Experimental investigations of Non-Volatile particle number concentration from a range of multi-utility vehicles over emission cycle complying different norms

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Abstract

The current regulated particle metric in vehicle emissions is the total mass, while during last decade; interest in number size distribution has increased. Various international studies on epidemiology and toxicology have reported the adverse effect of the particle matter on public health. The UNECE group of experts on pollution and energy (GRPE) under particle measurement program (PMP) are under the process of finalization long term certification standard concerning particle emissions. The current study was done in order to investigate the number concentration from a range of Indian multi utility vehicles. These were equipped with various sizes of diesel engine over the new European driving cycle (NEDC) cycle using same oil specification. The vehicles chosen were meeting emission norms ranging from Euro3 (E-3) to Euro5 (E-5) and using the corresponding fuel specification as specified for the norms. In order to meet the strict emission norms, penetration of common rail injection system in the Indian market is inevitable. The use of higher injection pressure, advanced after treatment systems such as diesel particle filters (DPF), is the motivation for the work to access the number concentration, an important metric of particle matter in view of future emission norms. It is clearly revealed that different vehicles equipped with different capacity engines exhibits similar diesel particle emission characteristics. Also, as the particle mass is decreasing with the stringent emission norms reduces the particle number concentration.

***Keywords**: Particle number, NEDC cycle, DPF*

1. INTRODUCTION

The technical improvements over the year in the engine in cylinder combustion and after treatments, particle mass are coming down from the vehicles. The particle measurement program was established under the auspices of the United Nations Economic Commission for Europe’s (UNECE) Group des Rapporteurs de Pollution et Energie (GRPE) to identify candidate systems for the measurement of ultrafine particles emitted from heavy and light duty vehicles. The aim is to develop a new measurement system that could replace or complement the existing particulate mass measurement system [1,9,13].

The mandate for PMP from GRPE includes:

To develop regulatory test protocols, with instrumentation, to assess and control nano-particle emissions from (a) light-duty vehicles and from (b) heavy-duty engines within the range of 10 to 500 nm (the exact size range to be confirmed).

The tests should be based on transient cycles and, if possible, conform to current regulated test cycles, i.e. European Light-duty and Heavy-duty (ETC) cycles, US Federal test cycles and also the World Heavy-duty Drive Cycle (WHDC).

The protocol should focus only on the accurate assessment of carbonaceous particles within the measurement range indicated.

To provide an assessment of current and advanced particulate control technology, as measured on the new protocol, to facilitate the development of new regulations aimed at further reductions in nano-particle emissions.

Need of Particle number measurement as an important metrics

Particles from diesel engines are complex mixtures of chemical compounds in a variety of shapes sizes over a large range of aggregate sizes, suspended in a carrier gas. In view of the suspected health effects of particles, there has been a recent focus on a reduced set of particle properties, namely mass, surface, number, size, solubility and phase (solid/liquid). Of the particle emitted in urban and city area, diesel particles accounts highly significant portion. Effect of diesel exhaust exposure result in the irritation of eyes, nose, lung function changes, respiratory changes, headache, fatigue etc [3, 13]. As particle emissions from vehicles are reduced by new engine technologies such as use of particle traps, higher injection pressure used in common rail injection system, sensitivity of the measurement methods becomes more of an issue, which further narrows down the choice of available metrics. When it finally comes to a decision between nearly equivalent metrics, the one based on a simpler concept is likely to be favored over a more complex one. Figure 1 shows the size and the number spectrum of diesel particles from a modern diesel engine. It shows that the highest number concentration of particle number is in the range of 100 nm mobility diameter whereas the corresponding mass is in the range of 230 nm. The study done by Andrea Bertola et. al. [4] shows that the use of higher injection pressure used in the diesel engine shifts the higher number spectrum to mobility diameter in the range of 50 nm and corresponding mass is reduced significantly. This can be seen from the figure1 with the thick dotted line. [2]

Figure 2 gives the alveolar deposition of particles in a healthy person [2] Due to the high diffusivity of smaller particles coming from the modern diesel engine; they have more probability of deposition than the larger ones. The tendency of the lungs to hold the smaller particle is a suspected to have major health concern. It has been estimated that the particulate emissions per travelled distance is 10 times higher than the same powered gasoline engine running with the same power.

From figure 1, though it appears as with modern common rail diesel engine, the mass is coming down, but the concerns associated with the smaller particles are increasing. It is this concern which demands for the need to look beyond the mass as regulated emissio

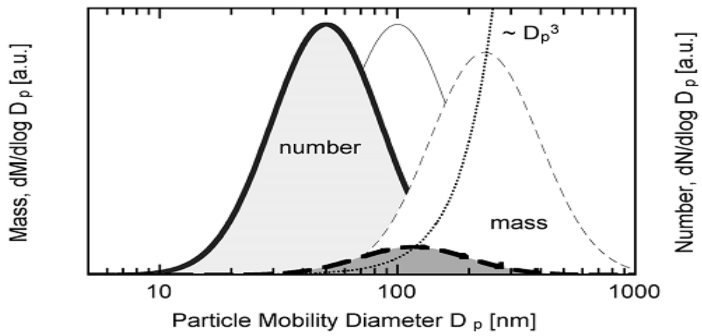


Fig1. Number size distribution from a typical diesel engine [2]

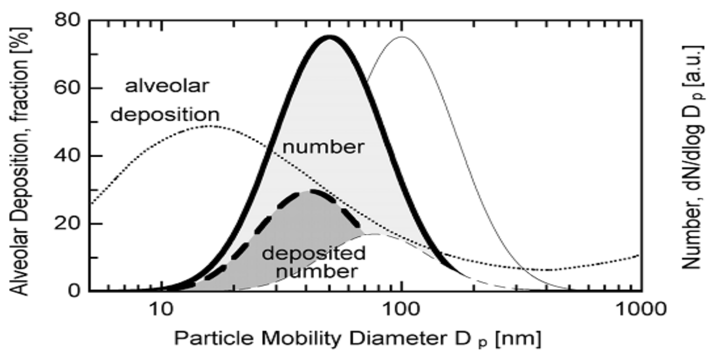


Fig2. Alveolar deposition of particle in healthy person [2]

2. TEST SET UP AND MEASUREMENT PROCEDURE

The tests were carried out in vehicles meeting various stages of emission norms and are equipped with a series of engine with different cubic capacity. Table 1 gives the three groups.

Table 1. Classification of engine capacity equipped with the vehicles tested.

Engine Group	Engine capacity	Injection System	Injection Pressure	Total engines
A	1.5L -1.8L	Common rail	up to 1400 bar	1
B	1.9L -2.2L	Common rail	up to 1600 bar	1
C	2.2L -2.5L	Common rail	up to 1600 bar	2

The particle number was measured during the NEDC cycle. The fuel used during the test is specified as per the Table 2 given below

A condensation particle counters (CPC) from

AVL was used during all the tests. This device is as per the recommendation of GRPE PMP program.

AVL CPC has got highest linearity independent from particle size with a very low maintenance;

switch between high and low dilution without

changing the rotating disk. **[4]**

The dilution air used for the primary dilution of the exhaust in the constant volume sampler (CVS) tunnel was first passed through a high-efficiency particulate air (HEPA) filter, charcoal scrubbed, and then passed through a secondary HEPA filter. The volatile particle remover (VPR) provides heated dilution, thermal conditioning of the sample aerosol, and secondary dilution for the cooling and freezing of sample evolution prior to entry into the particle number counter (PNC). In this way, in order to draw a sample from the CVS, the particle-sampling system is required to classify it according to size, to transfer it to a diluter, and to condition the sample so that only solid particles of suitable concentration are measured and sent to the particle counter. Figure 3(a) to (b) shows the schematic diagram of the PNC. The VPR consists of a first particle number diluter (PND1), an evaporation tube (ET), and a second particle number diluter (PND2). The PND1 is a rotating-disc diluter with the hot dilution set at 1500C and HEPA-filtered dilution air. . After the first diluter, the sample is further divided into two separate flows. The flow will be conducted to the ET and held at a constant temperature of 3000C. Finally, the sample is diluted again in the PND2 at a dilution ratio of approximately 8.0:1 and transferred to the PNC. The VPR is designed to achieve a greater than 99 per cent reduction of 30 nm tetracontane (C 40) particles and a greater than 80 per cent solid particle penetration at 30 nm, 50 nm, and 100 nm particle diameters.[4,10,14]

Table.2 . Fuel specifications during the testing (as per norms)

FUEL PARAMETERS	E-3	E-4	E-5
	EN-590	EN-590	EN-590
Density, kg/m^3	820 - 845	820-845	820-845
Viscosity @40°C, cst	2 to 4.5	2 to 4.5	2 to 4.5
Cetane No. Min.	51	51	51
Sulphur, ppm (mg / kg), Max	350	10	10
Lubricity, micron, Max. (HFRR)	460	460	460
Flash Point, °C, Min.	35	55	55
T 95, % v/v, °C, Max (Distillation Recovery)	360	360	360
PAH %, Max (Poly Aromatic Hydrocarbons)	11	11	11
Water Content, mg/kg, Max	200	200	200
CFPP, °C, Max (Cold filter plugging point)	6	6 different grades of range +5 to	To -20 and 4 Arctic grades up to -44
Oxidation Stability, g/ m3, Max	25	25	25

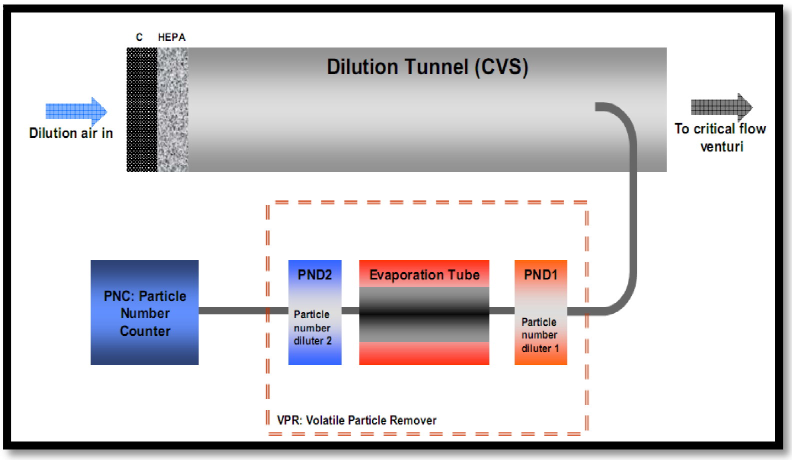
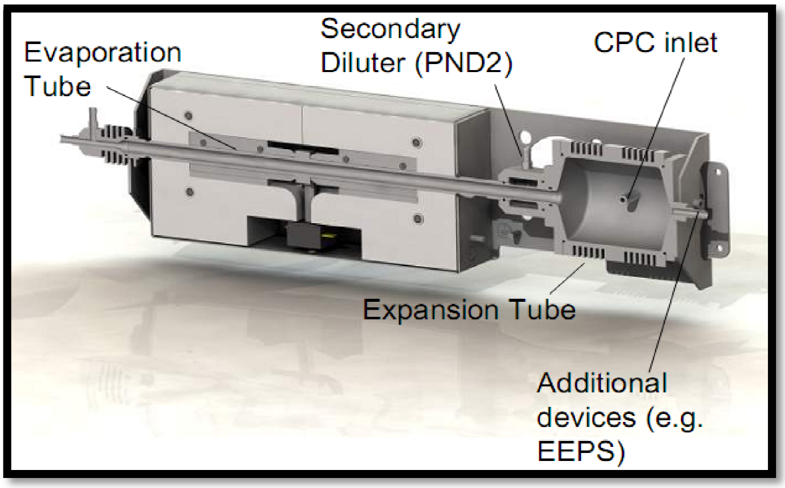


Fig3. (a): Particle number counter used during experiments [4]



Fib4 (b): Particle number counter used during experiments sectional view [4]

3. RESULTS AND DISCUSSION

3.1 Particle number reduction potential with a wall flow DPF technology.

For meeting emission norms beyond E-4, the need of diesel particle filter (DPF) is essential. Figure 4 gives the comparison of particulate emissions (both mass and number) in phase1 and phase2 of NEDC cycle when tested with and without DPF. The tested engine belongs to Group C. (Refer Table 1 above). This vehicle uses a wall flow type of a DPF. A diesel oxidation catalyst (DOC) is placed as per the design in front of the DPF. It clearly shows a reduction of non-volatile number with the use of DPF. From the emission test results, particle mass reduced by 92% and 98% respectively. The number concentration reduced by 56.80% and 56.82% in both the phases respectively. The reduction in number is same in both the phases compared to the particle mass in the corresponding phases. Similar study performed by Mitsuru Hosoya et.al. [5] [8] Shows the particle number reduction potential up to 97% in a steady state engine speed of 1080 rpm and 25% of load. The huge difference in the particle number reduction efficiency can be attributed to the fact that the DOC and DPF volumes are 8.5L in their experiments compared to 1.65L and 2.5L in our case. The engine capacities differ from 7.96L to 2.2L. Also, the measurement performed by Mitsuru Hosoya et.al. is at steady state whereas, this study is in transient NEDC cycle. However, the sulphur content in both the cases was matching closely at 0.0036% wt. Figure 5 gives the particle number traces in the NEDC cycle for with and without DPF experiments for more understanding

3.2 Particle number with emission norms upgrade

In market like India where two different emissions norm exist at the same time frame. It is essential to know the effect of various levels of emission and the contribution of particle number due to it to access the overall contribution. To understand the situation of particle number emission with upgrade of emission norms, results were compared from Group B (E-3 and E-4) and Group C (E-5) engine. The inclusion of Group C engine with E-5 emission is due to the limitation of Group B engine equipped vehicle for meeting E-5 emission norms. Also, the engine capacities are very close and vehicle application is same with same power train. From figure 6, where in phase wise particle numbers are mentioned, are more or less similar in phase1 except the case of E-4. However, phase2 shows slight higher particulate number for E-5 case.

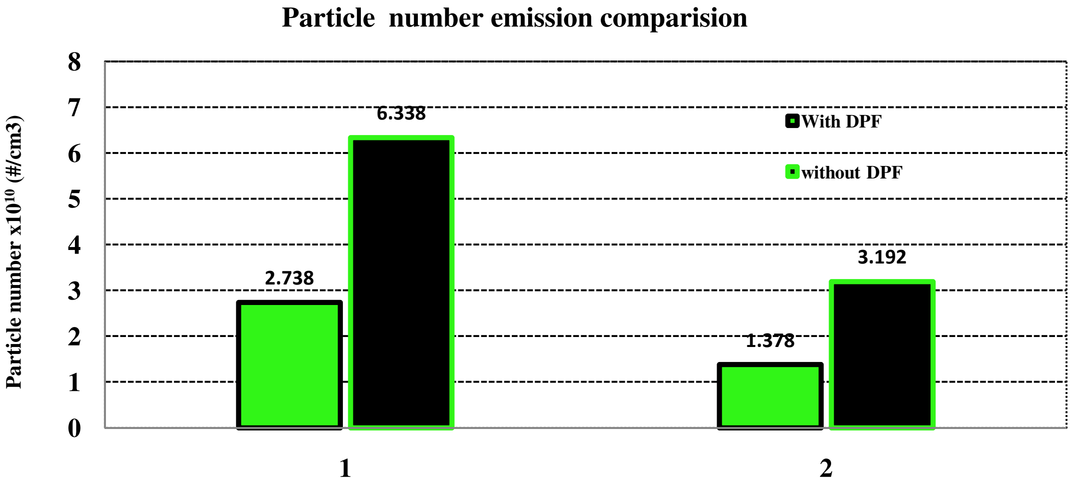


Fig4. Comparison of particle number during NEDC cycle phases for with and without DPF vehicle.

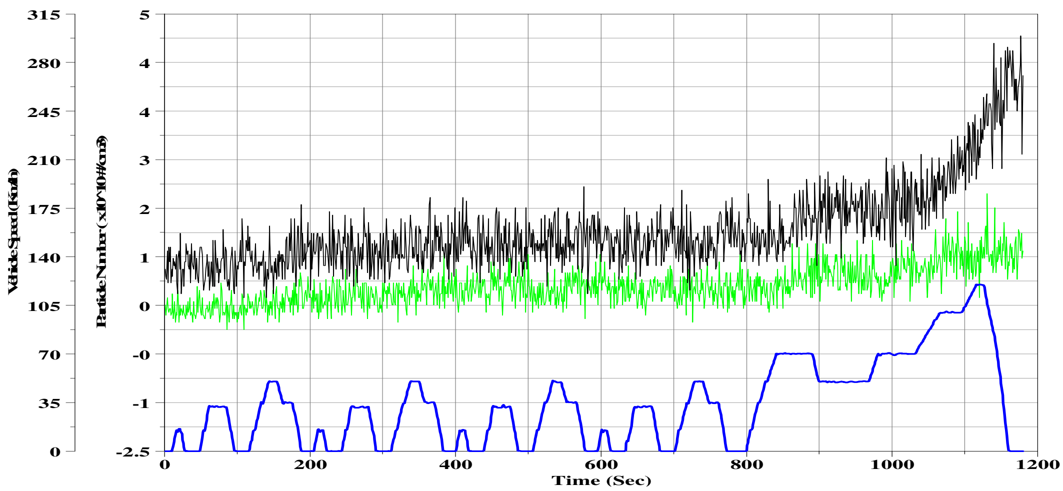


Fig5. Comparison of particle number during NEDC cycle for with and without DPF vehicle

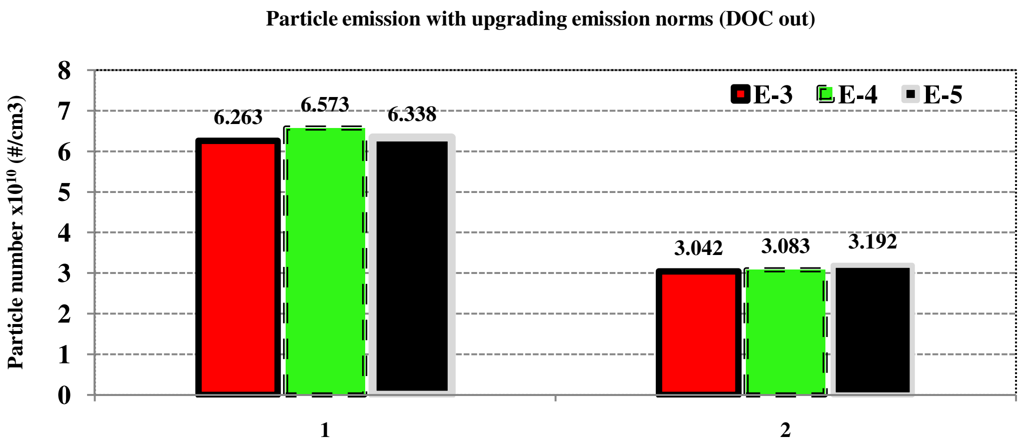


Fig6. Comparison of particle number emission (DOC out) with emission norms upgrade.

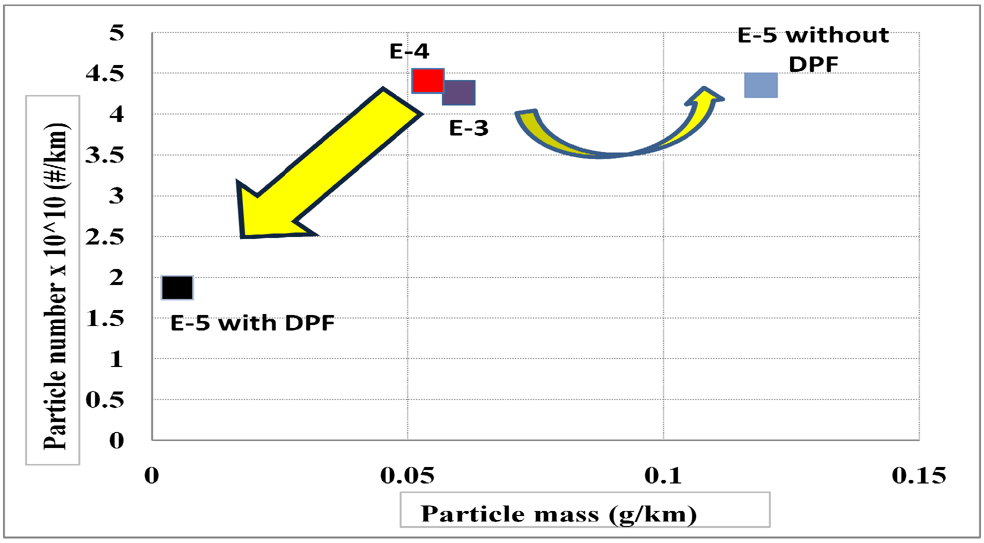


Fig7. Particle mass and emission trends in NEDC cycle.

To understand the result trends, it is worth mentioning some of the facts. All these emission compliant vehicles are powered with engines which uses common rail injection system capable of up to 1600 bar pressure. The vehicle configuration for E-3 and E-4 are same with Group B engine. However, E-5 test vehicle is different with Group C engine. Group B uses only DOC as an emission reduction device whereas DOC+DPF are required in case of Group C to meet E-5 emission. But, in this experimental study, E-5 test is done with no DPF. The objective of the study is to understand the particle number emission at DOC out condition. The engine out (or DOC out) particulate number emission appears to be similar. Only, DPF reduces them substantially if it is present in the exhaust system.

Table 3 gives the results of particle mass and particle number emission over NEDC cycle for emissions tests starting from E-3, E-4, and E-5 without and with DPF. Also, the same is plotted in figure 7. From figure 7, it is clear that with the improvement in the emission targets from E-3/E-4 to E-5, the particle mass is coming down and so the particle number **[15]**. This is mainly achieved by DPF in the system. As mentioned by Mitsuru Hosoya **[5]**, a wall flow DPF bring down the particle mass of non

Table 3: Particle mass and emission trend with emission upgrade.

Emission Level	P mass (g/km)	PN number (# x 10^{10})
E-3	0.06	4.261
E-4	0.054	4.406
E-5 (without DPF)	0.119	4.352
E-5 (with DPF)	0.0049	1.873

volatile fraction and its number. Similarly, the test results presented by Leonidas Ntziachristos et.al.**[16]** shows the particle number reduction with DPF for passenger cars and truck application with both urban and highway driving. But, the interesting fact is that E-5 level vehicle has got more particles mass and hence the number. This can be explained as, with higher level of NOx reduction demands, the overall exhaust gas recirculation (EGR) rates are comparatively higher. Also, the injection strategies favor the in cylinder NOx reduction for E-5 engine than E-3/E-4 engine. This increases the particle mass. This is ultimately reduced by having DPF in the exhaust system which gives filtration of non volatile fraction as high as over 99%. One more observation from the result is similar particle number emission from like to like condition of testing i.e. DOC out irrespective of emission up gradation. However, H A Nakhawa et.al. found significant difference in particle number for various model year emission tested over NEDC cycle.**[12]** This could be due to the difference in the technology prior to 2005 and post 2005. This confirms the observation by Chao He et.al. [**6**] of similar particle number with two different emission level (E-2 and E-3) in a unit injector when tested in a 6 cylinder inline diesel engine. Figure 8 shows the particle number traces for the above experiments.

3.3. Particle number emission from vehicles equipped with same capacity engine

The aim of this section is to understand the diesel particle number emission from same capacity engine equipped vehicle in NEDC cycle. These two engines are meeting E-4 emission norms and are equipped in the same vehicle. Both the engine employees 1600 bar common rail injection system and the cubic capacity of both engine is 2.5L. The emissions of particle numbers are given in figure 9 as shown below. Figure 9 clearly indicates that the diesel particle number emissions in two different phases are showing opposite trends for both the engines. i.e. Engine1 shows higher particle number in phase1 of NEDC compared to Engine2. Opposite trend can be seen in Phase2.

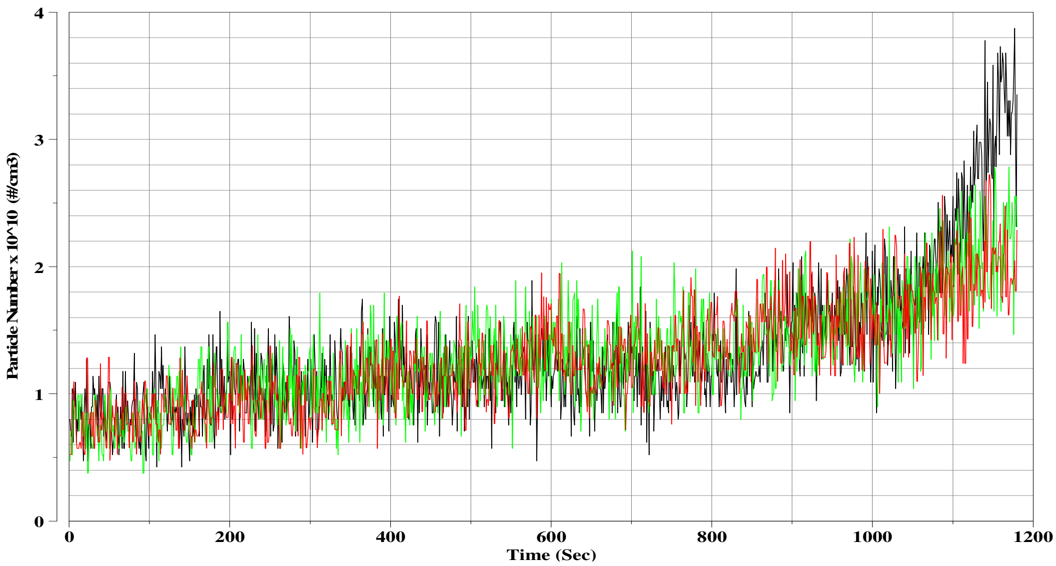


Fig8. Particle number emission traces at DOC out during NEDC cycle.

Table 4: Two different engines specifications.

Parameters	Engine1	Engine2
Bore(mm) x Stroke (mm)	94 x 90	88.9 x 100.3
Cubic capacity (L)	2.5L	2.5L
Aspiration	Turbocharged with intercooler	Turbocharged with intercooler
FIE system	BOSCH Gen2, 1600 bar	BOSCH Gen2, 1600 bar
After treatment system	With DOC	With DOC
Emission compliant	E-4	E-4
Vehicle application	Multipurpose vehicle (MPV) with two different final drive ratio	

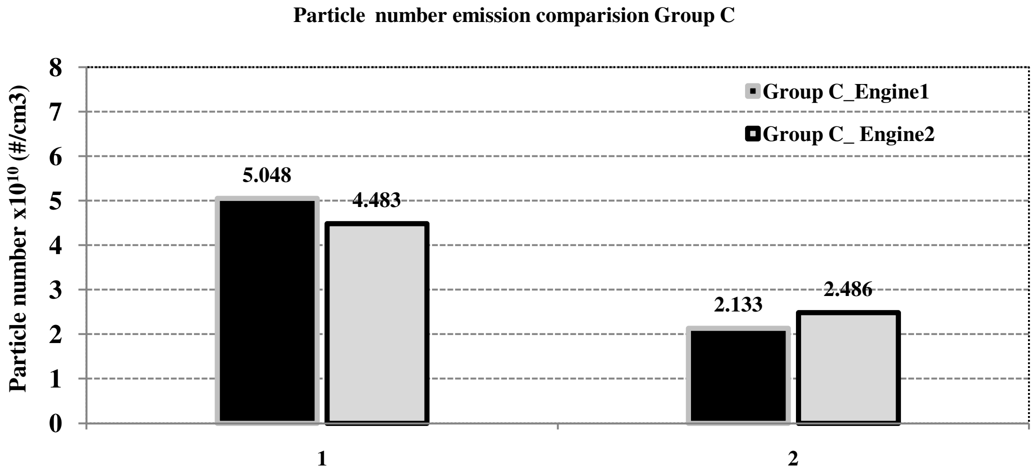


Fig9. Particle number emission with same capacity engine during NEDC cycle

For better understanding of particle number trends in the above tests, a detailed injection calibration parameters i.e. Rail pressure (RP), main injection timing (MI) and amount of EGR needs to be investigated. Engine calibration for the Engine1 is in such a way that it uses lower rail pressure compared to Engine2 in both the phases. But, the injection timings is calibrated in such a way where most of the part, it is advanced for Engine 1 compared to Engine2. The gravimetric particle mass of Engine 1 is higher by 14.6% in phase1 than that of Engine2. For phase2, it is 17.5% higher.

The EGR rates are on a higher side for Engine1 than Engine2 as seen from figure11. For Engine1 calibration is such that phase1 has higher EGR rates. The MI timing is calibrated as for some part advanced and then retarded with RP is on a higher side. It is presented that higher RP favors the lower particles **[11]**. Andrea Bertola et.al. **[7]** in their experiments, presented that to reach the minimum particulate matter concentrations in the exhaust one has to

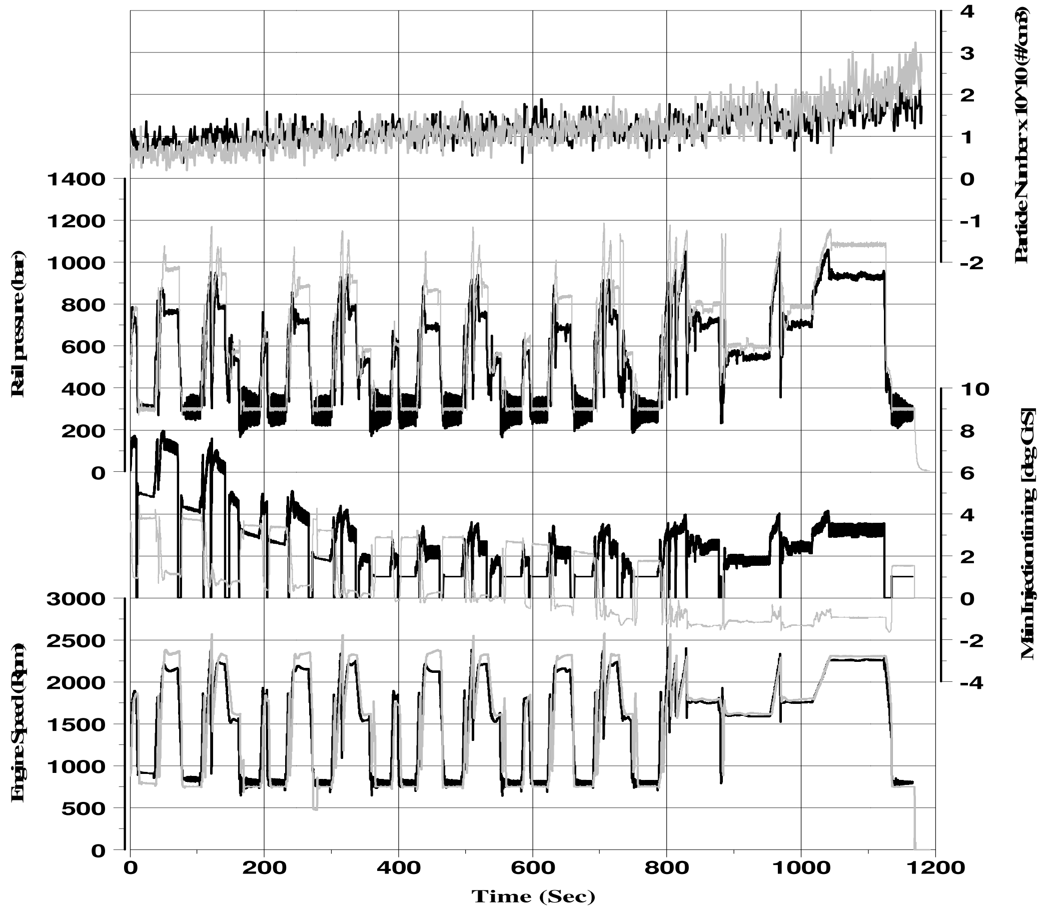


Fig10. Injection parameter trends for two engine applications.

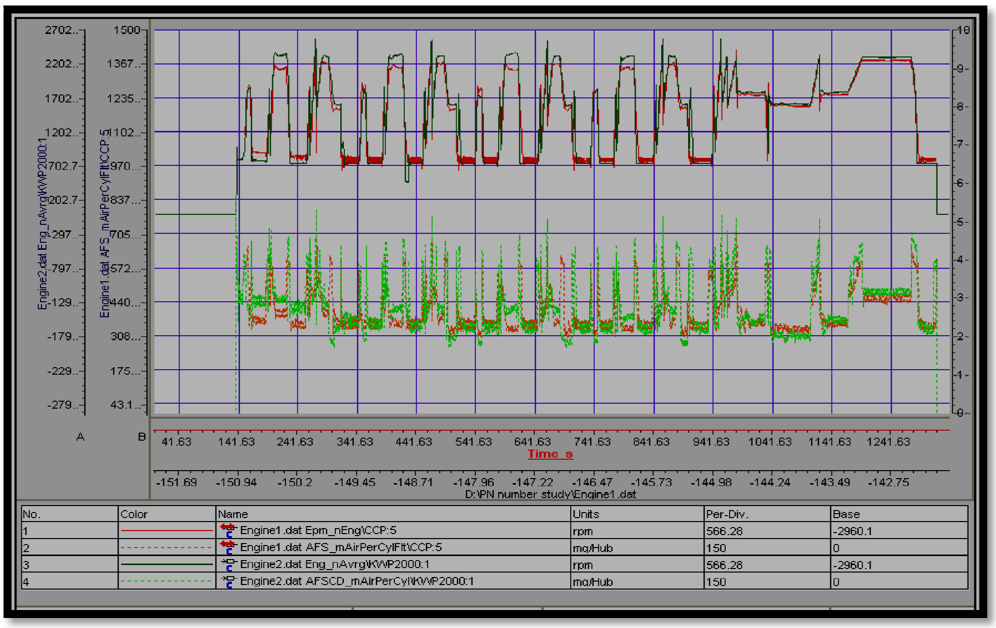


Fig11. EGR rate comparison (In terms of air flow) for Engine1 and Engine2

[7] in their experiments, presented that to reach the minimum particulate matter concentrations in the exhaust one has to operate with the maximum Injection pressure (RP) and advanced start of injection (MI). The higher EGR in case of Engine1 can be seen from figure 11 by lower flow rate values. (Note: higher air flow indicated lowers EGR and vice versa)

Thus, higher EGR rates in phase1 of Engine1 seems to be the major cause of the higher particle number. For particle number reduction in phase2 of Engine1 compared to Engine2 can be explained as below. Though Engine 1 operates with a RP of 200bar lower value, but the MI timing is advanced by 4 deg BTDC than Engine2. Also, the EGR rates are comparable as can be seen from figure11. Thus, MI is sensitive for particle number emission production for the higher engine speed and load of phase2.

4. CONCLUSIONS

As the particle mass is reduced, the particle number emission is found to be reducing due to reduction of mass.

A wall flow DPF exhibits around 56% particle emission reduction potential for the current application.

Different vehicles equipped with different engine capacities shows similar particle number emission per distance travelled.

For the same capacity engine meeting same emission norms, the particle number emission can differ based on the calibration strategies.

EGR, RP and MI timing, as mentioned in the earlier researches found to be sensitive in particle number emission production.

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