

Engine Friction Accounting Guide and Development Tool for Passenger Car Diesel Engines

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ABSTRACT

The field of automotive engineering has devoted much research to reduce fuel consumption to attain sustainable energy usage. Friction reductions in powertrain components can improve engine fuel economy. Quantitative accounting of friction is complex because it is affected by many physical aspects such as oil viscosity, temperature, surface roughness and component rotation speed.

The purpose of this paper is two-fold: first, to develop a useful tool for evaluating the friction in engine and accessories based on test data; second, to exercise the tool to evaluate the fuel economy gain in a drive cycle for several friction reduction technologies.

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INTRODUCTION

To make development decisions, engineers want to know the sensitivity of engine component options on fuel consumption. Once a specific friction improvement technology is developed on the engine, the project manager wants to determine whether the decision will be a worthwhile investment. But it is very difficult to estimate the effects of these changes in a specified engine in a driving cycle without a system tool to address the integrated aspect of the improvements. The purpose of this work is to develop such a tool.

Before the market paradigm shifts to electric vehicles, which will have to have cost and energy competitiveness, internal combustion engines will need to support transportation demands with optimized technology such as control logic, better engineering and scientific capability. Therefore, research on improving the internal combustion engine is still relevant in the immediate future.

Research on engine friction has been done by many scientists using multiple approaches[1, 2, 3, 4, 5]. To estimate Friction Mean Effective Pressure(FMEP), D.Sandoval[3] studied the basic scaling factors governing friction for an internal combustion engine. This study adds modifications

based on the basic framework of Ref. [3] using further correlations from measured data.

To consider thermal effects, Paul J. Shayler [4] introduced a power law dependence of the various FMEP's on oil viscosity which was evaluated at the operating temperatures. He calibrated the power law exponent using test data.

Using data and theoretically based scaling relationships, a FMEP estimation tool named "GUIDE" has been developed in this work. Basic investigation of friction behavior and a systematic sensitivity analysis are also done by using GUIDE.

Next stage development would have to apply cost factors which need to consider the tough automotive market, customer needs, the fuel economy effect, and the impact on GHG (Green House Gas) emission.

TEST DATA BASED SIMULATION MODEL

This study is organized as follows. First, a brief overview of the engine component friction model is presented. This model is divided into three categories: mechanical friction of engine moving parts, basic auxiliaries, and belt-driven auxiliaries.

Basic auxiliaries are oil pump, fuel supply pump for diesel application, and water pump. Belt driven auxiliaries are air conditioning compressor, electric generator, and power steering pump. With increased application of MDPS (Motor Driven Power Steering System), however, power steering pump has been removed from the list of engine auxiliaries.

The engine indicated torque is not entirely delivered to the wheels, because the torque is lowered by losses such as the pumping, mechanical friction and front auxiliary power consumption.

Motoring friction differs from firing friction. There is difference due to the gas pressure loading on the piston, the pumping losses of intake throttle and the exhaust process. This study considered pumping loss as intake throttle loss from measured data and the model is calibrated by the measured friction data sets which are collected by the strip down motoring test in each engine.

Normally, rig test and engine friction test are carried out to obtain friction loss in the steady state. Hence it is difficult to assess the losses related to individual component friction in a transient driving cycle. Therefore it is very useful to embed the FMEP model in a quasi-static manner but with measured component temperature data in a transient driving cycle model.

Of course, there are significant uncertainties in the friction test data. But it is necessary to establish a standard power consumption data base for each engine and standard data sets are very important to develop new friction related technology. This study establishes the methodology to use standard data sets for real driving cycles and to estimate fuel economy improvement with FMEP distribution.

Calibrating Component Friction Correlation with Measured Data

Table.1. Engine Specifications for the study

ENG	A	B	C
Displacement[cc]	1,685	1,995	2,497
No. of cylinders	4	4	4
Bore [mm]	77.2	84	91
Stroke [mm]	90	90	96
Fuel system	Common Rail	Common Rail	Common Rail
Balance shaft	X	O	O

The engine friction model is divided into basic moving systems, basic auxiliaries, and alternative auxiliaries. The basic moving parts are classified as 4 main moving systems: crank shaft drive, piston and connecting rod, valve train, and balance shaft drive. Auxiliaries comprise two categories: essential one and alternative one. With theoretical formulae derived by D.Sandoval [3], coefficients were evaluated by non-linear equation fitting and linear equation fitting method

applied to engine data obtained from three different size passenger car diesel engines, the engine specifications are shown in [Table 1](#).

Crank shaft

Crank shaft drive power consumption is divided into 3 categories [3]. These consumptions consist of front and rear oil seal, main bearing hydrodynamic friction and turbulent dissipation. The FMEP of the crankshaft drive is shown in [equation \(1\)](#).

$$C_{fmeep} = C_{c1} \times \frac{D_b}{B^2 S_{nc}} + C_{c2} \times \left(\frac{\mu}{\mu_0}\right)^n \times \frac{D_b^3 L_b n_b}{B^2 S_{nc}} N + C_{c3} \times \frac{D_b^2 n_b}{n_c} N^2 \quad (1)$$

Coefficients of each term have meaning and can be used to compare which design is better in view of friction loss when the coefficients have been determined. The coefficients may be used as a metric to compare hydrodynamic, turbulent dissipation, and seal friction for the various designs.

[Table 2](#) shows the correlation coefficients which have been evaluated for engines A, B and C.

Table 2. Correlated coefficients of Crank shaft FMEP

ENG	$C_{C1}[x10^{-1}]$	$C_{C2}[x10^{-1}]$	$C_{C3}[x10^{-4}]$
A	1.5	9.5	0.36
B	1.22	7.4	0.36
C	1.22	7.5	0.35

Piston and connecting rod

Piston and connecting rod power consumptions are divided into 4 categories. Those consumptions consist of piston friction to the bore, piston ring friction with gas pressure loading, and hydrodynamic journal bearing friction. FMEP of piston and con-rod is shown in [equation \(2\)](#)

$$r_{fmeep} = C_{r1} \times \left(\frac{\mu}{\mu_0}\right)^n \frac{S_p}{B} + C_{r2} \times \frac{F_t}{F_{t0}} C_r \left[1 + \frac{100}{N} \right] \left[\frac{1}{B^2} \right] + C_{r3} \times \left(\frac{\mu}{\mu_0}\right)^n \frac{ND_b^3 L_b n_b}{B^2 S_{nc}} + \frac{P_i}{P_a} \left[0.088 \left(\frac{\mu}{\mu_0}\right)^n r_c + 0.182 r_c^{(1.33-2KS_p)} \right] \quad (2)$$

The coefficients for each category are shown [table 3](#).

Table 3. Correlated coefficients of Piston& Con rod FMEP

ENG	$C_{r1}[x10^1]$	$C_{r2}[x10^{-2}]$	$C_{r3}[x10^{-2}]$
A	13.9	5	9.5
B	17	3.9	9.6
C	8	7.6	9.56

Valve train drive

Valve Train power consumption is divided into 4 categories. They are camshaft journal friction, cam and follower friction, oscillating hydrodynamic friction, and oscillating mixed lubrication friction. The total valve train FMEP is shown in [equation \(3\)](#).

$$V_{fmeP} = C_{v1} \times \left(\frac{\mu}{\mu_0}\right)^n \frac{N n_{cb}}{B^2 S n_c} + C_{ff} \times \left[1 + \frac{500}{N}\right] \frac{n_v}{S n_c} + C_{rf} \times \left[\frac{N n_v}{S n_c}\right] + C_{oh} \left(\frac{\mu}{\mu_0}\right)^n \left[\frac{L_v^{1.5} N^{0.5} n_v}{B S n_c}\right] + C_{om} \times \left[1 + \frac{500}{N}\right] \frac{L_v n_v}{S n_c} \quad (3)$$

The coefficients for [equation \(3\)](#) are shown in [table 4](#) for engines A, B, and C.

Table 4. Correlated coefficients of Valve Train FMEP

ENG	$C_{v1}[x10^{-9}]$	C_{ff}	$C_{rf}[x10^{-6}]$	C_{oh}	C_{om}
A	105.0	0	5.0	0.080	20.80
B	92.5	0	9.5	0.135	12.00
C	90.0	0	5.0	0.100	18.00

Balance shaft drive

Balance shaft power consumption is divided into categories similar to the crank shaft drive except for the oil seal term. These consumptions consist of main bearing hydrodynamic friction, turbulent dissipation, and a speed independent value. The expression for the balance shaft FMEP is shown in [equation \(4\)](#).

$$B_{fmeP} = C_{b0} + C_{b1} \times \left(\frac{\mu}{\mu_0}\right)^n \frac{N_b D_{bb}^3 L_{bb} n_{bb}}{B^2 S n_c} + C_{b2} \times \frac{D_{bb}^2 N_b^2 n_{bb}}{n_c} \quad (4)$$

The fit coefficients are shown in [table 5](#) for engines B and C. Engine A does not have a balance shaft. Engine C has a substantially high value for C_{b0} (the speed independent term). The difference between the two engines is attributed to the structural difference of the two respective balance shafts.

Table 5. Correlated coefficients of Balance shaft FMEP

ENG	C_{b0}	C_{b1}	$C_{b2}[x10^{-5}]$
B	0.2	3.2	4.8
C	8.0	0.9	4.8

The [equations \(1, 2, 3, 4\)](#), together with the calibration coefficients in [Tables \(1, 2, 3, 4, 5\)](#), form the basic friction model for the engine. Fidelity of the model depends very much on the component friction data set used for calibration. The calibration, however, can easily be updated when revised data are available.

Thermal and oil viscosity effect

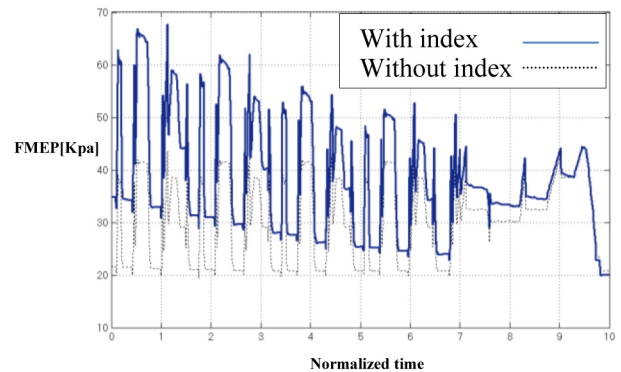
The friction terms due to hydrodynamic lubrication need to be modified to account or the effect of temperature on the oil viscosity. Power law dependence as depicted in [equation \(5\)](#) has been proposed by P.Shayler [4].

$$FMEP'_0 = FMEP_0 \times \left(\frac{\mu}{\mu_0}\right)^n \quad (5)$$

Table 6. Correlated Viscosity-Friction Index of Engine components

Engine component	Viscosity-Friction Index
Crank shaft friction	0.5
Piston & Con Rod friction	0.35
Valve Train friction	0.5
Oil pump power consumption	0.3
Vacuum pump Power consumption	0.3

Using component friction data measured at a variety of temperatures, the Viscosity-Friction Index(n) in [equation \(5\)](#) is tabulated in [table 6](#) for the different engine components.

**Figure 1. The effect of viscosity-friction index through the NEDC cycle**

When the temperature effect on oil viscosity is included, the values for FMEP in the warm-up process can be calculated for a specified test cycle. [Figure 1](#) shows the temperature effect on FMEP via viscosity change in the NEDC (New European Driving Cycle).

The impact of warm up strategy on friction can also be assessed. [Figure 2](#) shows four oil temperature curves taken from NEDC measured data: one applies to base oil temperature and the others to employing faster warm-up period of 10%, 20% and 30% shorter than the base value. The