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REAL TIME MEASUREMENT OF ULTRAFINE AND NANO PARTICLES AND SIGNIFICANCE OF OPERATING GEARS

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Abstract

This research paper focuses on characterization of ultrafine and nanoparticle emissions from diesel vehicle to investigate their physical characterization in terms of number and size as they are more vulnerable and responsible for toxicity, mutagenicity and carcinogenicity. An investigation has been carried out to identify the significance of different operating gears, clutch, declutch and gear change operations for their contributions to particle number(PN) on urban and extra urban part of the driving cycle. A bi-modal particle size distribution pattern was observed for both urban and extra urban parts where almost all the particles are below 200 nm and particle number peaks appear at 7 to 8 nm and at 70 nm. Nano particles contribute approximately, 70% of total particle number over urban part. Experimental investigation shows that the most significant gear for their contribution to particle number are 3rd and 5th gears on urban and extra urban part of the driving cycle respectively.

Keywords: Particulate matter, Particle number, Nano particle, Characterization, Size distribution.

1. Introduction

World Health Organization (WHO) report points out the vulnerable effect of diesel particles in terms of carcinogenicity and severe health effects of diesel fuel used in automotive sector and it is estimated that two thirds of the global burden of disease due to urban outdoor air pollution is particularly in Asian countries [1]. Various types of cancers spreading in all age groups in the society leading to premature death due to ultrafine particles from the automotive exhaust [2]. Most recent studies support that PM produces high risk for cardiovascular compared to pulmonary

Abbreviations

4WD1	4 wheeler diesel vehicle No.1
CFV	Critical Flow Venturi
CMVR	Central Motor Vehicle Rules
CVS	Constant Volume System
DISI	Direct Injection Spark Ignition
DPF	Diesel Particulate Filter
EEPS	Engine Exhaust Particle Sizer
EGR	Exhaust Gas Recirculation
EOI	End of Injection
HEPA	High Efficiency Particulate Air
MIDC	Modified Indian Driving Cycle
MORTH	Ministry of Road Transport and Highways
PFI	Port Fuel Injection
PM	Particulate Matter
PN	Particle Number
PNC	Particle Number Counter
SOI	Start of Injection
TAP115/116	Type Approval Document for CMVR 115 and 116
UN	United Nations
WHO	World Health Organization

diseases for both short term and long-term exposures [3]. The World Bank estimates that in Delhi, a death every 70 minutes in 1995 from air pollution and the exposure to suspended particulate matters causes mortality estimated to be 1 in 10,000 for current levels of PM in Los Angeles, and the same effects may be expected in other countries with similar exposures [4].

Generally, particles are classified based on their size as nano particles (size ≤ 50 nm), ultrafine particles (50 nm< size ≤ 100 nm), fine particles (100 nm < size ≤ 2.5 µm), and coarse particles (size > 2.5 µm) [5-7]. Nuclei mode particles fall nearly entirely within the nanoparticle range while the accumulation mode particles can be in the fine and ultrafine ranges. The nuclei and accumulation modes are formed at different times and have different compositions [8]. Nanoparticles typically consists of hydrocarbons or sulphates and formed by nucleation during dilution and cooling of the exhaust, whereas, ultrafine particles can either be mainly carbonaceous soot agglomerates formed directly by combustion and metallic particles. Metal oxide particles of nano size coming out of diesel and gasoline engine exhaust are due to incomplete combustion of fuels or lub oil and because of abrasion of metal components [9].These ultrafine and nanoparticles cause more adverse health effects compared to larger particles. Nano particles (size <50 nm) contribute more than 90% towards total particle number (PN), whereas, accumulation mode particles which are in the size range between 50 nm to 1 µm contributes approximately 8 to 10% towards total PN and approximately 80% towards total particulate mass [10-12].

Generally, diesel engines irrespective of the design, emit most of the solid particles in the range of 100 nm at a concentration of the order of $>10^6$ particles/cc

[13]. For diesel passenger car particle number found to increase due to increase in load and EGR rates, and EGR rate is more significant [14]. A substantial increase in the number of particles can be observed for the early start of injection (SOI) and late EOI (End of Injection) due to wall wetting or impingement on the piston [15-17]. In-cylinder particle formation found to be dependent up on the engine parameters such as injection timing and spark timing for gasoline port fuel injection engine, which in turn affect in-cylinder oxygen content and temperature [6, 18]. Mike Braisher found that PN and PM emissions are generally in the order as, Non-DPF diesel > DISI > PFI ≈ DPF diesel [19].

WHO Working Group considered the range of long-term average $PM_{2.5}$ concentrations associated with adverse effects on chronic cardiovascular and respiratory disease in epidemiological studies and set the guideline level 10 $\mu g/m^3$ as an annual average [10, 20]. It is important to understand the characteristic behaviour of particulate emissions when the vehicle is operated in different gears on a regulatory driving cycle. Very limited research work has been carried out particularly in this context on diesel passenger car at national and international level. An experimental investigation is carried out particularly on the Indian diesel passenger car of BS-3 technology by operating on Modified Indian driving cycle (MIDC).

2. Experimental Setup and Test Method

Test setup used for the experimental study complies with Indian emission regulation MoRTH/CMVR/ TAP-115/116 and UN Regulation No.83 Rev.4 [21]. Briefly, the test setup comprise of a single roller chassis dynamometer of variable load curve type with electrical inertia simulation. Vehicle cooling blower of variable speed type used to simulate vehicle cooling effect and was synchronized with chassis dynamometer roller speed. A CFV type Constant Volume Sampling System (CVS) was used for diluting exhaust gas and maintaining constant flow rate. A sampling venturi takes a proportionate sample of dilute exhaust from the main stream which gets collected into CVS bags for further analysis using dilute exhaust gas analysis system to measure the gaseous pollutants. A full flow dilution tunnel of 48 inch diameter and PM dilution sampling system fitted with HEPA (High Efficiency Particulate Air) filter was used to measure $PM_{2.5}$. A Pre-classifier located before the PM filter holder used to cut down the particles above 2.5 μm. Diluted exhaust gas sample is then passed through PM filter holders fitted with fluorocarbon coated glass fiber filters to collect the particulates on it. These PM filter papers were first conditioned in PM conditioning chamber for minimum 1 hr and then weighed using micro balance to measure $PM_{2.5}$.

Test setup used for emission measurement is shown in Fig. 1 and the MID cycle used is shown in Fig. 2. Driving cycle is comprised of part-1 which represents urban driving and part-2 which is extra urban driving part, represents highway driving conditions. Urban part is of total 780 seconds which is between 0 to 780 seconds and further in continuation, vehicle to be driven on extra urban part starting from 781 seconds until 1180 seconds. This means extra urban part is of total 400 seconds.

To measure the particle number (PN), vehicle was driven on chassis dynamometer to follow the MID cycle. Chassis dynamometer simulates the road load condition in the laboratory. While, vehicle is driven on the cycle, a diluted exhaust gas sample was collected in the CVS bags and analysed at the end of the test to measure gaseous pollutants and the PM sample which was collected on the particulate filter. During the test diluted exhaust gas sample was also passed through volatile particle remover to remove the volatile particles so as to measure number of the solid particles only using condensation particle number counter (PNC) as per the regulatory procedure. The diluted exhaust gas same sample is also distributed to Engine Exhaust Particle Sizer (EEPS) for measuring the particle concentration over 32 different particle sizes between 5.6 nm and 560 nm.

Fig. 1. Test setup for emission testing.

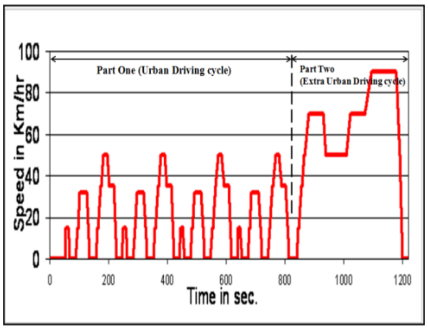

Fig. 2. Modified Indian driving cycle.

An experimental study was carried out on the Indian diesel passenger car (4WD1), of 2008 model year fitted with 37 kW, IDI, 4 stroke, 1.405 litre capacity diesel engine, EGR & catalytic converter exhaust after treatment device. Vehicle was tested with Euro-III diesel fuel. A road load equation in the form $F = 165.10 + 0.0401\,V^2 + 1130\,dV/dt$ from type approved vehicle model was used to simulate the road load on chassis dynamometer. Test results obtained are in vehicle loading conditions with pay load of 150 kg in line with regulation. This data analysis will help optimization of engine to meet regulatory norms. Details of engine specifications of diesel vehicle 4WD1 are given below in Table 1.

Table 1. Engine specifications of diesel vehicle 4WD1.

Engine Type	**Diesel, Indirect Injection, Water Cooled**
Cylindrical Bore	75 mm
Stroke	79.5 mm
Compression Ratio	22:1
Maximum Power	37 kW @ 5500 rpm
Maximum Torque	85 Nm@ 2500 rpm
Displacement	1405 cm^3
Ignition	Microprocessor Controlled Digital
Transmission	Manual 5-speed gear
Fuel Tank capacity	37 litres
No. of Cylinder	4 cylinder in line

Test vehicle was operated in different gears on urban and extra urban part of the driving cycle and its detailed break up in terms of operating time is given in Table 2. This time wise break up is used to characterize the ultrafine and nano particle emissions on urban and extra urban parts of the MID cycle.

Table 2. Operating time in gears for urban and extra urban part of cycle.

	On Urban Part of MID cycle		**On Extra Urban Part of MID cycle**	
Operation State	**Time in operation (s)**	**% of Urban time**	**Time in operation (s)**	**% of Extra Urban time**
1st Gear	96	12.3	5	1.25
2nd Gear	212	27.2	9	2.25
3rd Gear	164	21.0	8	2
4th Gear	NA	NA	99	24.75
5th Gear	NA	NA	233	58.25
Gear Change	32	4.1	6	1.5
Clutch engaged	140	17.9	20	5
Clutch disengaged	136	17.4	20	5
Total	780	100	400	100

3. Results and Discussions

Information about raw data output file from EEPS and the analysis steps used to characterize ultrafine and nanoparticles are discussed in this section.

3.1. Raw data output file from nano particle equipment

A raw data output file from EEPS gives PN concentration over 32 different sizes between 5.6 nm and 560 nm, therefore over entire MIDC which is of 1180 seconds and comprised of urban part of 780 seconds and extra urban part of 400 seconds, generates total 32 X 1180 = 37760 data points. There is no post processing software developed so far to analyse such a complex and large data. Test data is analysed using step by step approach is a novel methodology of data analysis devised to obtain useful inferences which are discussed below.

3.2. Analysis steps to characterize ultrafine and nano particles

To analyse the PN data under different driving conditions the complete MIDC is divided into urban part and extra urban part. PN concentration is integrated over respective time periods for size distribution. Particle size (PS) distribution patterns for urban, extra urban parts and over entire MIDC is shown in Fig. 3. Data analysis shows that almost 94% of the total particles over MIDC are of size below 200 nm and the larges peak appears at 70 nm, this was also reported by Hall et al. [22]. Size distribution pattern show that the accumulation mode peak appears in the range between 30 and 100 nm and it depends on the engine operation conditions and the nanoparticles contributed significantly [23]. Millo et al. [24] and Kinnunen et al. [25] found that increase in particle size range from 40 nm to 100 nm for diesel engine was observed when EGR changed from 0% to 100% and irrespective of the design mostly diesel engines emit solid particles in the range of 100 nm [13]. Karjalainen et al. [26] observed that for GDI vehicle, number size distribution consists of two modes with mean particle size below 30 nm and the other near 70 nm. Significant particle emissions were also observed during decelerations. From data analysis it is also observed that appx. 70% of total PN over urban cycle part comes from nanoparticles and rest from ultrafine particles.

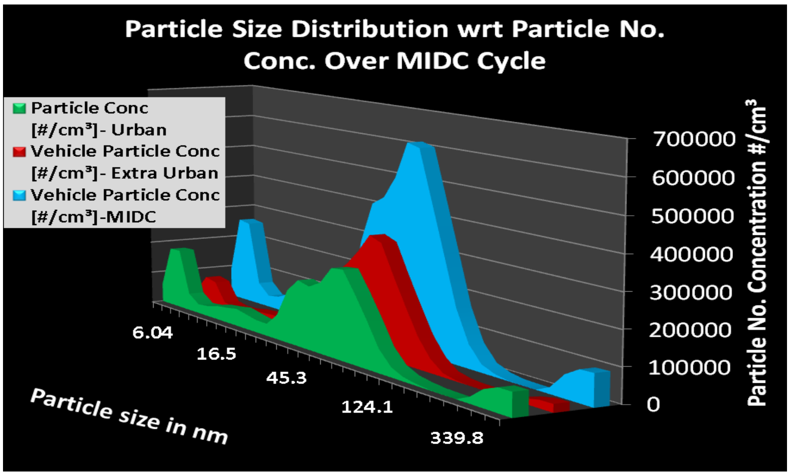

Fig. 3. Particle size distribution on urban, extra urban and MIDC.

Mayer et al. [27] found that during experimental investigation that for nearly all operating conditions, more than 50% of the particle number, and less than 1% of the particle mass were contributed by nuclei mode particles. In bimodal particle size spectrum for both urban and extra urban part, a first PN peak appear at 7 to 8 nm and second peak at 70 nm (Refer to Fig. 3). Experimental study carried out by Mayer et al. on direct injection diesel engine observed the similar phenomenon of bimodal size distributions with the nuclei mode particles in the size range between 7 to 15 nm and the accumulation mode particles in the range between 30-40 nm [27]. George et al. reported that for diesel vehicle geometric mean diameter of particles observed between 70 nm and 100 nm, however, for conventional gasoline vehicles it is well below 40 nm [11]. Mark S. Peckham et al. also observed that for the vehicle tested, the mean particle size range of accumulation mode particles falls within 50 nm to 150 nm [28]. Here, experimental data analyses also revealed that contribution by urban and extra urban part of the cycle for diesel vehicle is approximately 53% and 47% respectively. On urban part of the cycle nano particles and ultrafine particles contribute approximately 58% and 88% of their respective total particles on urban part. Similarly, on extra urban part contribution of nano and ultrafine particles is 36% and 91% respectively. This also shows that around 90% of total particles are of ultrafine nature which is very harmful.

From the online traces of particle number over the Indian driving cycle shown in Fig. 4 it can be observed that particle number follows the vehicle speed trend. Initial PN concentration peaks are larger in cold condition and further it reduces in hot condition this was also observed by Goodfellow et al. [22]. Particle number concentration goes on increasing as the vehicle is accelerated to the higher speeds. As soon as there is change in the acceleration rate a PN peak of nano size particles 8 to 10 nm appear however, further stabilization in the operation of the vehicle on the constant acceleration rate shifts the particle size between 60 nm and 70 nm. This may be due to rich fuel - air mixture required to be supplied during acceleration mode. Particle number concentration also increases with increase in constant speed and maximum PN can be observed on extra urban part of the cycle at 90 km/h cruising speed (Refer to Fig. 4).

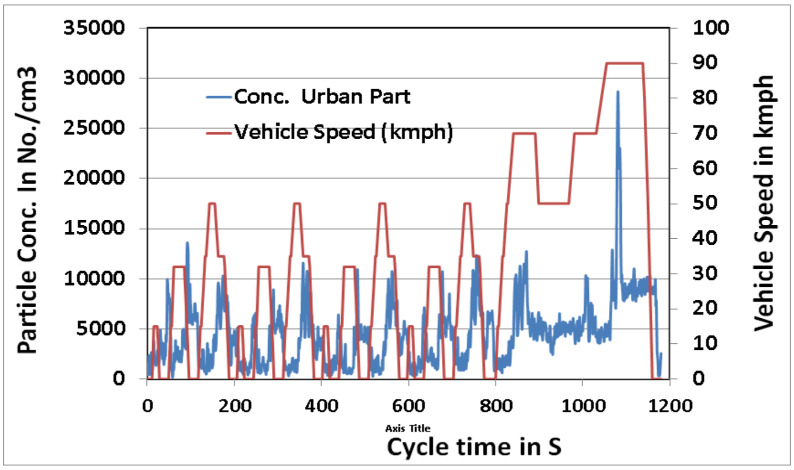

Fig. 4. Transient behaviour of particles on entire MID cycle.

We know that in the real world vehicles are operated in different conditions. Diesel vehicle particle emissions under transient operating conditions on MID cycle need to be understood in order to develop realistic particle number emission models. Gear wise analysis will also help in development of DPF for future technology vehicles to meet very stringent PM and PN emission norms. Gear wise analysis explained below is carried out for urban and extra urban part to understand the influence of operating gears on the particle number concentration specifically for diesel vehicle.

Analysis shows that for diesel vehicle 3rd gear is observed to be significant contributor on the urban part of the MIDC cycle and it contributes approximately, 27% of PN emissions on urban part. Figure 5 shows % contribution of PN when vehicle is operated in different gears, clutch, declutch and gear changing operations. While driving on urban part 4th gear doesn’t come into picture as the maximum speed on urban part is 42 km/h. In 3rd gear vehicle remains for total 41 second in operation which is 21% of total time in urban part of the cycle. The PN contribution in 1st and 2nd gear is approximately, 9.9% and 22.9% respectively, whereas, operations like gear change, clutch engaged and clutch disengaged conditions contribute approximately, 3.6%, 14% and 22.7% respectively. Table 1 shows the detail analysis of urban cycle itself carried out gear position wise which is required to analyse the data for the above inferences.

Entire urban part of the cycle is made of 4 repeat patterns of 195 seconds each, so total urban part of the cycle is of 780 seconds, Data analysed for these four subparts of urban part for different gears and other operating conditions is also analysed further and shown here in Fig. 6 to understand PN emission trends on them when the vehicle is driven on the cycle. It can be seen from Fig. 6 that among 4 subparts in urban part of the cycle, 1st gear is the most contributor (11.7%) in 4th subpart, 2nd gear is the most significant contributor (25.5%) in 1st sub part and 3rd gear is the most significant contributor (28%) in both 2nd and 3rd sub parts. Similarly, other operations such as clutch dis-engagement is the most significant (24.6%) in 2nd subpart, clutch engagement is the most significant contributor (14 -15%) in both 1st and 3rd sub parts.

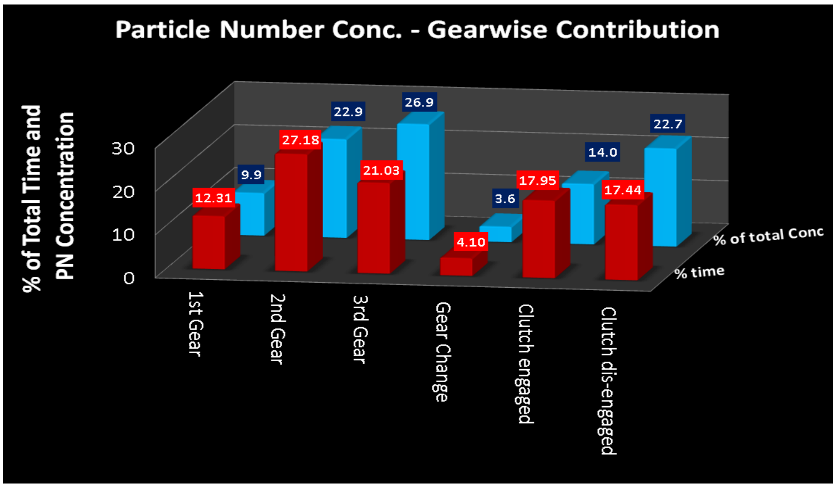

Fig. 5. Gear wise particle characterization on urban part.

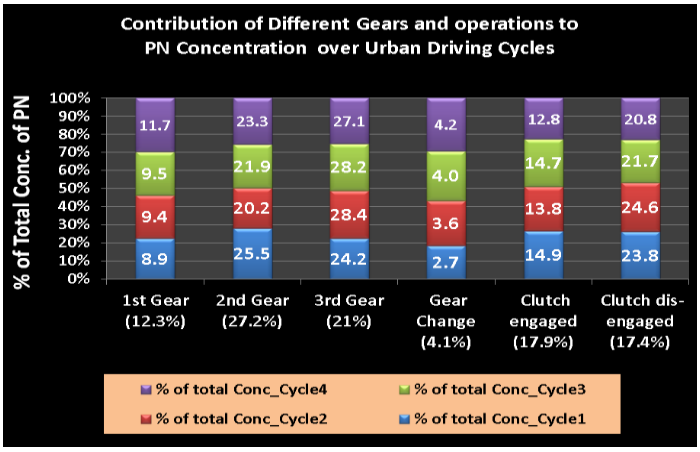

Fig. 6. Gear wise particle characterization on urban part.

Similarly, data analysis on extra-urban part of driving cycle is carried out. Analysis shows that for diesel vehicle when driven on the extra urban part of the MIDC cycle 5th gear is observed to be significant and it contributes appx. 73% for PN emissions (refer to Fig. 7). Graskow et al. [29] reported during their experimental investigation on S.I. engine that on European driving cycle particle number emissions at constant speed of 120 km/hr were in the order of 10^{11}-10^{12} particles per kilometer.

While driving the vehicle on extra urban part of the cycle vehicle also operates in 1st , 2nd and 3rd gear but their contribution to PN is very low below 1% as their % time of total operation itself is about 5.6%, except 4th gear operation which contributes appx. 17% to particle number concentration emissions; this is shown below in Fig. 7. Analysis for the gear change, clutch engaged and clutch disengaged conditions contribute appx. 0.4%, 3.8%, 3.8% respectively to PN. Table 2 shows the detail analysis of extra urban cycle itself carried out gear position wise which is required to analyse the data for the above inferences.

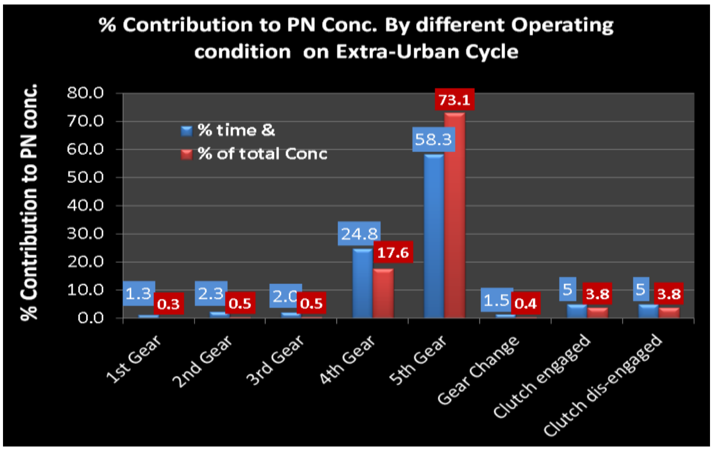

Fig. 7. Gear wise particle characterization on extra urban part.

4. Conclusions

Experimental investigation has been carried out to characterize the ultrafine and nanoparticle emissions for their real time behaviour on regulatory driving cycle and to find out significance of contribution by operating gears. Experimental study identified the most dominant gear for PN emissions on urban and highway driving conditions. Technique has been devised to analyse the huge and complex data from EEPS and to pinpoints exactly where engine and transmission designer need to focus for optimization. This will certainly benefit technical community to save their resources in terms of time, money and efforts.

- Study reveal that urban part of the cycle is the most significant and it contributes 53% to total PN over MID cycle compared to 47% for extra urban part. Real time particle measurement shows bimodal size distribution patterns on both urban as well as on extra urban part of the cycle. The PN concentration peaks appeared near to 8 nm and 70 nm.

- PN concentrations observed to increase at higher acceleration rate and also at higher cruising speeds due to rich fuel-air ratio to meet the demand at increased load. Investigation shows that the 3rd gear is the most significant contributor to PN emissions on urban part and 5th gear is the most significant on the extra urban part of the MID cycle.
- These findings are based on the limited data for one diesel vehicle pertaining to specific vehicle technology and test fuel used. Future studies on different fuels and wide technology spectrum is recommended.

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