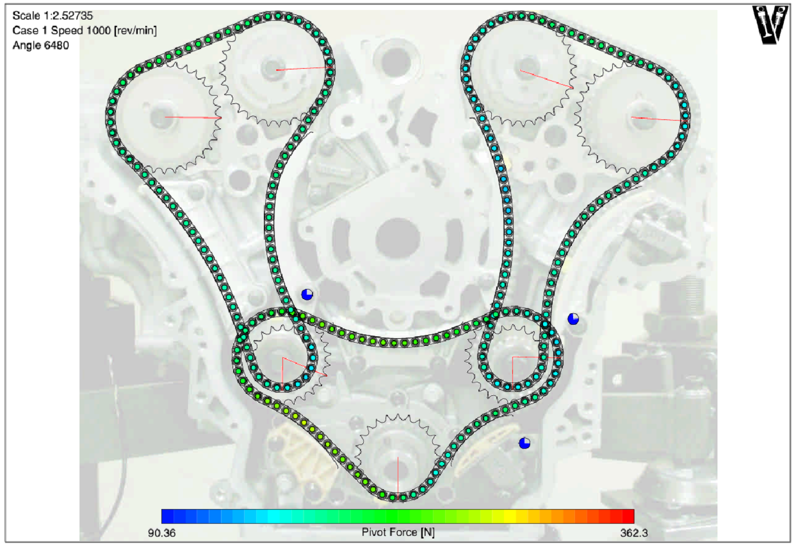


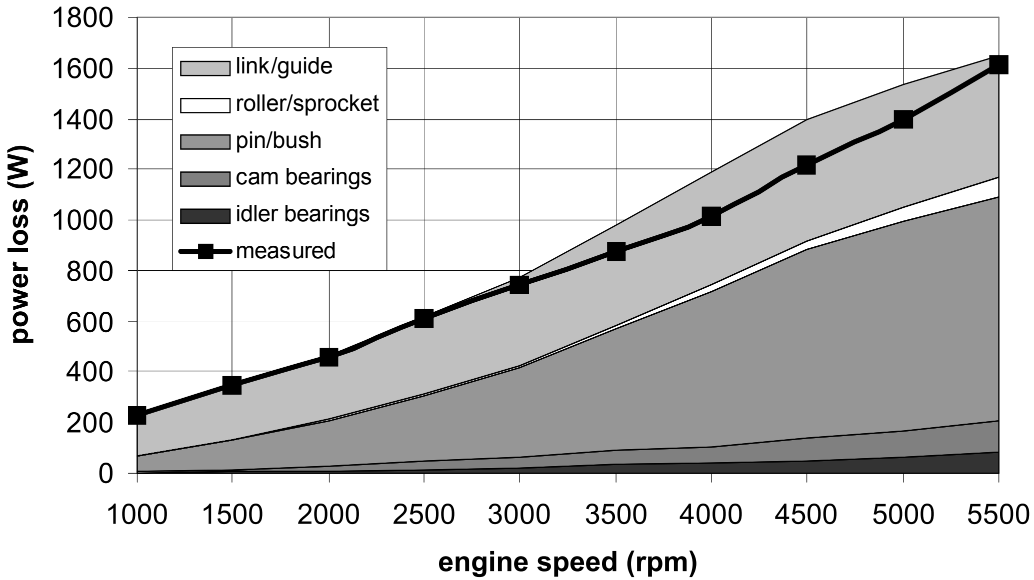




Timing drive friction - VALDYN

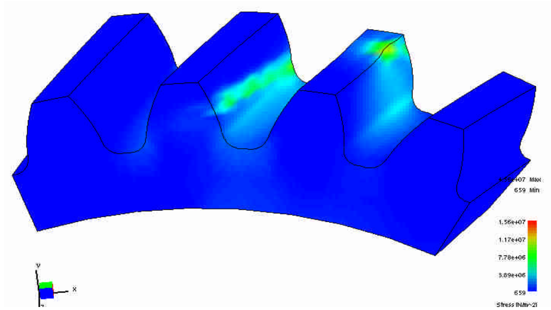
- VALDYN has the capability to calculate the losses in chain timing drives
  - Models have been validated validated against measured data at passenger car engine speeds
  - Results can be very dependent on tensioner design

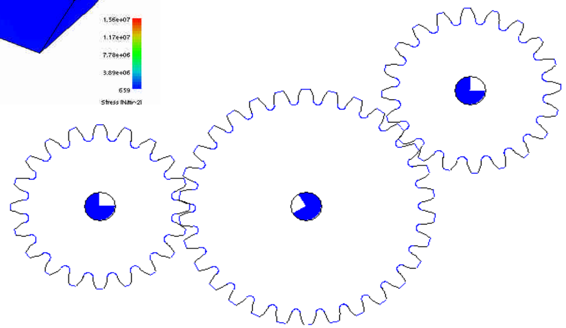


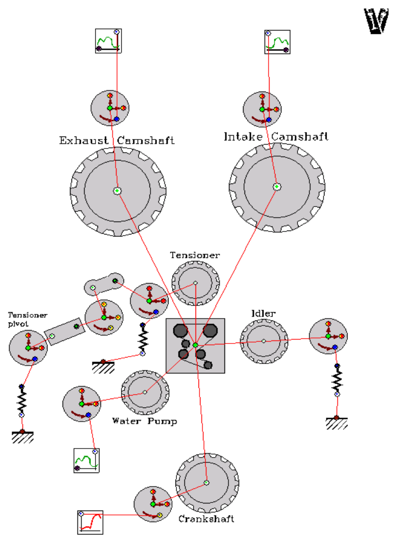


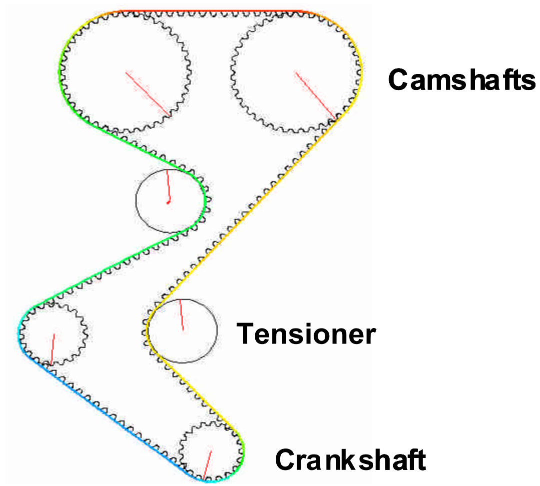
Timing drive friction - VALDYN

- VALDYN has gear models for calculation of contact forces and sliding speeds
  - Friction coefficients can be entered to calculate losses at gear meshes
  - But actual losses in high speed gears are mostly caused by windage and oil churning effects which cannot be modelled with confidence
- VALDYN can model belt drive dynamics but detailed sources of loss are not understood so cannot be predicted
  - Belt material hysteresis?
  - Rubbing losses between teeth and pulleys?
  - Pumping air out during meshing?









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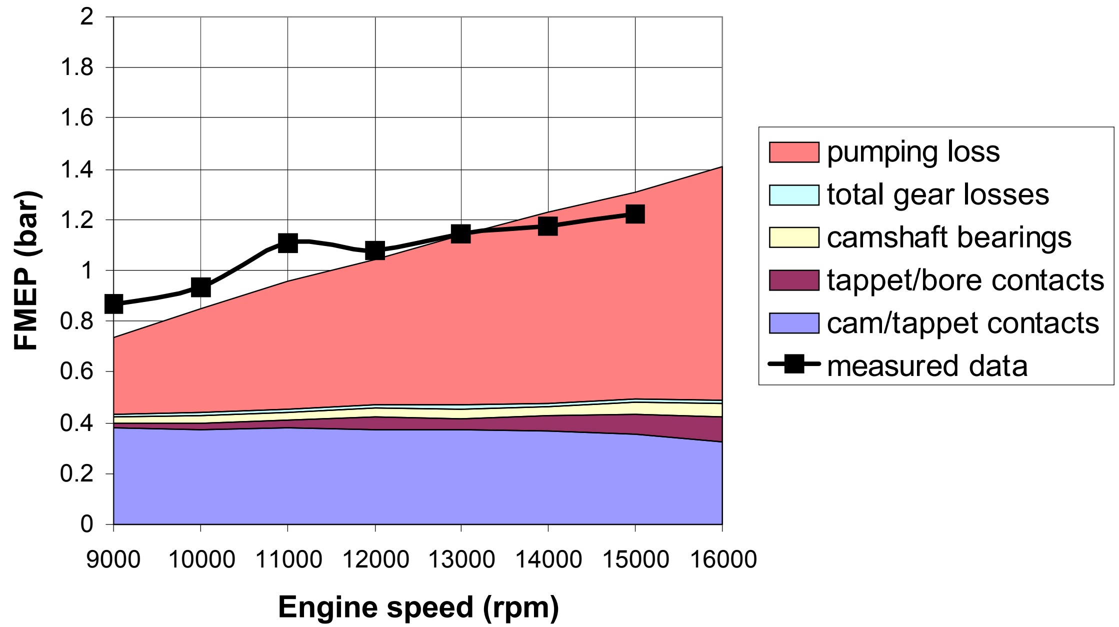
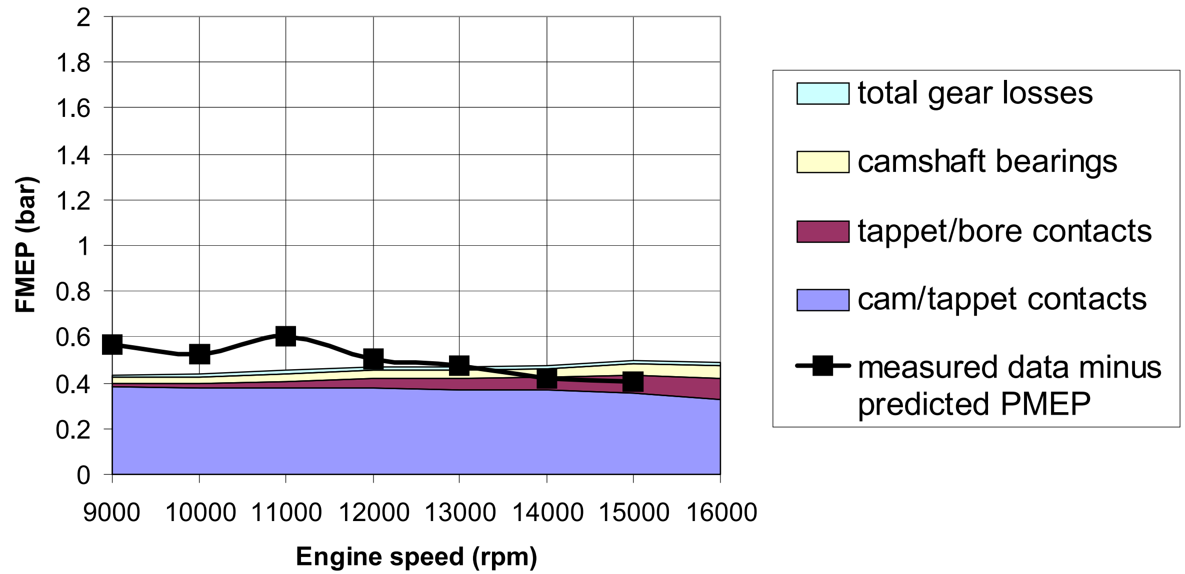
Case study

- The following slides illustrate the use of CAE tools and the results of motored teardown test to understand the distribution of friction in a racing engine
- The engine was motored and a 4-stage teardown test was made
  - 1 Whole engine with intake and exhaust systems
  - 2 Intake and exhaust systems removed
  - 3 Cylinder head removed
    - including upper timing gears
    - Cylinder head removed by plate to maintain bolt loads on structure
    - Plate was non restrictive so no pumping losses
  - 4 Pistons and rods removed
    - Replaced by dummy weights
- All stages include driven oil pump, water pump and transmission

Case study - Valve train group friction

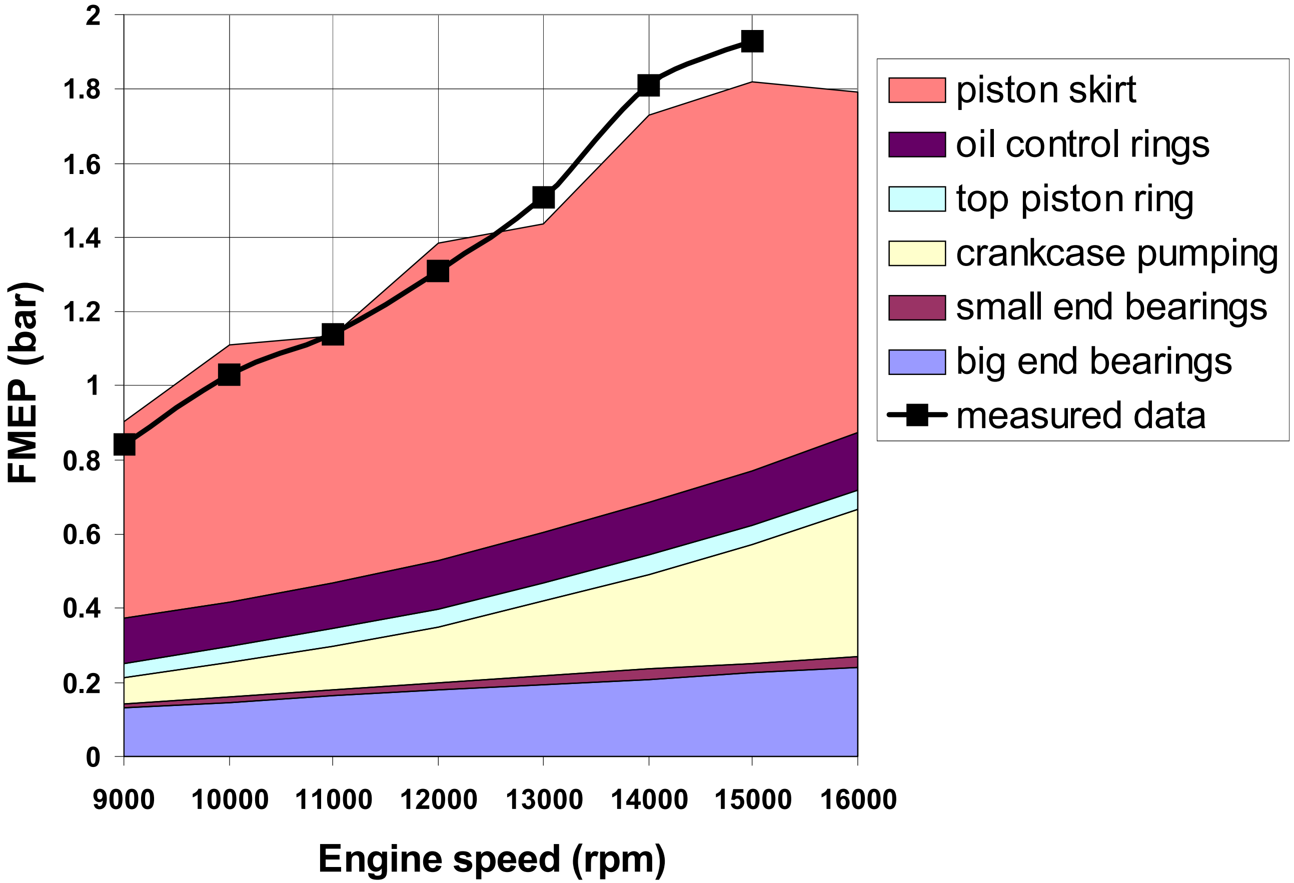
- Measured data obtained by subtraction
  - Test 2 – Test 3
- Pumping loss under motored conditions calculated using WAVE
- Camshaft bearing friction calculated using ENGDYN
- Cam/tappet losses and tappet/bore losses calculated using VALDYN
- Gear contact losses estimated using loads from VALDYN and friction coefficients
  - Windage losses estimated





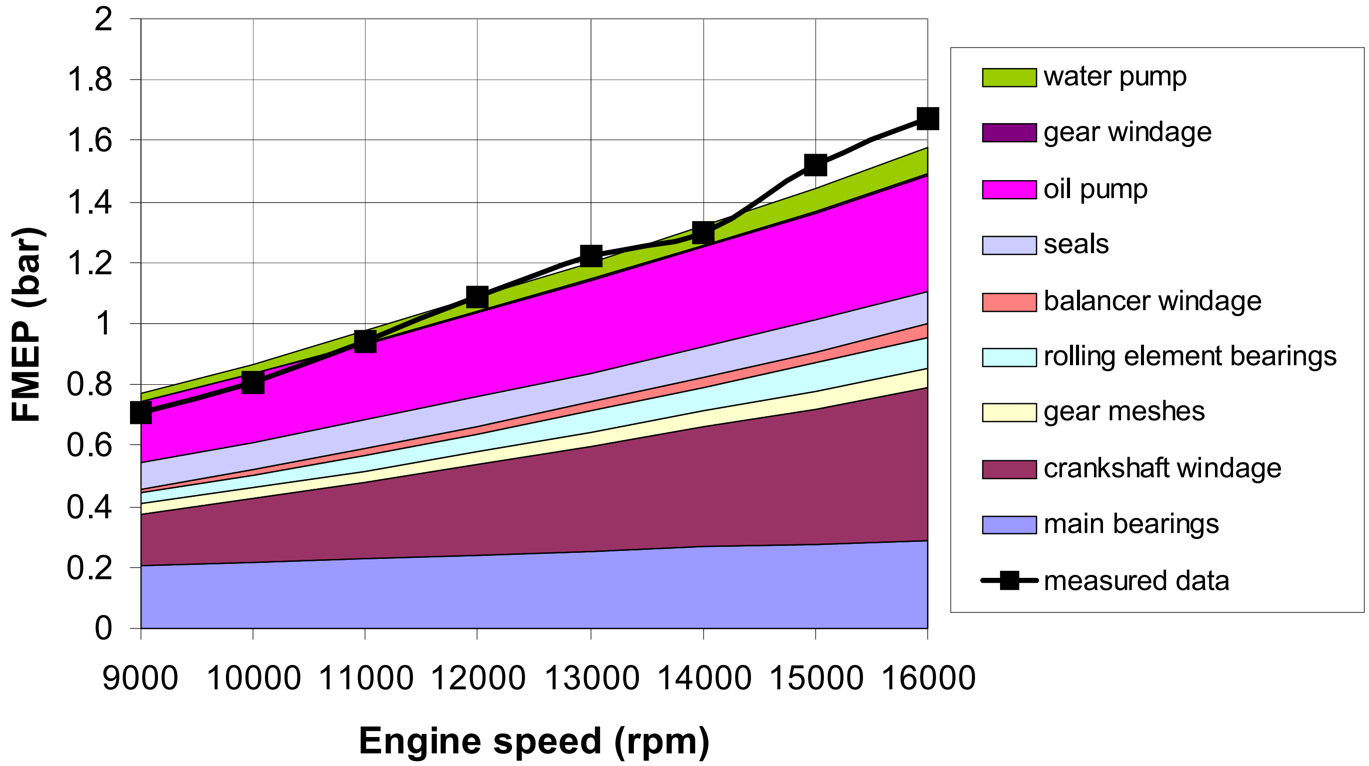
Case study - Reciprocating component group friction

- Measured data obtained by subtraction
  - Test 3 – Test 4
- Piston skirt friction loss and small end bearing loss calculated using PISDYN
- Piston rings friction loss calculated using RINGPAK
- Crankcase pumping loss calculated using WAVE
- Big end bearing loss calculated using ENGDYN



Crankshaft/transmission group friction

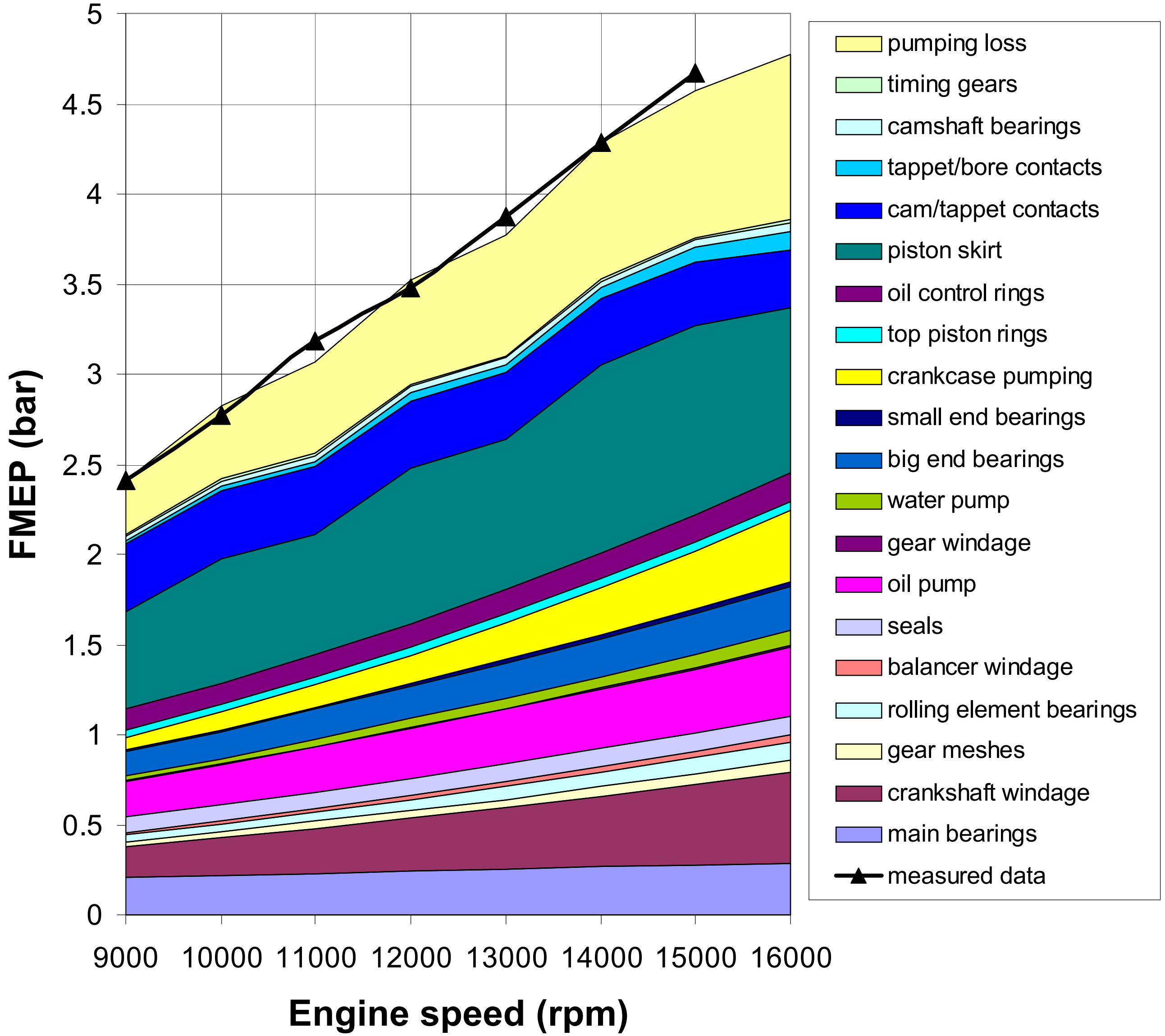
- Measured data obtained directly Test 4
- Main bearing loss calculated using ENGDYN
- Windage losses estimated using simple approach
- Gear contact losses estimated using simple approach
- Oil pump losses and water pump losses estimated



- Rolling element bearing losses calculated using calculated loads and friction coefficients
- Seals losses estimated using suppliers database

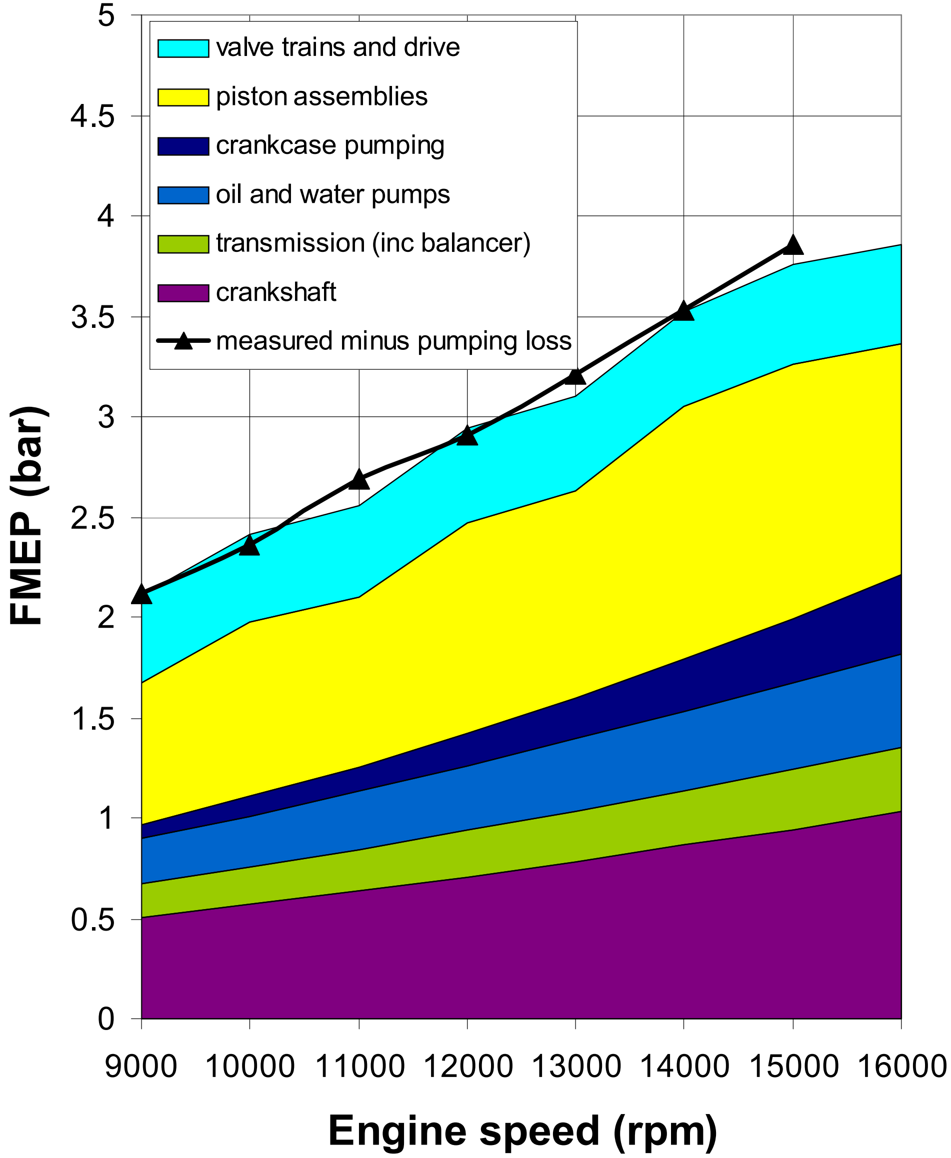
Whole engine motored friction loss (1)

- With motored pumping losses included
- Additional loads at main bearings due to inertia of pistons and rods accounted
- Allowance in calculations for additional loads at pistons and bearings due to motored gas force with cylinder head on



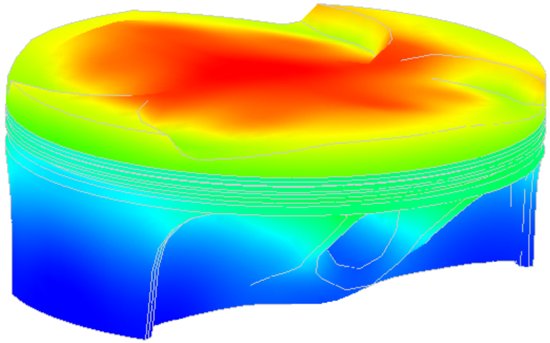
Whole engine motored friction loss (2)

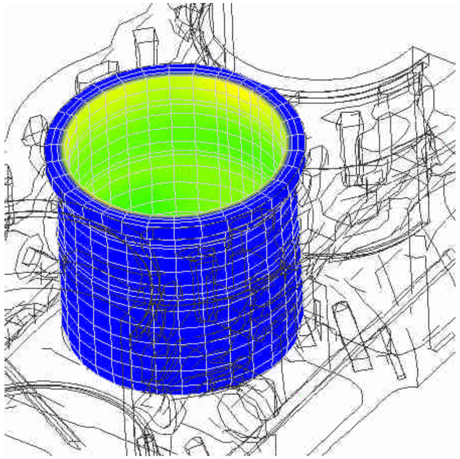
- Same data but with results grouped by subsystem
- Pumping losses excluded
- At 15000 rpm
  - Crankshaft 25.1%
  - Transmission 7.9%
  - Pumps 11.4%
  - Crankcase pumping 8.5%
  - Pistons 33.9%
  - Valve trains 13.2%



Full load fired friction loss by analysis

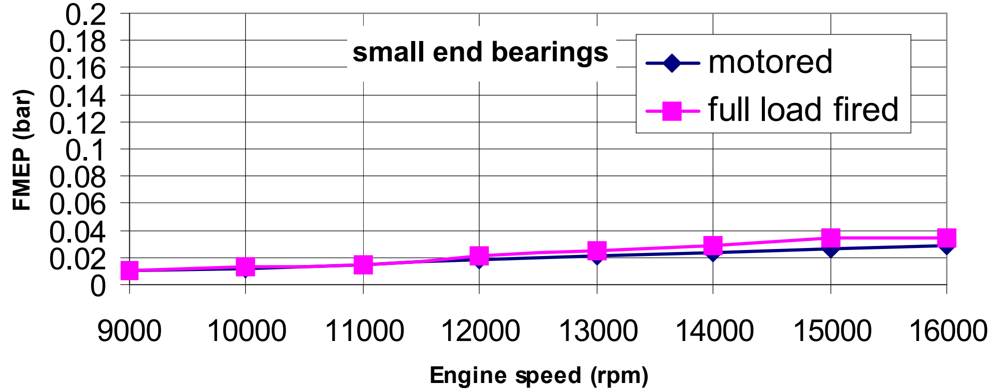
- Next step was to use CAE tools to model the following under fired engine conditions
  - Piston rings
  - Piston skirt
  - Small end bearing
  - Big end bearings
  - Main bearings
- The following were accounted for
  - Increased cylinder pressure
  - Increased component temperature and effect on clearances
  - Increased oil temperature and effect on oil viscosity

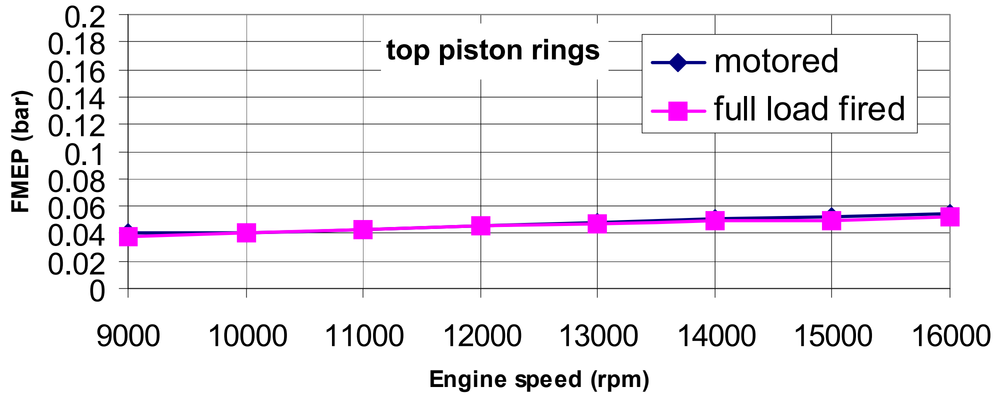


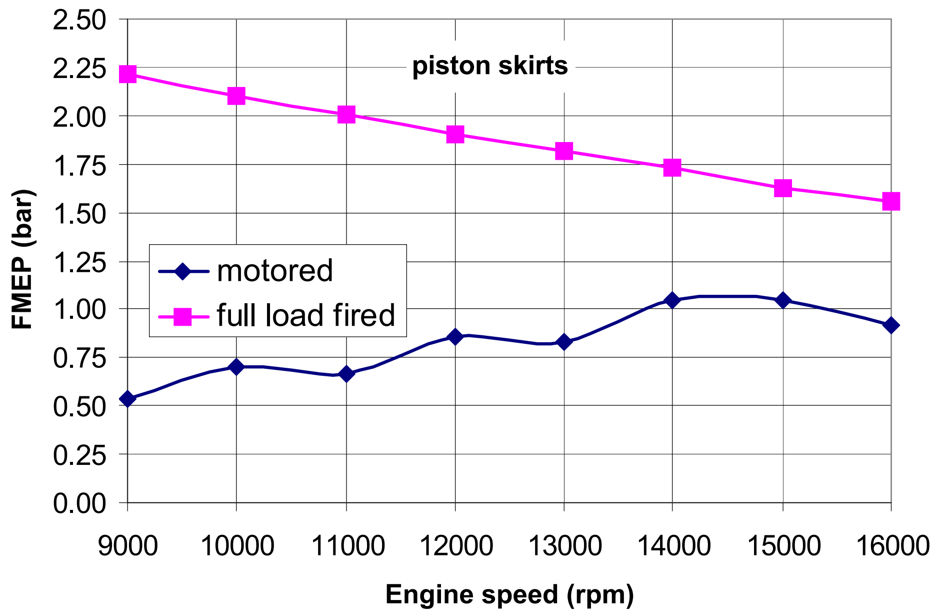


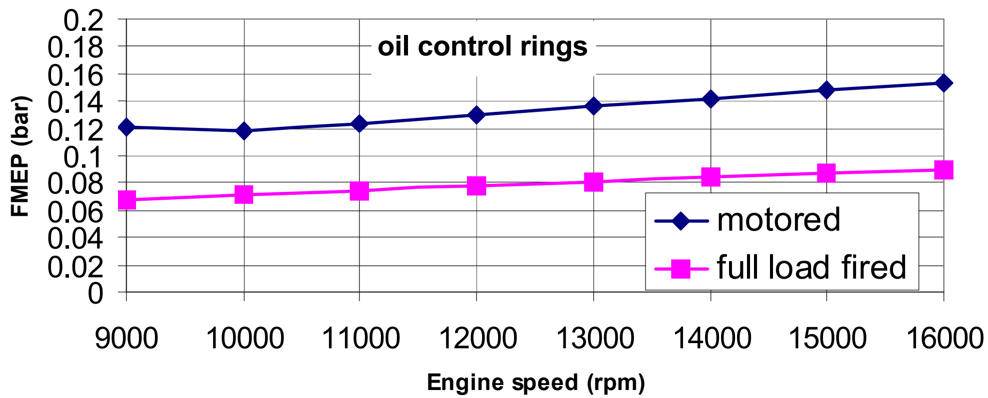
Full load fired friction loss at piston group (1)

- Fired conditions lead to
  - slightly higher loss at small end bearings
  - no significant change at top piston rings
  - reduced loss at oil control rings
  - significantly increased loss at piston skirt (particularly at lower engine speeds)



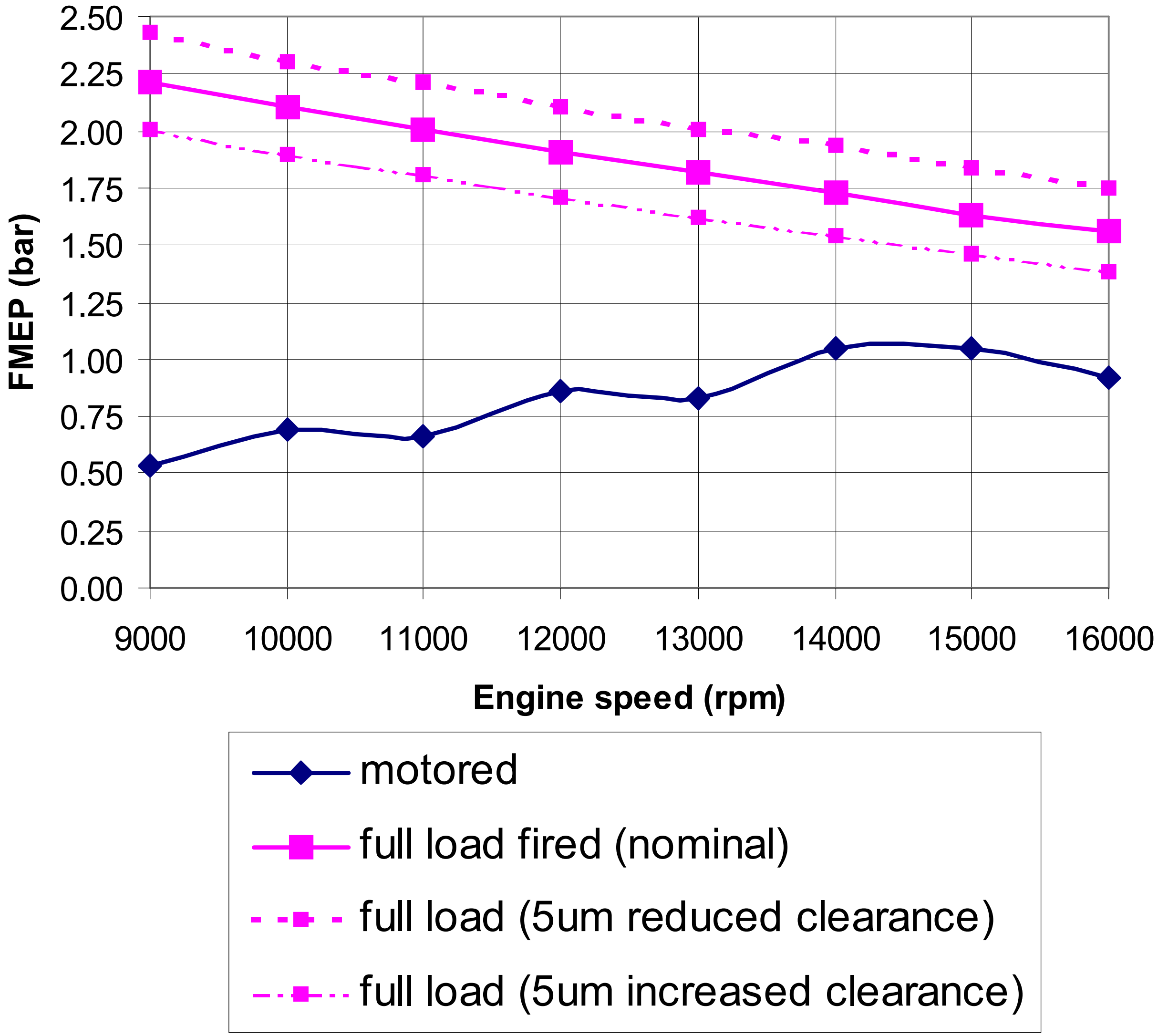






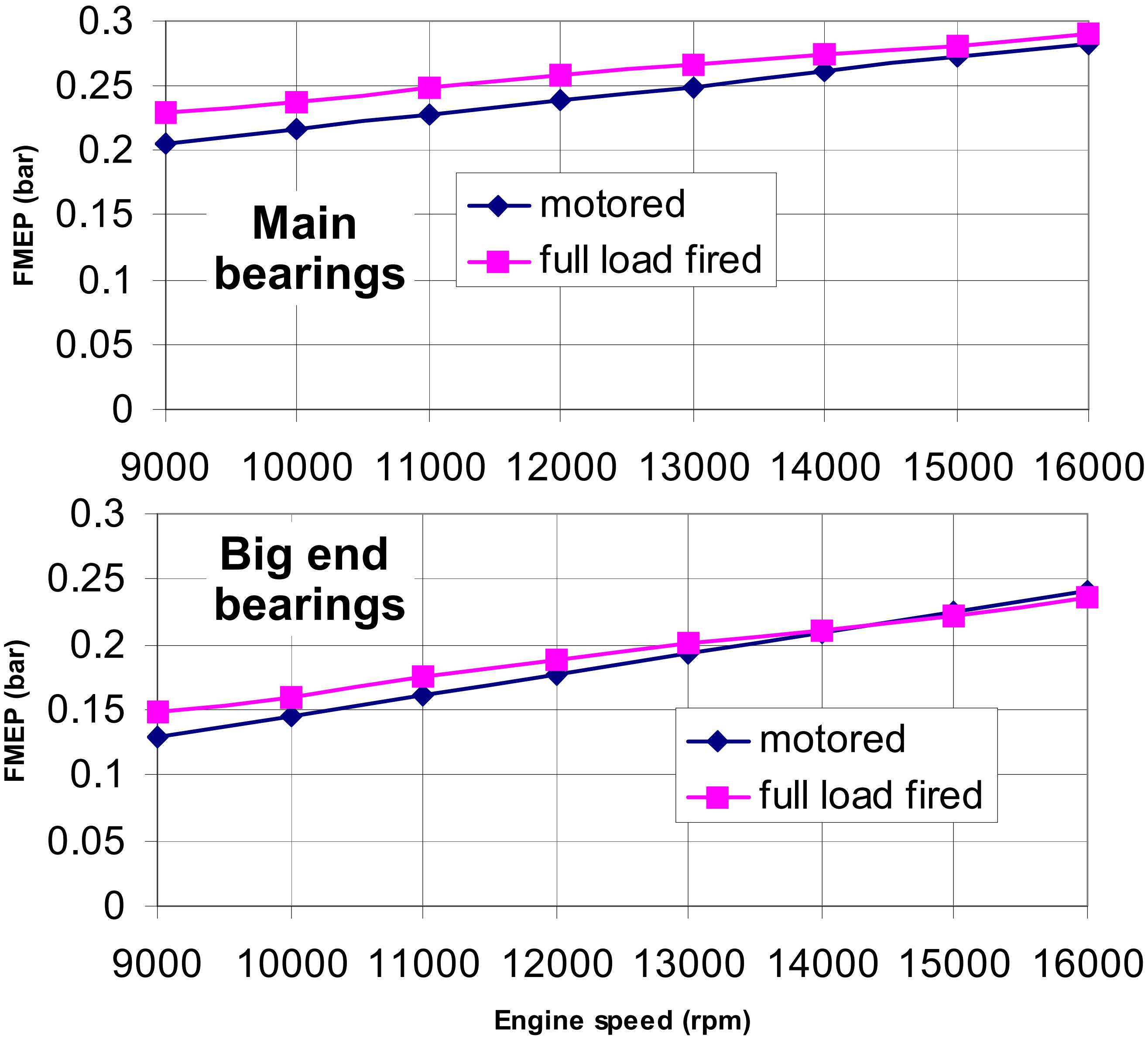
Full load fired friction loss at piston group (2)

- Predicted losses at piston skirt are highly sensitive to skirt/liner clearance which is sensitive to assumed component temperatures
  - Results shown with +/-5 micron clearance
  - No change in component or oil temperatures
- Model could be refined with better knowledge of component temperatures



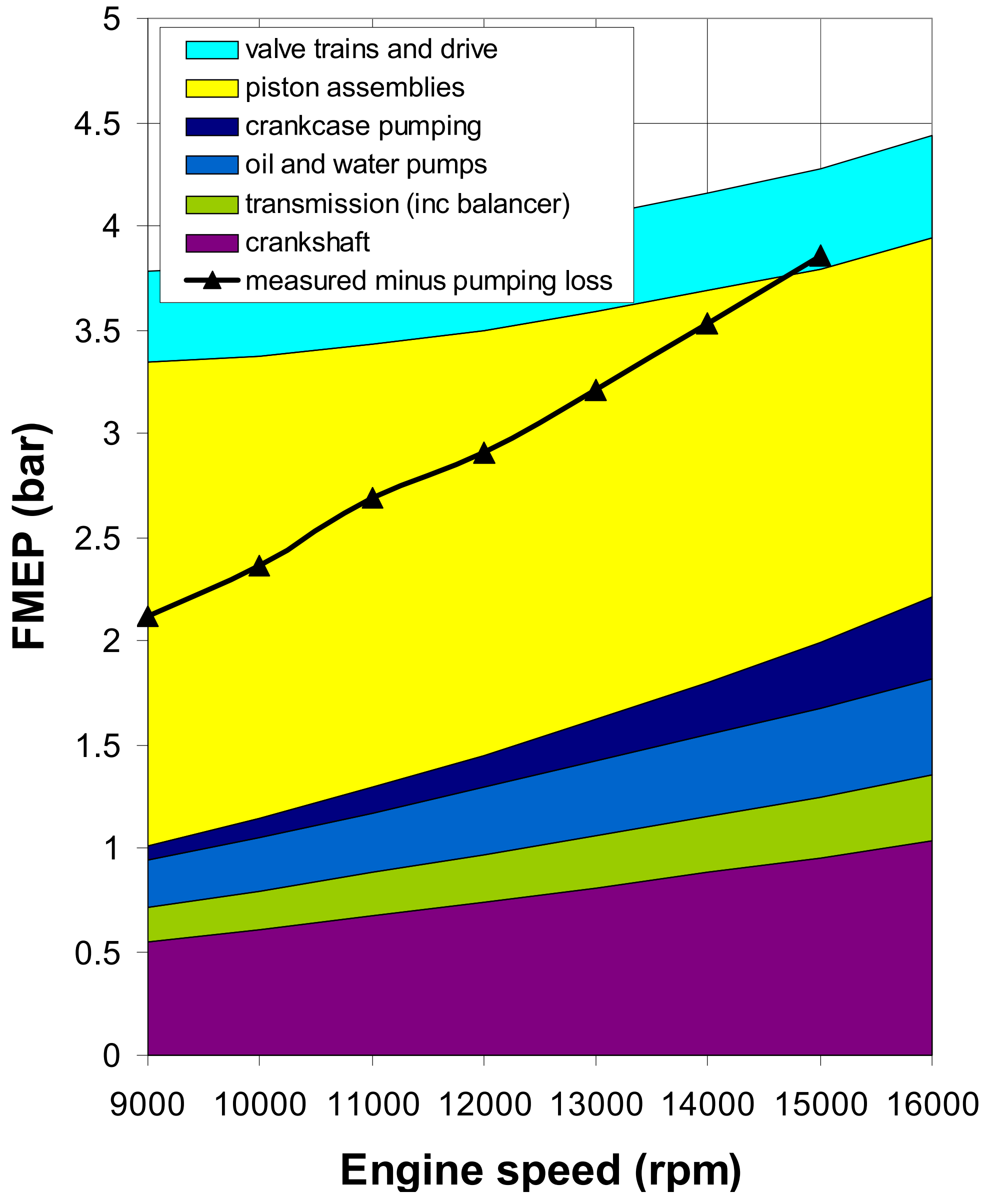
Full load fired friction loss at crank train bearings

- Fired conditions lead to
  - slightly higher loss at lower speeds
  - but similar losses at high speed as inertia forces dominate



Whole engine full load fired friction loss

- Results grouped by subsystem
- Pumping losses excluded
- Measured line is whole engine motored data for comparison
- At 15000 rpm
  - Crankshaft 22.2%
  - Transmission 6.9%
  - Pumps 10.0%
  - Crankcase pumping 7.5%
  - Pistons 41.9%
  - Valve trains 11.5%



Presentation contents

Conclusions

- Overall friction level can be estimated easily based on historical data
- If more complex calculations are performed there are many problems
  - All major contacts involve asperity contact losses and oil shear losses
  - Asperity contact losses dominate if dimensions from drawings are used
    - but as components wear during run-in period these losses reduce
  - This makes true prediction difficult
    - but if worn component geometry and surface roughness data are used as model inputs then better results are possible
- Some interesting insights can be obtained by
  - use of relatively inexpensive motored strip test
  - combined with use of advanced CAE tools
- But to make further progress we need
  - measured data from fired engines at high speed to validate software
  - improved models of mixed lubrication including 3D surface texture effects

Thank you for your attention

Any Questions?