The impact of Coefficient Of Friction reduction on potential fuel consumption in Internal combustion engines

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The most popular sources of energy are transport internal combustion engines. At the same time, they cause substantial pollution of the environment due to harmful discharge of exhausted gas and consume a lot of oil-products.

Therefore, fuel economy is one of the most important factors for both customer satisfaction and environmental protection. In order to improve fuel economy great efforts are being made to reduce **mechanical losses** by reducing **friction loss**. Components and their tribology plays an important role in reducing friction.

As follows from [1,2], the specific fuel consumption ($b_{s.f.c.}$), or the fuel consumption per unit of the effective (brake) power in unit time is

$$b_{s.f.c} = \frac{3600}{H_u \cdot \eta_b} \qquad (1)$$

Here, $\eta_b = \eta_i \cdot \eta_m$, where η_b –effective efficiency, η_i – indicatory efficiency and η_m – mechanical efficiency of the engine.

Considering above (1) we obtain

$$b_{s.f.c} = \frac{3600}{H_u \cdot \eta_i \cdot \eta_m} \qquad (2)$$

where H_u – low heat value of fuel.

The mechanical efficiency $\eta_m = p_b/p_i$, where $p_b = p_i - p_{m.l.}$; p_b is the mean effective pressure, p_i is the mean indicatory pressure and $p_{m.l.}$ is mean mechanical losses pressure of engine working cycle. From these definition it follows that $\eta_m = 1 - p_{m.l} / p_i$, thus allowing to derive from (2) the following expression for the fuel consumption per hour:

$$b_{s.f.c} = \frac{3600}{H_u \cdot \eta_i \cdot \left(1 - {p_{m.l.}}/{p_i}\right)} \, . \qquad (3)$$

This formula (3) defines the relations between specific fuel consumption ($b_{s.f.c.}$), and mechanical losses ($p_{m.l.}$). It should be noted that internal combustion engines are divided into two types: spark ignition engines and diesel engines.

Each engine type has it's own operating cycle parameters, including mechanical losses, as illustrated in Fig.1.The data was obtained from [1,2,3] and generalized by testing medium power engines ($N_b = 50 \div 100$ KW where N_b is the break power of the engine).

From expression (3), it can be observed that a 10% decrease of $p_{m.l.}$ (from $p_{m.l.} = 0.2$ MPa to $p_{m.l.} = 0.18$ MPa) will decreases fuel consumption by ~ 2.5% (for identical combustion conditions $p_i = 1.0$ MPa).

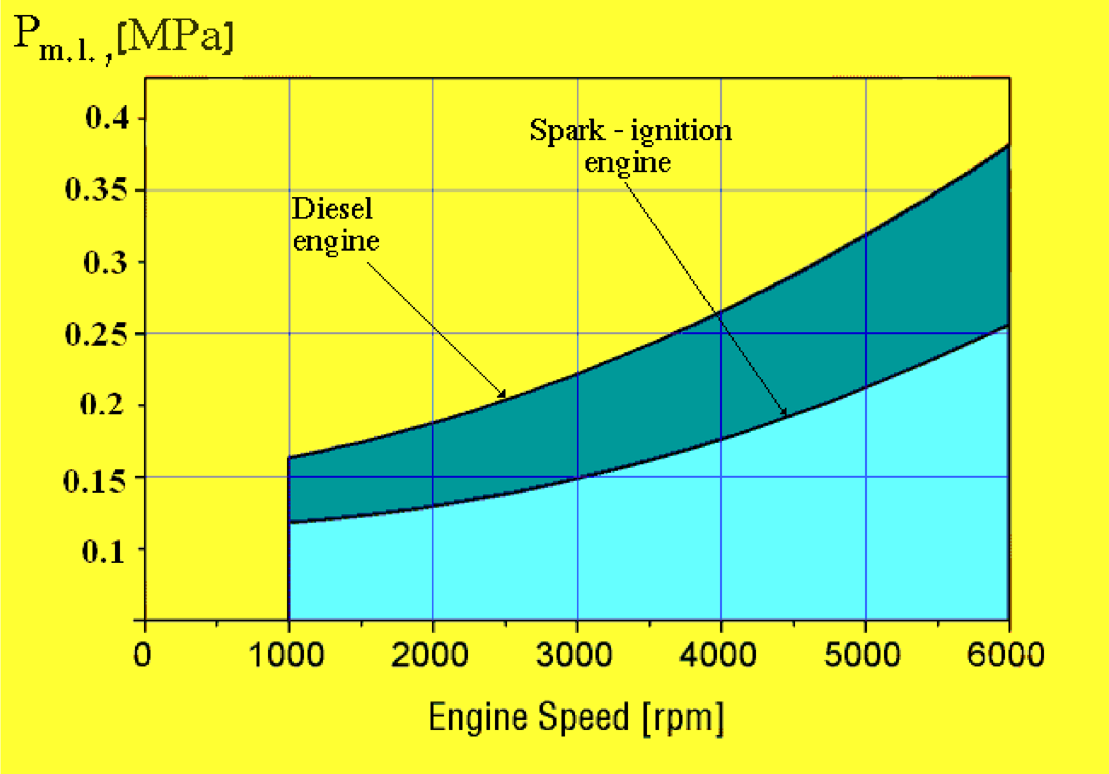

Fig.1. Mean mechanical losses (friction) as a function of engine speed.

Total engine mechanical losses are the sum of the friction losses in the engine's separate sub-assemblies, units and auxiliaries such as cylinder – piston group, crankshaft mechanism, valve-train mechanism and other parasite drives as illustrated in Fig.2.

In Fig.2 it can be observed that the largest share of engine's mechanical losses is at the cylinder – piston group – about 46%; the second largest cause of friction losses is the crankshaft mechanism including the large bearing of the connecting rod – about 15%; Valve-train mechanism causes about 2.5% and so on.

The mechanical losses of every one of theses components can be normalized against the engine's piston area ($A_{piston} = \pi D^2_{pist.}/4$) and expressed as a function of the average friction force (F_i), that is

$$p_{m.l.i} = F_i / A_{piston} . \qquad (4)$$

Here, $F_i = \sum L_{m.l.i}/S_{stroke.}$, where $\sum L_{m.l.i}$ is the sum of friction work per cycle; $S_{stroke.}$ is the piston stroke and $L_{m.l.i} = N_i \cdot f_i \cdot S_{fr.}$. Here N_i is the normal load; f_i is the friction coefficient and $S_{fr.}$ is the friction way. These values are particular to every given component.

That is why
$$p_{m.l.i} = \frac{N_i \cdot f_i \cdot S_{fr.}}{S_{str} \cdot A_{piston}} . \qquad (5)$$

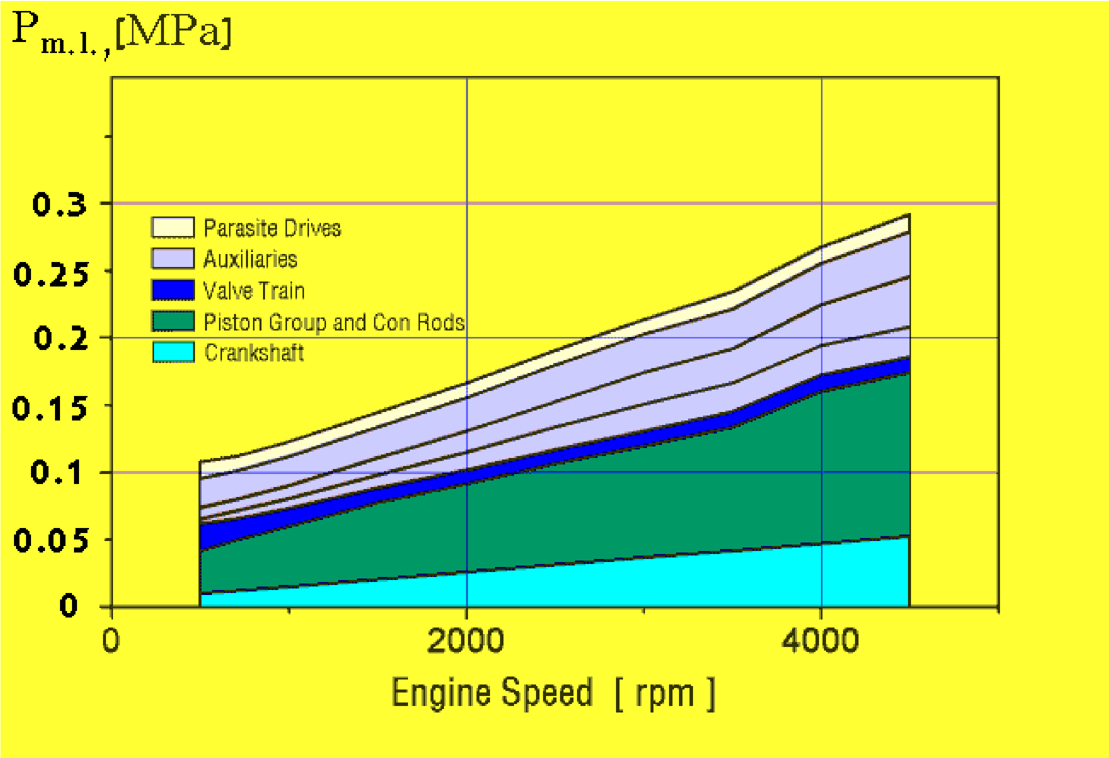

Fig.2. Engine components' contribution to mechanical losses.

Therefore, the sum of total mechanical losses of an engine can be presented as a sum of partial values [1,2,3] of each component for $S_{fr.} = S_{stroke}$:

$$p_{m.l.} = \frac{1}{A_{piston}}[A(N_i \cdot f)_{piston} + B(N_i \cdot f)_{p.r.} + C(N_i \cdot f)_{c\text{-}r} + D(N_i \cdot f)_{cr\text{-}sh.} + E(N_i \cdot f)_{v\text{-}tr.} +$$

$$+ G(N_i \cdot f)_{auxiliar.}]. \qquad (6)$$

In eq.(6) the coefficients A,B,C,D,E and G represent the contribution of each component to the sum of engine's mechanical losses.

From Fig.2 and Ref.[1,2,3] it can be deduced that the share of each component in the total mechanical losses is:

Cylinder – Piston Rings – B= 0.3;

Cylinder – Piston – A= 0.2;

Connecting-Rod Bearings – C= 0.1;

Crank- Shaft Bearings – D= 0.05;

Valve-train Mechanism – E= 0.03;

Auxiliaries – G= 0.32.

For determination of the friction coefficient influence of each component on the total mechanical losses equation (6) can be used with initial values of friction coefficient of components as specified in Ref.[4] and shown in table 1.

Interface	**Baseline friction coefficient**	**Simulation program used**	**Friction model**
Cam–follower	0.005	VALDYN	Simple
Cam–cam bearing	0.02	VALDYN	Simple
Rocker arm–rocker support	0.02	VALDYN	Simple
Pushrod socket–pushrod	0.05	VALDYN	Simple
Rocker tip–valve bridge	0.05	VALDYN	Simple
Piston skirt–cylinder liner	0.08	PISDYN	Detailed hydrodynamic & boundary lubrication
Piston rings–cylinder liner	0.12	RINGPAK	Detailed hydrodynamic & boundary lubrication
Piston pin–piston	0.08	PISDYN	Detailed hydrodynamic & boundary lubrication
Connecting rod small end	0.12	ORBIT	Detailed hydrodynamic & boundary lubrication
Connecting rod large end	0.12	ORBIT	Detailed hydrodynamic & boundary lubrication

Interface	**Baseline friction coefficient**	**Simulation program used**	**Friction model**
Crankshaft main bearing	0.12	ORBIT	Detailed hydrodynamic & boundary lubrication
na	na	na	na

Table1. Baseline friction coefficients at each interface [4]

From table (1), eq. (6) can can be written as:

$$p_{m.l.} = \frac{N_i}{A_{piston}}(0.2 \cdot 0.08 + 0.3 \cdot 0.12 + 0.1 \cdot 0.12 + 0.05 \cdot 0.12 + 0.03 \cdot 0.03 + + 0.32 \cdot 0.1)$$

$$p_{m.l.} = 0.1029 \frac{N_i}{A_{piston}}. \qquad (7)$$

For the diesel used by FriCSo for testing – a John Deer 4 cylinder type – with piston diameter = 102 mm, $A_{piston} = 81.7\ cm^2$ and $p_{m.l.} = 0.2$ MPa. In the case of this specific engine, using equation (7), the special normal load $N_i = 15.9 \cdot 10^3 N$.

Therefore, for this diesel expression (6) can be written as follows:

$$p_{m.l.} = 1.947\,(0.2 \cdot f_{piston} + 0.3 \cdot f_{p.r.} + 0.1 \cdot f_{c-r} + 0.05 \cdot f_{cr-sh.} + 0.03 \cdot f_{v-tr.} + +0.32 f_{auxiliaries}). \qquad (8)$$

The initial friction coefficients of the individual components are obtained from Ref [4] and Table 1. They can be used to calculate the total mechanical losses of components for given John Deere diesel as:

$p_{m.l.} = 0.2$ MPa.

A decrease of **20%** in the initial COF of every component in equation (8) results in reduced mean effective mechanical losses pressure to: $P_{m.l.}$ = 0.17 MPa.

The reduction of mechanical losses in this case is 17.6% that in accordance with equation (3) amounts to a **fuel consumption reducing of ~3.5%** (for identical combustion conditions p_i =1.0 MPa – see above).

If the initial COF's are decreased by reducing each of the individual friction coefficient values **by 40%**, the mean effective mechanical losses pressure $P_{m.l.}$ will be 0.144 MPa. Such decrease corresponds to a 28% reduction in mechanical losses yielding a **fuel consumption reduction of ~7%.**

Extrapolation these results quantities the benefits of a **90%** reduction in COF as yielding a **fuel economy improvement of ~ 11.5%.** Therefore, for a medium power diesel engine (all other conditions being held constant), a reduction in friction coefficient in the range of 10% to 90% should yield an improvement in fuel economy of between ~2.0% to ~11.5%.

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References

1. Heywood, J.B., Internal Combustion Engine Fundamentals, by McGraw-Hill Book , Co – Singapore,1988, 789 p.
2. Lukanin , V.N. ' " Internal combustion engines " , Publishing House "Mir" , 1990 , 310 p.
3. FEV Motorentechnik GmbH , (www.fev.com) , Germany – European Technical Center
4. Fox , I.E. " Numerical evaluation of the potential for fuel economy improvement due to boundary friction reduction within heavy-duty diesel engines " , J. Tribology International 38 , 2005 , pp. 265-275

Attachment A

ref.: Dr. G. Ryk et. al. (The impact of Coefficient of Friction on potential fuel consumption in Internal combustion engines)

1. Friction Related Mechanical Losses in a John Deere 4 Cylinder Engine and Impact of Reduced Coefficient of Friction:

	Relative Share of Mech Losses	Baseline Friction Coefficient					Change in COF	New Pm.l.	Change in Pm.l.	Increase in Fuel Economy
							-10.0%	0.182	-9.09%	2.16%
							-20.0%	0.167	-16.67%	3.95%
Cylinder-Piston Rings	20.0%	0.08	0.016	15.5%			-30.0%	0.154	-23.08%	5.47%
Cylinder-Piston	30.0%	0.12	0.036	35.0%			-40.0%	0.143	-28.57%	6.78%
Connecting Rods Bearings	10.0%	0.12	0.012	11.7%			-50.0%	0.134	-33.33%	7.91%
Crank Shaft Bearings	5.0%	0.12	0.006	5.8%			-60.0%	0.125	-37.50%	8.89%
Valve Train	3.0%	0.03	0.0009	0.9%	Ni		-70.0%	0.118	-41.18%	9.77%
Auxiliaries	32.0%	0.10	0.032	31.1%	A piston	P m.l.	-80.0%	0.111	-44.44%	10.54%
Total	100.0%		**0.1029**		**1.94614**	**0.200**	-90.0%	0.105	-47.37%	11.24%

Formulae:

$$b(sfc) = \frac{3600}{Hu \times Nb}$$

where Nb = Ni x Nm, where Nb = effective efficiency, Ni = indicatory efficiency, and Nm = Mechanical efficiency of engine

or

Bsfc = 3600/(Hu x Ni x (1- (Pml/Pi))

Ni/A piston =	1.9461										
A piston =	81.7	cm2									
COF Change =	0.0%	-10.0%	-11.3%	-20.0%	-30.0%	-40.0%	-50.0%	-60.0%	-70.0%	-80.0%	-90.0%
Pm.l. Change =	3600	-9.09%	-10.16%	-16.67%	-23.08%	-28.57%	-33.33%	-37.50%	-41.18%	-44.44%	-47.37%
Pm.l. =	0.200	0.182	0.180	0.167	0.154	0.143	0.134	0.125	0.118	0.111	0.105
Pi =	1.0										
Ni =	15.9										
Hu =	138,700										
Pm.l. x =	0.0020	0.0020	0.0020	0.0019	0.0019	0.0019	0.0019	0.0019	0.0018	0.0018	0.0018
Bsfc Change =	na	2.16%	2.41%	3.95%	5.47%	6.78%	7.91%	8.89%	9.77%	10.54%	11.24%

2. Friction Related Mechanical Losses in a Typical Passenger Car and Impact of Reduced Coefficient of Friction:

	Friction Pm.l.	Relative Share of Mech Losses	Baseline Friction Coefficient					Change in COF	New Pm.l.	Change in Pm.l.	Increase in Fuel Economy
								-10.0%	0.160	-8.12%	1.88%
								-20.0%	0.149	-14.92%	3.45%
Bearings	1.00	15.2%	0.120	0.0181818	20.1%			-30.0%	0.138	-20.66%	4.77%
Valve Train	1.30	19.7%	0.030	0.0059091	6.5%			-40.0%	0.128	-25.58%	5.91%
Piston Assembly	2.80	42.4%	0.104	0.0441212	48.9%			-50.0%	0.119	-29.84%	6.89%
Accessories	1.10	16.7%	0.100	0.0166667	18.5%	Ni		-60.0%	0.112	-33.57%	7.75%
Other	0.40	6.1%	0.089	0.0053636	5.9%	A piston	Pm.l.	-70.0%	0.105	-36.86%	8.51%
	6.60	ERR		**0.0902424**	100.0%	**1.984**	0.179	-80.0%	0.099	-39.79%	9.19%
								-90.0%	0.094	-42.40%	9.79%

Formulae:

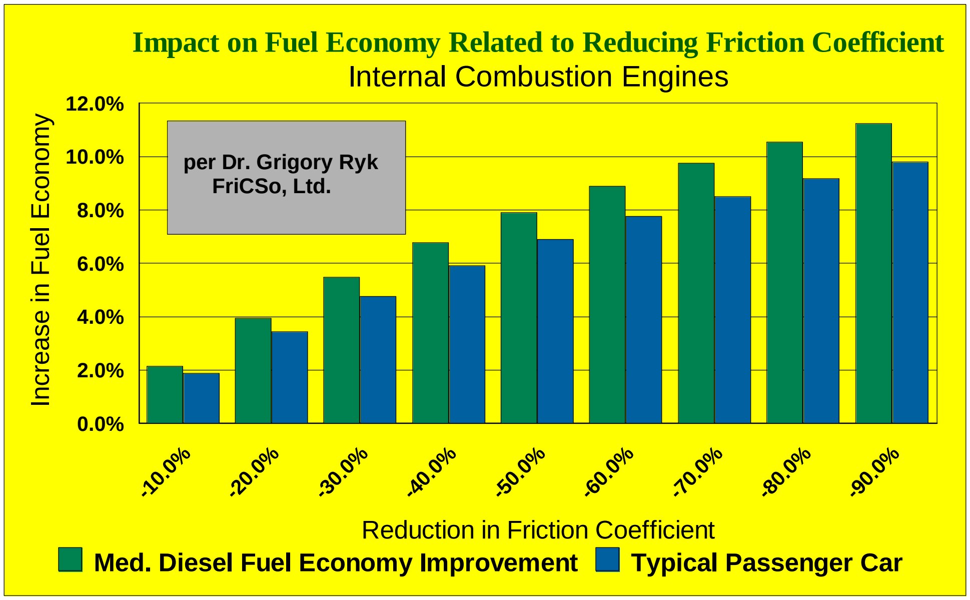
$$b(sfc) = \frac{3600}{Hu \times Nb}$$

where Nb = Ni x Nm, where Nb = effective efficiency, Ni = indicatory efficiency, and Nm = Mechanical efficiency of engine

or

Bsfc = 3600/(Hu x Ni x (1- (Pml/Pi))

Ni/A piston =	1.984										
A piston =	161.78	cm2									
COF Change =	0.0%	-10.0%	13.8%	-20.0%	-30.0%	-40.0%	-50.0%	-60.0%	-70.0%	-80.0%	-90.0%
Pm.l. Change =	3600	-8.12%	-10.84%	-14.89%	-20.62%	-25.53%	-29.79%	-33.51%	-36.80%	-39.72%	-42.33%
Pm.l. =	0.179	0.163	0.157	0.149	0.138	0.128	0.119	0.112	0.105	0.099	0.094
Pi =	1.0										
Ni =	32.1										
Hu =	125,000										
Pm.l. x =	0.0011	0.0011	0.0011	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010
Bsfc Change =	na	1.88%	2.51%	3.45%	4.77%	5.91%	6.89%	7.75%	8.51%	9.19%	9.79%


Impact on Fuel Economy Related to Reducing Friction Coefficient
Internal Combustion Engines
per Dr. Grigory Ryk
FriCSo, Ltd.
Increase in Fuel Economy
12.0%
10.0%
8.0%
6.0%
4.0%
2.0%
0.0%
-10.0%
-20.0%
-30.0%
-40.0%
-50.0%
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Reduction in Friction Coefficient
Med. Diesel Fuel Economy Improvement
Typical Passenger Car