

## Table of contents

<b>Abstract.....</b>	<b>3</b>
<b>Foreword.....</b>	<b>4</b>
<b>List of abbreviations .....</b>	<b>8</b>
<b>1   Introduction.....</b>	<b>10</b>
<b>2   Overview of the particulate emission reduction methods in use .....</b>	<b>12</b>
<b>3   Legislation concerning emissions from diesel engines.....</b>	<b>14</b>
3.1   On-road vehicles .....	14
3.1.1   Passenger cars and light-duty vehicles .....	14
3.1.2   Heavy-duty vehicles.....	18
3.2   Off-road vehicles .....	20
3.3   Ships and boats .....	23
3.4   Locomotives.....	25
3.5   Power plants.....	26
<b>4   Formation of particulate emissions in compression ignition combustion ....</b>	<b>27</b>
4.1   Compression ignition combustion .....	27
4.2   Formation of polycyclic aromatic hydrocarbons .....	28
4.3   Formation of particles .....	30
4.4   Combustion temperature, air-to-fuel ratio, and fuel oxygen content.....	32
<b>5   Reduction of particulate emissions by engine design .....</b>	<b>34</b>
5.1   Control of air and fuel mixture .....	35
5.1.1   Cylinder charge and swirl .....	35
5.1.2   Combustion chamber design.....	36
5.1.3   Fuel injection technology.....	37
5.1.4   Prediction of particle formation by engine simulation .....	38
5.2   Turbocharging.....	39
5.3   Exhaust Gas Recirculation (EGR) .....	41
5.4   Water injection.....	42
5.5   Lubrication technology .....	44
5.6   Thermal barrier coatings in the combustion chamber.....	46
<b>6   Particulate emissions with different types of fuels.....</b>	<b>48</b>
6.1   Diesel fuel oil (DFO) .....	49
6.1.1   Sulphur content .....	49
6.1.2   Aromatic compounds .....	50
6.1.3   Cetane number and cetane index .....	50
6.1.4   Density .....	51
6.1.5   Distillation curve.....	51
6.1.6   Oxygenates.....	51
6.2   Biodiesel fuels.....	52
6.3   Synthetic diesel fuels .....	55
6.4   Heavy fuel oil (HFO).....	56
6.5   Orimulsion® .....	59
6.6   Water-fuel emulsions .....	60

6.7	Natural gas .....	62
6.8	Liquefied petroleum gas (LPG) .....	64
6.9	Ethers and acetals .....	65
6.9.1	Dimethyl ether (DME).....	65
6.9.2	Diethyl ether .....	68
6.9.3	Dimethoxy Methane .....	68
6.10	Hydrogen .....	69
6.11	Alcohols .....	69
6.11.1	Ethanol ( $C_2H_5OH$ ) .....	69
6.11.2	Methanol ( $CH_3OH$ ).....	71
6.12	Additives for fuels, combustion enhancers.....	72
6.12.1	Bimetallic platinum-cerium additive .....	73
6.12.2	Cerium and iron .....	73
6.12.3	Magnesium .....	73
6.12.4	Hydrocarbon or non-metallic additives .....	73
6.12.5	Dibutoxymethane (Butylal) .....	74
6.12.6	CETANER <sup>TM</sup> .....	74
6.12.7	Elastomers.....	74
6.13	Oxygenates .....	74
6.14	Other possible alternatives.....	75
6.14.1	Recycled oil from plastics .....	75
6.14.2	Spent vegetable oil.....	76
<b>7</b>	<b>After-treatment of the diesel particulate emission .....</b>	<b>77</b>
7.1	Diesel oxidation catalysts (DOC) .....	77
7.2	$NO_x$ reduction catalysts .....	78
7.3	Diesel particulate filters (DPF) .....	79
7.3.1	Overview.....	79
7.3.2	Filter types .....	80
7.3.3	Filter regeneration techniques.....	86
7.3.4	Case study: PSA Peugeot Citroën HDi engine .....	92
7.4	Integrated after-treatment systems.....	93
7.5	Water scrubbers .....	94
<b>8</b>	<b>Alternative working cycles and combustion processes.....</b>	<b>96</b>
8.1	The Miller cycle.....	96
8.2	Low temperature combustion concept.....	97
8.3	Premixed diesel combustion.....	98
8.3.1	Homogenous Charge Compression Ignition (HCCI) .....	98
8.3.2	Premixed Charge Compression Ignition (PCCI) .....	99
8.3.3	Premixed combustion processes with late injection .....	100
<b>9</b>	<b>Conclusions.....</b>	<b>102</b>
9.1	Nature of the PM emission problem.....	102
9.2	In-cylinder measures.....	103
9.3	Combustion development .....	104
9.4	Fuel properties and alternative fuels.....	105
9.5	After-treatment devices .....	107
9.6	Cost-effectiveness of the measures.....	108
9.7	Probable measures to fulfil future emission regulations.....	109

9.8 Recommendations for minimising PM emissions .....	110
<b>10 Summary.....</b>	<b>112</b>
<b>References.....</b>	<b>114</b>