Supplementary Information

Effective density and metals content of particle emissions generated by a diesel engine operating under different marine fuels

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Table S1: Technical details of the test engine

Parameter	**Value**
Engine description	1 VDS 18/15
Mixture formation	Direct injection
Charging system	Externally supplied
Stroke	180 mm
Bore	150 mm
Displacement	3.18 dm^3
Rod length	332 mm
Compression ratio ε	13 (15, 16)
Nominal power output	72 kW
Maximum cylinder pressure	170 bar
BMEP	20 bar

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Nominal speed	1500 RPM
Combustion process	4-stroke
Cooling	Water cooled
Injection system	1-cycle common rail, heavy fuel oil capable
Maximum injection pressure	1300 bar
Injection nozzle	9 hole; 0.19 mm bore; 155° spray angle
Maximum exhaust gas temperature	550 °C
Outlet valve opens	143 °CA a. TDC
Inlet valve opens	310 °CA a. TDC
Outlet valve closes	405 °CA a. TDC
Inlet valve closes	560 °CA a. TDC

Fuels

The measurements were carried out with three alternative bunker fuel qualities:

1. Diesel oil according to DIN EN 590,
2. DMOA grade fuel (ISO 8217) with <1000 ppm Sulfur content.
3. Heavy fuel oil 1: IFO 560. Fuel specifications are summarized in Table S2.

Table S2: The specifications of the test IFO 560

Parameter	**Test procedure**	**Unit**	**Value**
Density at 15°C	DIN EN ISO 12185	kg/m³	1006.5
Density at 40°C	DIN EN ISO 12185	kg/m³	991.0
Density at 45°C	DIN EN ISO 12185	kg/m³	988.4
Density at 50°C	DIN EN ISO 12185	kg/m³	985.3
Density at 55°C	DIN EN ISO 12185	kg/m³	982.1
Density at 60°C	DIN EN ISO 12185	kg/m³	978.5
Density at 65°C	DIN EN ISO 12185	kg/m³	975.1
Density at 70°C	DIN EN ISO 12185	kg/m³	972.4
Density at 75°C	DIN EN ISO 12185	kg/m³	969.5
	DIN EN ISO 12185	kg/m³	966.6
Kinematic viscosity 40°C	ASTM D 7042	m²/s	1.132×10^{-3}
Kinematic viscosity 45°C	ASTM D 7042	m²/s	7.32×10^{-4}
Kinematic viscosity 50°C	ASTM D 7042	m²/s	4.84×10^{-4}
Kinematic viscosity 55°C	ASTM D 7042	m²/s	3.31×10^{-4}

Kinematic viscosity 60°C	ASTM D 7042	m²/s-	2.33×10^{-4}
Kinematic viscosity 65°C	ASTM D 7042	m²/s	1.69×10^{-4}
Kinematic viscosity 70°C	ASTM D 7042	m²/s	1.26×10^{-4}
Kinematic viscosity 75°C	ASTM D 7042	m²/s-	9.6×10^{-5}
Kinematic viscosity 80°C	ASTM D 7042	m²/s-	7.6×10^{-5}
Water content	DIN 51777	% (V/V)	0.029
Carbon residue value	DIN EN ISO 10370	% (m/m)	9.3
Calorific value	DIN 51900-1.-2.-3	kJ/kg	38957
Carbon content	Elemental analysis	% (m/m)	87.6
Hydrogen content	Elemental analysis	% (m/m)	10.6
Nitrogen content	Elemental analysis	% (m/m)	0.3
Sulfur content	Elemental analysis	% (m/m)	0.8
Sulfur content	E DIN 51400-10	% (m/m)	0.7
Ash(oxidized)	ISO 6245	% (m/m)	0.04
Vanadium	DIN 51790-6	ppm	24
Flame point	ISO 2719	°C	124
Pour point	ISO 3016	°C	1

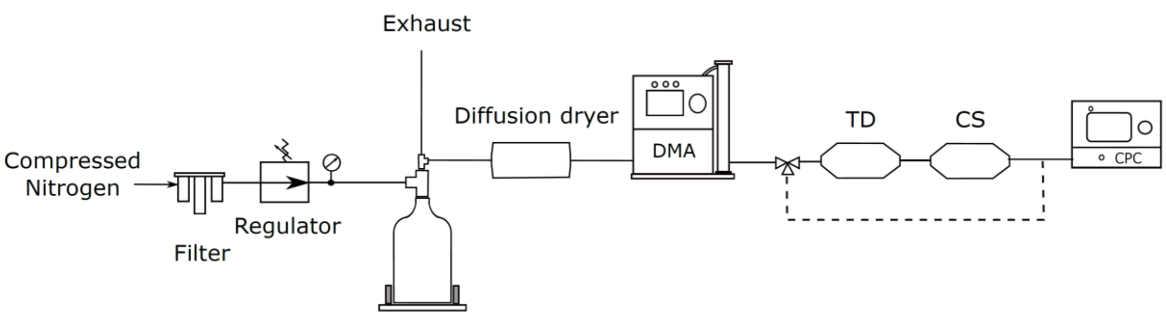

Figure S1. Schematic of the test setup for measurement of penetration

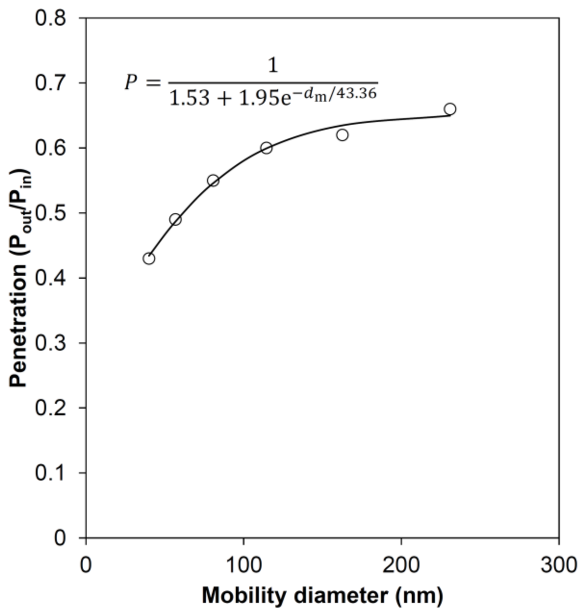

Figure S2. Ratio of particle concentrations from denuder line to bypass line

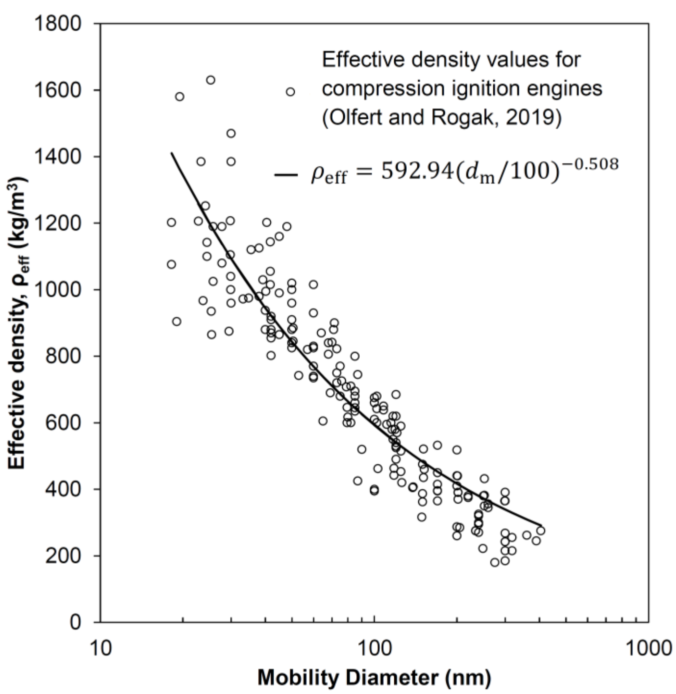

Figure S3. Effective density function for particulate emissions from compression ignition engines. The data points are taken from Olfert and Rogak (2019).

Table S3: Mass-mobility refactors and exponents for undenuded and denuded particles

	Diesel		DM-A		IFO	
	Undenuded	Denuded	Undenuded	Denuded	Undenuded	Denuded
Mass-mobility prefactor	1.96×10^{-7}	NA	2.25×10^{-7}	3.19×10^{-6}	2.09×10^{-6}	3.24×10^{-5}
Mass-mobility exponent	3.18	NA	3.14	2.54	2.74	2.16

Table S4: Metal elements measured by ICP-MS and their corresponding species in the exhaust of marine diesel engine (Note that metal species are assumed not measured)

Metal elements	**Symbol**	**Metal species**
Phosphorus	P	$Ca_3(PO_4)_2$
Sulfur	S	Na_2SO_4
Vanadium	V	V_2O_5, VO_2
Nickel	Ni	NiO
Copper	Cu	$CuO,\ Cu_2O$
Zinc	Zn	ZnO
Sodium	Na	$Na_2O,\ Na_2SO_4$
Iron	Fe	Fe_2O_3
Calcium	Ca	CaO
Lead	Pb	Pb