

# Table of Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Overview: background and context.....	3
1.1.1	Energy Consumption in Transportation .....	4
1.1.2	Energy consumption in passenger cars .....	7
1.1.3	Mechanical losses in ICE .....	8
1.1.4	Modeling friction losses in ICE .....	9
1.2	Objectives of the thesis.....	10
1.2.1	Validate a steady-state friction model .....	10
1.2.2	Validate a transients friction model .....	10
1.2.3	Assessment of performance of different Low Viscosity Engine Oils in model validated .....	11
1.2.4	Evaluation of different cylinder surfaces in the model validated .....	11
1.3	Thesis document structure .....	12
1.4	Thesis publications .....	13
	Bibliography .....	14
<b>2</b>	<b>Literature Review: Friction losses in ICE</b>	<b>17</b>
2.1	Introduction .....	19
2.2	Lubrication in ICE .....	21
2.2.1	General lubrication theory.....	21

---

2.2.2	Hydrodynamic lubrication . . . . .	22
2.2.3	Elastohydrodynamic lubrication . . . . .	24
2.2.4	Mixed lubrication . . . . .	24
2.2.5	Boundary lubrication . . . . .	25
2.2.6	Engine oil properties . . . . .	26
2.2.6.1	Introduction . . . . .	26
2.2.6.2	Viscosity . . . . .	28
2.2.6.3	Effect of temperature on viscosity . . . . .	29
2.2.6.4	Effect of pressure on viscosity . . . . .	30
2.2.6.5	Effect of shear rate on viscosity . . . . .	31
2.2.6.6	Viscosity index . . . . .	32
2.3	Mechanical losses in ICE . . . . .	33
2.3.1	Piston assembly . . . . .	33
2.3.1.1	Piston rings . . . . .	34
2.3.1.2	Piston skirt . . . . .	36
2.3.2	Crankshaft . . . . .	37
2.3.2.1	Journal bearings . . . . .	37
2.3.2.2	Con-rod bearings . . . . .	38
2.3.3	Valvetrain . . . . .	39
2.4	Numerical models applied to assess the friction in ICE . . . . .	41
2.4.1	Piston-ring assembly . . . . .	41
2.4.1.1	Classical Reynolds Equation and Stochastic Asperity Contact Models . . . . .	42
2.4.1.2	Average Reynolds Equation (Patir and Cheng's average flow model) . . . . .	43
2.4.1.3	Deterministic method - Quasistatic approximation . . . . .	44
2.4.1.4	Deterministic method - Full approximation . . . . .	45
2.4.1.5	Other piston ring model considerations . . . . .	46

---

2.4.2	Piston-skirt.....	47
2.4.3	Bearings .....	48
2.4.3.1	Impedance Approach .....	48
2.4.3.2	Mobility Approach .....	49
2.4.3.3	Reynolds equation.....	49
2.4.4	Valvetrain .....	50
	Bibliography .....	52
<b>3</b>	<b>Experimental tools and theoretical model</b>	<b>61</b>
3.1	Introduction .....	63
3.2	Experimental tools.....	63
3.2.1	Steady state: Engine and test cell characteristics	63
3.2.2	Transient state: Vehicle and test cell characteristics	66
3.3	Engine friction: steady state theoretical models .....	68
3.3.1	Piston-ring model .....	68
3.3.1.1	Gas pressure force: blow-by model.....	70
3.3.1.2	Ring tension force .....	72
3.3.1.3	Piston assembly temperature .....	72
3.3.1.4	Hydrodynamic friction force .....	74
3.3.1.5	Asperity friction force .....	76
3.3.1.6	Coefficient of friction measurement .....	77
3.3.2	Piston skirt model.....	81
3.3.3	Bearings .....	82
3.3.3.1	Mobility method .....	83
3.3.3.2	Reynolds equation.....	84
3.3.4	Valvetrain .....	85
3.3.5	Auxiliaries .....	87
3.3.5.1	Coolant pump .....	87
3.3.5.2	Oil pump power .....	88

---

3.3.5.3	Fuel pump power .....	89
3.4	Engine friction: transient theoretical model .....	90
	Bibliography .....	94
<b>4</b>	<b>Model results</b>	<b>97</b>
4.1	Introduction .....	99
4.2	Steady-state model .....	99
4.2.1	Methodology and boundary conditions .....	99
4.2.2	Global results .....	102
4.2.3	Piston-ring assembly .....	105
4.2.4	Piston skirt .....	109
4.2.5	Bearings .....	111
4.2.5.1	Connecting rod bearing .....	111
4.2.5.2	Journal bearing .....	113
4.2.6	Camshaft .....	115
4.3	Transient model .....	118
4.3.1	Introduction .....	118
4.3.2	Methodology .....	119
4.3.3	Results and model validation .....	119
4.3.3.1	Model validation: Drive cycle fuel consumption .....	119
4.3.3.2	Mechanical losses and its distribution during driving cycles .....	125
4.4	Conclusions .....	132
	Bibliography .....	135
<b>5</b>	<b>Optimization of friction losses in ICE</b>	<b>137</b>
5.1	Introduction .....	139
5.2	Friction reduction from the point of view of lubricant ...	139
5.2.1	Lubricant matrix .....	139

---

5.2.2	Results: Total engine friction .....	141
5.2.3	Results: Piston-ring and skirt assembly .....	143
5.2.4	Results: Engine bearings .....	146
5.2.5	Results: camshaft .....	148
5.2.6	Results: Evaluation of the engine oils in a WLTC cycle .....	151
5.2.6.1	Methodology .....	151
5.2.6.2	Main cycle characteristics .....	152
5.2.6.3	Fuel savings produced .....	153
5.2.6.4	Results: Total energy balance .....	156
5.3	Friction reduction from the point of view of surface finishing .....	159
5.3.1	Boundary conditions .....	159
5.3.2	Simulation results .....	161
5.3.2.1	Piston rings .....	161
5.3.2.2	Piston skirt .....	164
5.3.2.3	Journal bearings .....	165
5.3.2.4	Camshaft .....	165
5.3.2.5	Friction saving in the engine .....	167
5.4	Conclusions .....	170
	Bibliography .....	172
<b>6</b>	<b>Conclusions and future works</b>	<b>173</b>
6.1	Introduction .....	175
6.2	Conclusions .....	175
6.3	Future works .....	177
	<b>Bibliography</b>	<b>179</b>