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THE INFLUENCE OF LOAD VEHICLES IN ROAD TESTS ON THE PARTICLE MATTERS PARAMETERS

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Abstract

The emission of PM from combustion engines (given not only as mass but also number) has become the main determining factor influencing the design of drivetrains of modern vehicles. The PM measurement to date, based on the gravimetric method does not guarantee results on an expected accuracy and repeatability level. The introduction of emission standards, containing requirements related to the PM counting in the exhaust gases shows the need of identifying other PM parameters as well. The paper discusses the possibility of a synthetic approach to the parameters of PM generated by diesel engines. The authors felt compelled to realize the task following the obtainment of positive results of the PM parameters research under different operating conditions of diesel engines. The purpose of the tests described in the paper was to verify how the payload of vehicle effects on the PM emissions. It presents the results of road tests of commercial vehicles (LDV type) powered by diesel engines. The paper contains the results of measurements of concentration, mass and size distribution of PM emitted by the engines of these vehicles. The tests were conducted in actual traffic conditions. The AVL Micro Soot Sensor (measurement of the concentration and mass) and Engine Exhaust Particle Sizer 3090 by TSI Inc. (measurement of the size distribution) were used to measure the PM emissions.

Keywords: *exhaust emission, road test, particle matter, diameter distribution*

1. Introduction

Utility vehicles play an important role in cargo transport. There are many types of these vehicles available worldwide of different load capacities limited by their gross vehicle weight (GVW). The source of propulsion of these vehicles in most cases is diesel engines that are characterized by high values of torque. As far as vehicles for the heaviest duties are concerned (of GVW greater than 16,000 kg) their engines are diesel of high displacement, which is a direct reason for low gas mileage (high fuel consumption). This is a significant issue in terms of operating economy and profitability in the transport business. It thus makes a lot of sense to employ the vehicle's load capacity to the maximum (maximum cargo load yet not exceeding the GVW) and avoid 'empty runs'.

The investigations described in this paper were conducted to assess the influence of the vehicle payload on the particulate matter emission. The influence of the vehicle payload on the fuel consumption is easily measurable but in order to determine the PM emissions specialized test equipment is required [1, 3, 4].

2. Objects of investigations and measurement equipment

Two utility vehicles (*Light Duty Vehicles*) were subjected to the tests under actual operating conditions. These were: Peugeot Expert and Mercedes-Benz Vito. Both vehicles had similar external dimensions, gross vehicle weights and the powertrains were 4-cylinder diesel engines (Tab. 1). The main differences pertained to the transmission and operating parameters of the powertrains. Fig. 2 presents the objects of investigations together with the measurement equipment.

Tab. 1. Specifications of the vehicles used for the tests

Parameters	Vehicle A	Vehicle B
Engine, cylinders	Diesel, 4	Diesel, 4
Capacity	1.9 dm^3	2.2 dm^3
Injection system	rotary pump	common rail
Power	68 kW @ 4000 rpm	90 kW @ 3800 rpm
Torque	196 N·m @ 2250 rpm	300 N·m @ (1800–2500) rpm
Turbocharger	yes	yes
Gearbox	manual (5)	automat (4)
Power index	36 kW/dm^3	41 kW/dm^3
Mass index	21 kg/kW	19 kg/kW
Mileage	150,000 km	300,000 km

Fig. 2. Objects of the investigations together with the measurement equipment

Variation in the PM count in relation to its diameter can be seen during tests of loaded and unloaded utility vehicles mindful of the difference in the powertrain solutions. During the actual on-road operation of these vehicles we can determine the size distribution of PM (defined as a relation of their parameters and the aerodynamic diameter) under different traffic conditions depending on the payload. The resultant PM mass was determined going on the assumption that the PM density depends on their aerodynamic diameter and amounts to 1 g/cm^3.

For the measurement of the diameters of the particulate matter the authors used a mass spectrometer by TSI Incorporated – EEPS 3090 (*engine exhaust particle sizer*™). It enables a measurement of a discrete range of PM diameters (from 5.6 nm to 560 nm) based on their different velocities (Fig. 2). The range of the electric motility of the particulate matter is changed exponentially and the measurement of the size is done with the frequency of 10 Hz (basic data are shown in Tab. 2). The exhaust gases are directed through a dilution and temperature maintaining systems to the mass spectrometer. The preliminary filter traps the particles of the diameter greater than 1 µm being outside the measurement range of the device. Upon passing the neutralizer the particles are directed to the charging electrode; upon obtaining an electrical charge they will be classified according to their size. The particles diverted by the high voltage electrode go to the ring crevice that is a space between two cylinders. The crevice is surrounded by a stream of clean air fed from outside. The outlet cylinder is built in the form of a stack of insulated sensitive electrodes forming a ring. The electrical field between them results in that the particles are pushed away from the positively charged electrode. Next the particles gather on the external electrodes. Hitting the electrodes the particles generate electric current that is detected by the processing systems.

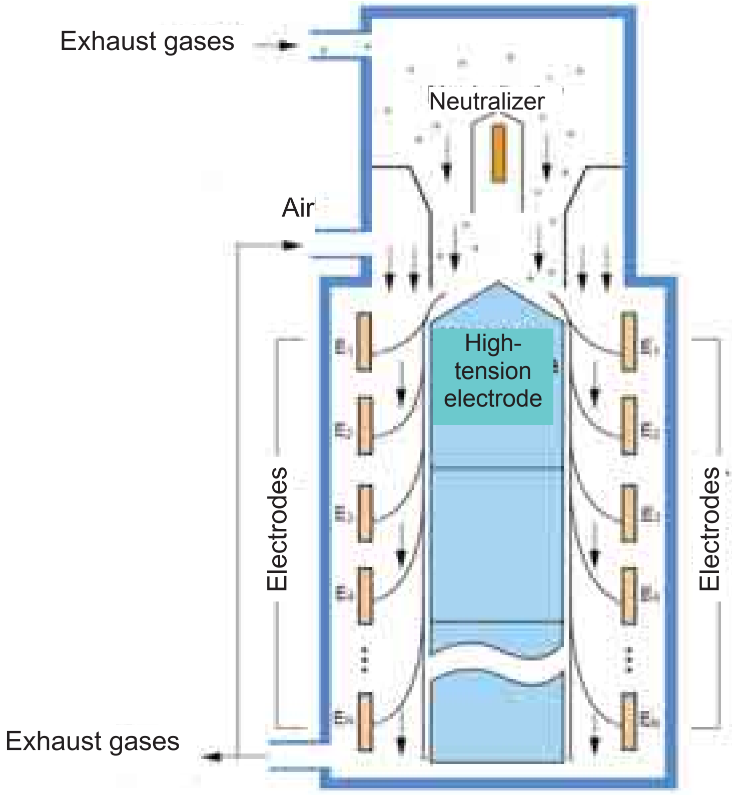

Fig. 2. Schematics of the EEPS 3090 particle sizer

Tab. 2. Technical specifications of the mass spectrometer by TSI

Parameters	Value
Particle size range	5.6 nm – 560 nm
Characteristics	PN = f(D), A = f(D), V = f(D), m = f(D)
Particle size resolution	16 channels per decade
Elektrometers channels	22
Maximum data rate	10 Hz
Flow rates – shealth air	2.4 m^3/h
Flow rates – aerosol inlet	0.6 m^3/h
Atmospheric pressure correction	$700 \cdot 10^2$ Pa – $1034 \cdot 10^2$ Pa
Inlet aerosol temperature	10°C – 52°C
Storage temperature	0°C – 40°C

3. Conditions of the measurements

The on-road tests of the PM emission were performed under actual traffic conditions on the route of Poznan–Wrzesnia (Fig. 3). The route was divided into three basic cycles (road portions), different in terms of traffic characteristics: urban, extra urban and expressway. The tests were performed on the same route with and without payload. The vehicle payload was approximately 500 kg (including the measurement equipment).

Fig. 3. Test route (marked red)

4. Test results and analysis

During the tests the concentration of particulate matter was measured in the exhaust gases generated by vehicles A and B on the individual road portions. The authors could thus determine the emission rate (in mg/s) of the said exhaust components for both the loaded and unloaded vehicles (Fig. 4 – 6). For both vehicles on the whole route (three road portions) a significant growth in the PM emission was observed when carrying a payload. The greatest differences were recorded for the urban traffic conditions (for both vehicles A and B). This mainly resulted from the high driving dynamics (frequent stops and abrupt accelerations) at a significant energy demand of the engine (vehicle). For the rest of the road portions the increase in the PM emission rate for the loaded vehicle was approximately 10 – 50%.

a) b) c)

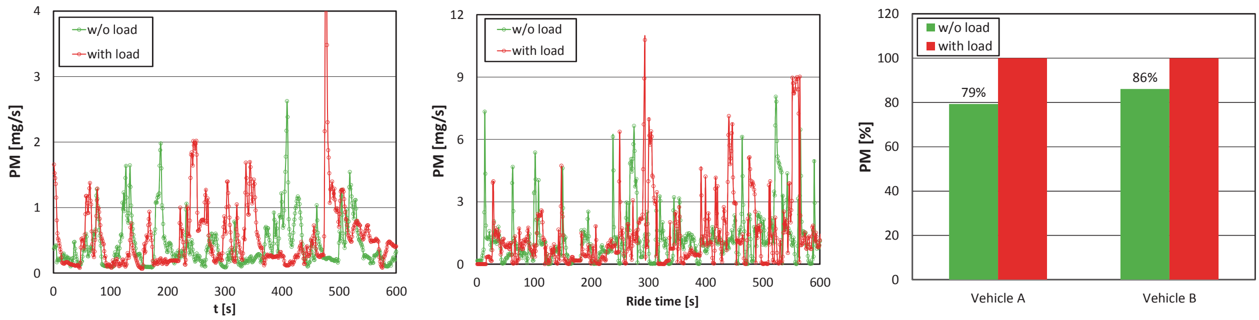

Fig. 4. PM emission rate on the urban road portion: a) vehicle A, b) vehicle B, c) relative values

a) b) c)

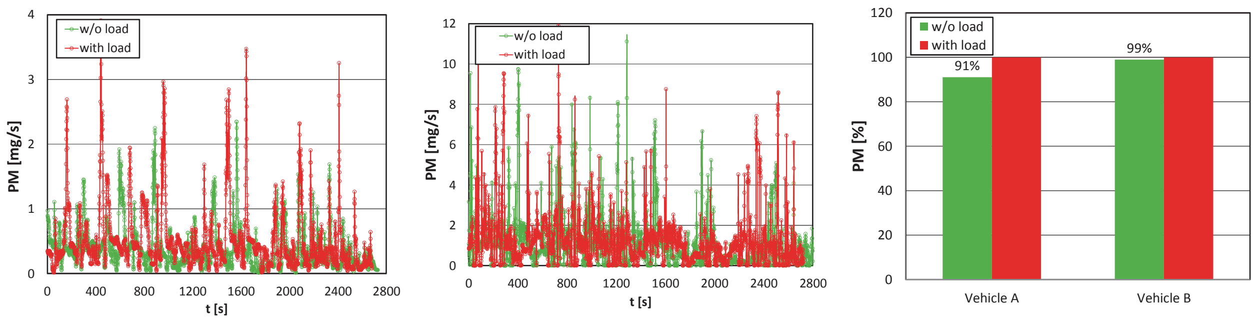

Fig. 5. PM emission rate on the extra urban road portion: a) vehicle A, b) vehicle B, c) relative values

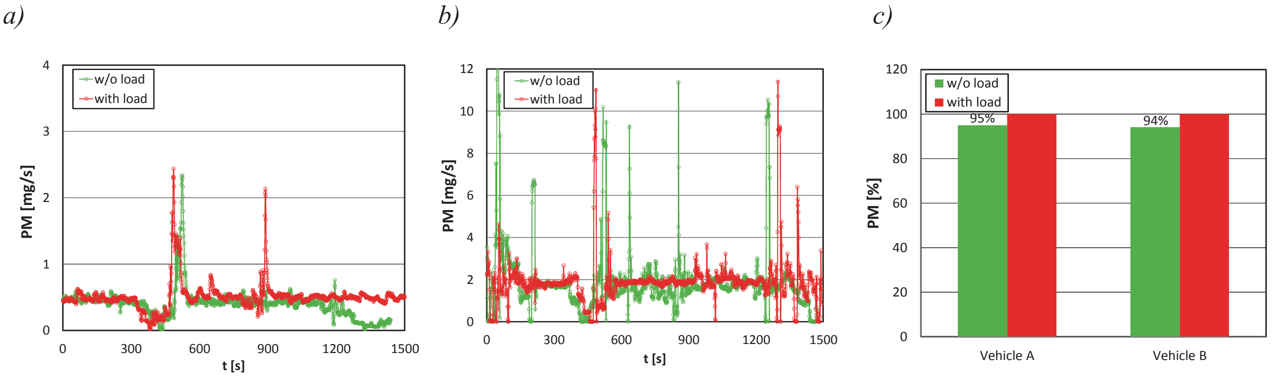

Fig. 6. PM emission rate on the expressway road portion: a) vehicle A, b) vehicle B, c) relative values

In the further part of the paper the authors use the term of particle number c_{PN}, area A, volume V and PM mass m. It is more universal to determine the concentration of these quantities as their values are given as e.g. a number of particles per unit of volume (1/cm^3). The same rules apply to determining of the area volume and mass of PM.

The way of describing of the particle number using devices of different measurement channels (resolution) may be misleading (Fig. 7), hence the need to normalize the measurement results. The normalization consist (*NC*) in providing the results as a quotient of the particle number in each measurement channel and the normalized width of this measurement channel:

$$NC = \frac{c_{PN}(D \pm \Delta D)}{\log[(D + \Delta D)/(D - \Delta D)]}, \tag{1}$$

where:
$c_{PN}(D \pm \Delta D)$ – particle number of the diameter of $(D \pm \Delta D)$ [1/cm^3],
$D + \Delta D$ – top value of the range of the measured particle diameter [nm],
$D - \Delta D$ – bottom value of the range of the measured particle diameter [nm].

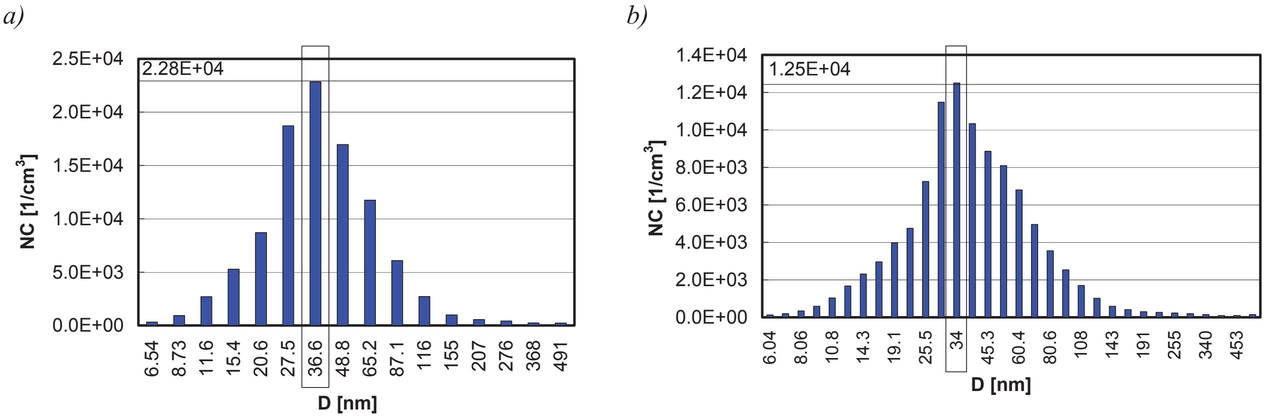

Fig. 7. Comparison of the normalized particle number depending on the diameter D using: a) 16 measurement channel analyzer, b) 32 measurement channel analyzer

The value of the normalized particle number (*NC*) is several hundred times greater than the non-normalized particle number, which results from a large number of the measurement channels hence their small width. In the further part of the paper, to determine the particle number depending on the particle size normalized particle number is used.

The investigations into the PM size distribution were performed under actual operating conditions of the utility vehicles on a road portion covering the urban, extra urban and expressway traffic conditions. The tests were repeated three times with and without load (approximately 500 kg of payload, including the measurement equipment).

The greatest PM number was recorded for the urban road portion (Fig. 8a); a growth in the payload results in a proportional increase in the PM number of all diameters, which is a result of a greater fuel dose and a lower air excess coefficient. The same applies to the extra urban (Fig. 8b) and expressway (Fig. 8c) roads portions yet it is characterized by lower absolute values of the growth of PM of individual sizes. If we take into account that a growth in the vehicle payload will require higher engine speed to balance the motion resistance then the effect of a larger PM number will be intensified by the growth in the exhaust gas rate. The differences between vehicles A and B take place under all operating conditions: in relation to vehicle B particle of diameters of approximately 10 nm do not appear. This is a result of an application of a different fuel injection system and a higher vehicle mileage.

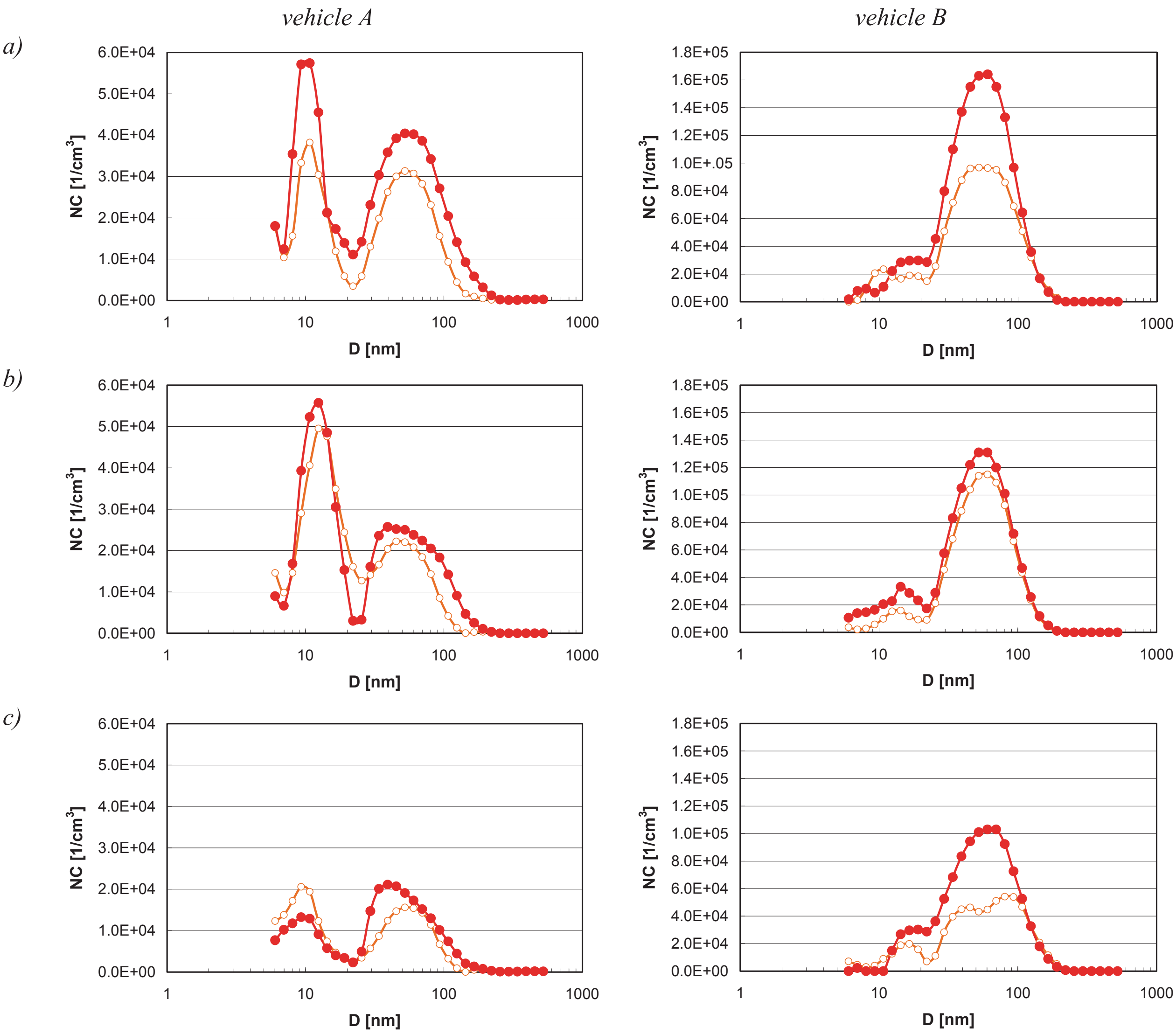

Fig. 8. Normalized particle number NC as a function of diameter D recorded on different road portions for vehicles A and B: a) urban, b) extra urban, c) expressway; ● – drive with load, ○ – drive without load

Similar properties were recorded while measuring the normalized PM surface concentration (Fig. 9). The basis for the calculation of the area of the PM is PM number of a given diameter. The particles of very small diameters up to 20 nm, created in the phase of nucleation, have a very little share in the overall area of all particles. Particles that are larger - of the diameters of 50 nm to 150 nm are characterized by the greatest surface concentration.

The concentration of PM was dependent on the vehicle operating conditions. The vehicle payload had a greater impact on the measurement results than in the previous two cases (Fig. 10). In the urban drive of the loaded vehicle a more than 100% growth was recorded of the mass concentration of PM of the diameters of 60 nm – 120 nm and the particles of the greatest diameters were the highest in concentration. The above property (higher mass concentration of PM of greater diameters) is observed for all operating conditions of the vehicles.

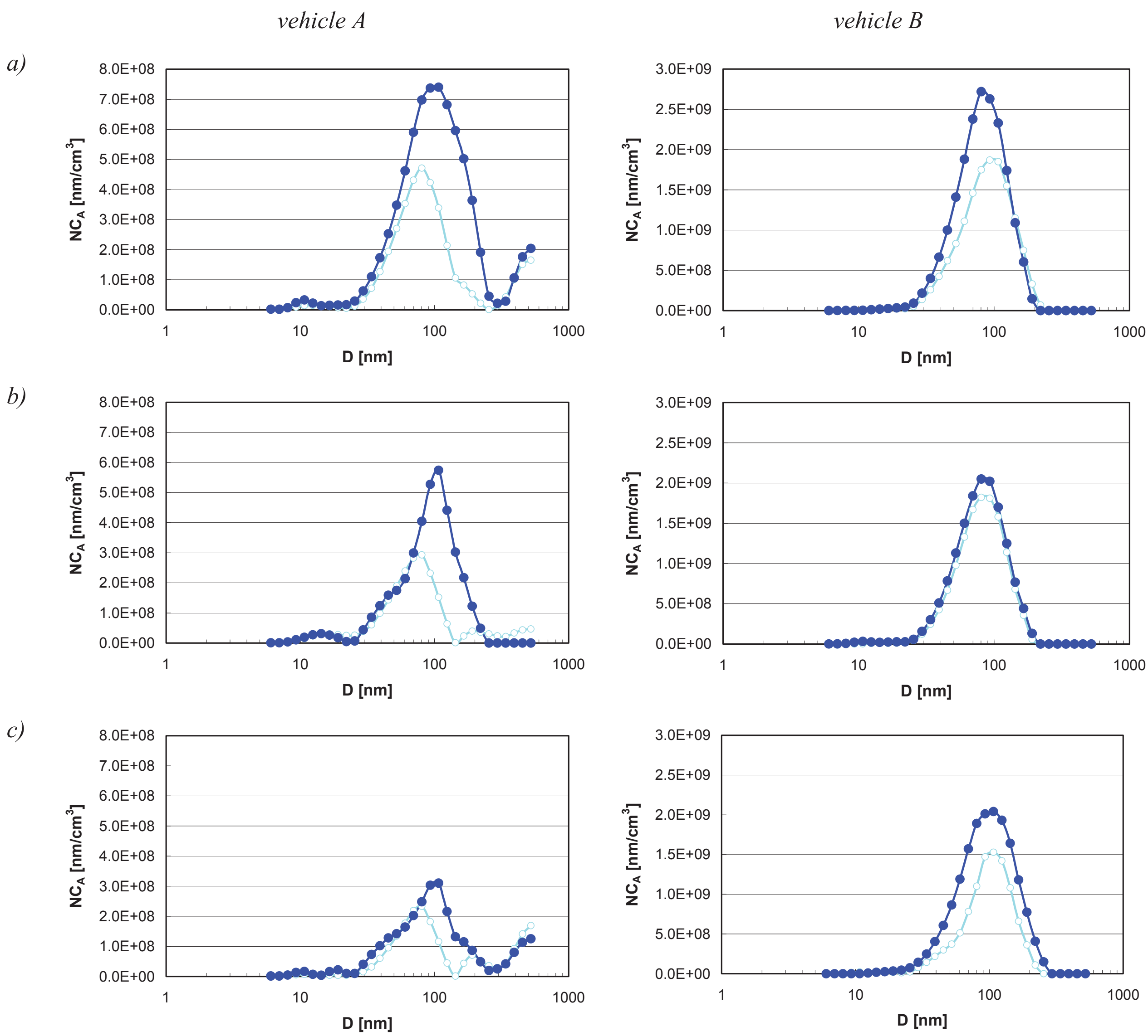

Fig. 9. Normalized surface concentration NC_A of PM as a function of diameter D recorded on different road portions for the tested vehicles A and B: a) urban, b) extra urban, c) expressway; ● – drive with load, ○ – drive without load

When comparing the relative accumulated PM numbers and masses (Fig. 11) we can observe that for vehicle A 90% of the number of all PM is only 15%–20% of its mass. Approximately 90% of PM contained in the exhaust gases has a diameter smaller than 100 nm whereas the growth of the PM mass is observed only when this diameter is exceeded. In relation to vehicle B approximately 90% of the number of all PM is 45%–55% of its mass. Approximately 90% of PM contained in the exhaust gases has a diameter smaller than 100 nm whereas the growth in the PM mass is observed when the diameter exceeds 30 nm. Comparing the two vehicles it was observed that vehicle A generates particles of smaller size than vehicle B. At the same time the lack of the emission of particles of small diameter by vehicle B is the reason for a different shape of the comparable accumulated courses of PM mass and number.

The conducted tests under actual operating conditions have shown a substantial influence of payload on the PM number and PM mass generated by the vehicle. From the performed measurements it results that the characteristics of the PM number (as a function of diameter) depends on the design of the fuel (injection) system, which, as a consequence, has impact on the participation

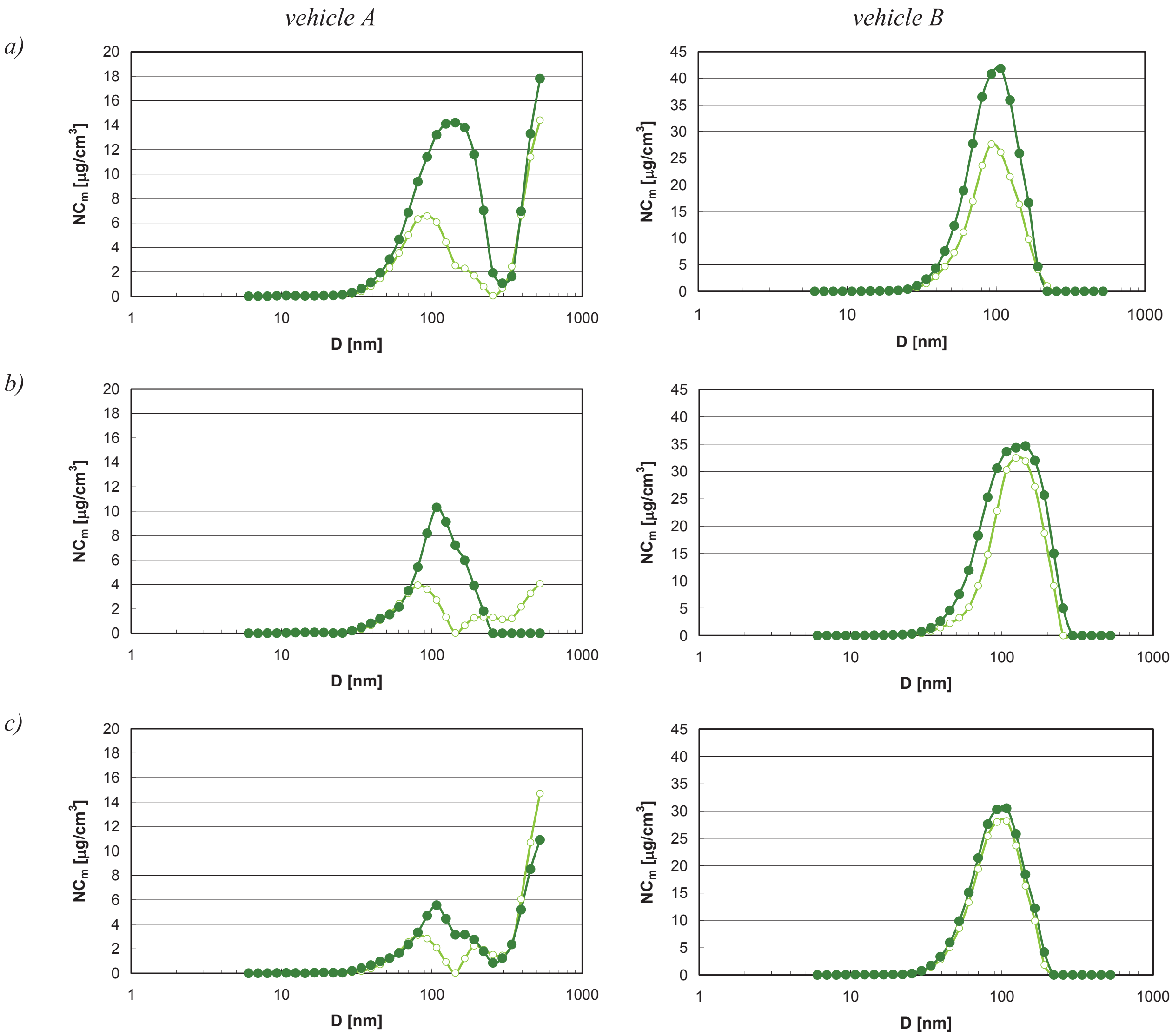

Fig. 10. Normalized mass concentration of PM NC_m as a function of its diameter D recorded on different road portions for vehicles A and B: a) urban, b) extra urban, c) expressway; ● – drive with load, ○ – drive without load

of the nucleation process in the formation of PM inside the cylinder of a combustion engine. A growth in the vehicle payload results in an increase of the PM number, PM surface concentration and PM mass concentration irrespective of the operating conditions of the vehicle.

The presented own investigations do not exhaust the possibilities of PM measurement. As a result of continuous improvement new replacement methods and techniques of PM measurement under actual traffic conditions are created. Despite very low emission of these compounds it is possible to measure them under variable traffic conditions. Based on the performed verification of the optical method (exhaust opacity measurement) for different types of vehicles in this work the authors have shown that such a measurement has a significant error rate and does not guarantee clear results. It needs to be noted that the measured value of the opacity may correspond to the value of the concentration of the particles (not the emissions) in the exhaust but only the large ones that, absorbing the light radiation, reduce the energy reaching the device sensor. The ambiguous nature of the results originates in their insufficient resolution and a lack of proportional relation between the mass of the PM and its size.

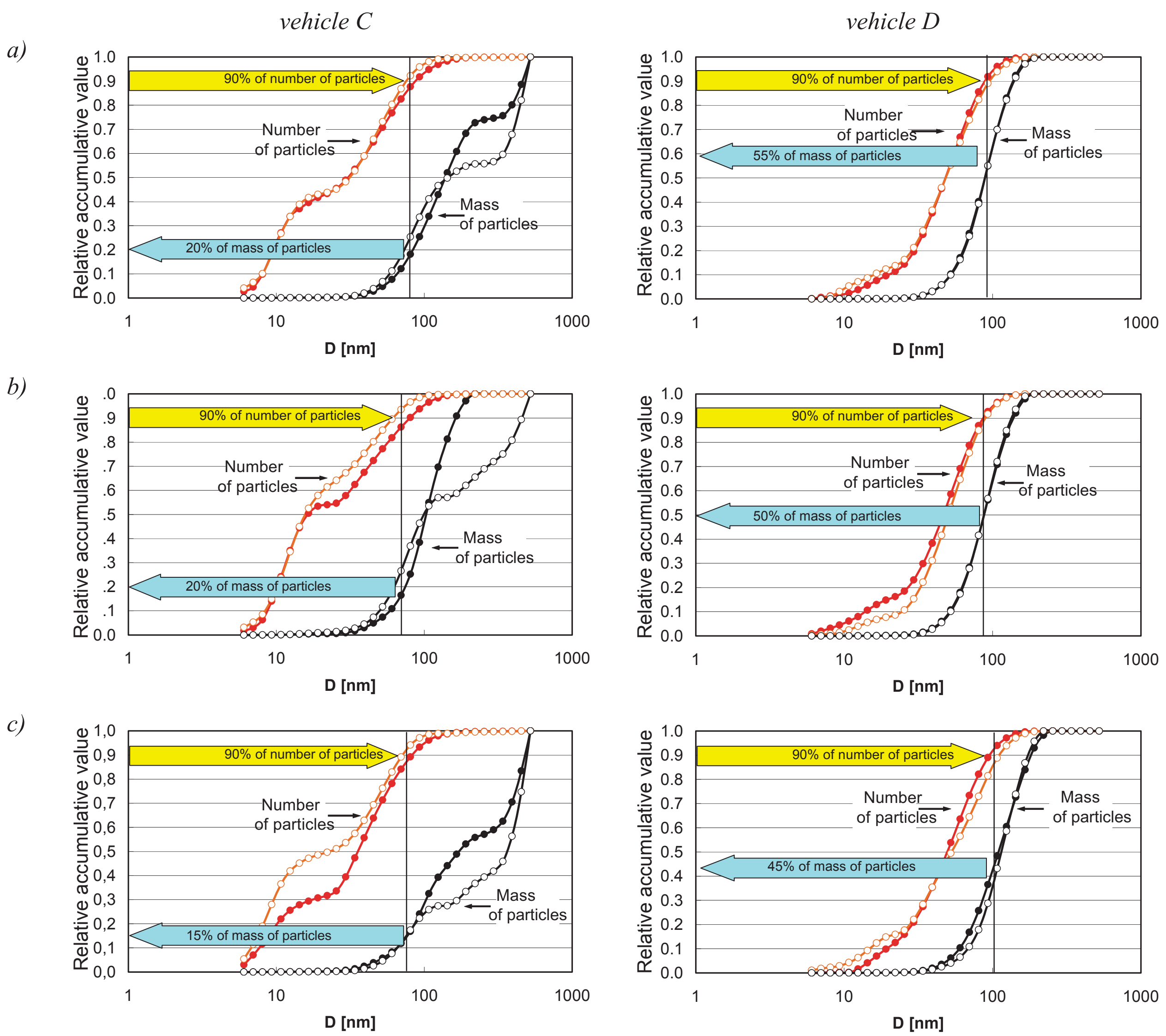

Fig. 11. Relative accumulated value of the PM number and mass as a function of its size recorded on different road portions for tested vehicles A and B: a) urban, b) extra urban, c) expressway; ● – drive with load, ○ – drive without load

5. Conclusions

The performed tests on the utility vehicles (light duty trucks) under actual traffic conditions have shown a significant influence of the vehicle payload on the PM emission. From the performed measurements it results that:

- the characteristics of the PM (as a function of its diameter) depends on the characteristics of the fuel injection, which in turn influences the participation of the nucleation process in the formation of PM inside the cylinder of a combustion engine,
- an increase in the carried payload results in an increase in the PM concentration, area and density irrespective of the traffic conditions in which the vehicle is operated,
- a more valuable measure related to the PM control is its number (or concentration), but mass (easier to measure) carries only 15% – 20% of the information on the PM number.

Mindful of the above it should be stressed that the frequently observed unnecessary carrying of loads by utility vehicles may have an adverse impact not only on the economy of operation (fuel efficiency) hence the profitability of the transport task but also on the natural environment and the human health. An analogy applies for light duty vehicles such as passenger vehicle for which (similarly to the utility vehicles) we also observe additional trunk 'occupation'. Hence, it is necessary to rationally approach the issues of carrying loads inside vehicles.

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