EXHAUST EMISSION STUDY OF TURBOCHARGED CI ENGINE UNDER TRANSIENT OPERATION USING BS IV AND BS VI DIESEL FUEL

Thesis submitted in the partial fulfillment of requirement for the award of the degree

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In

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Submitted by

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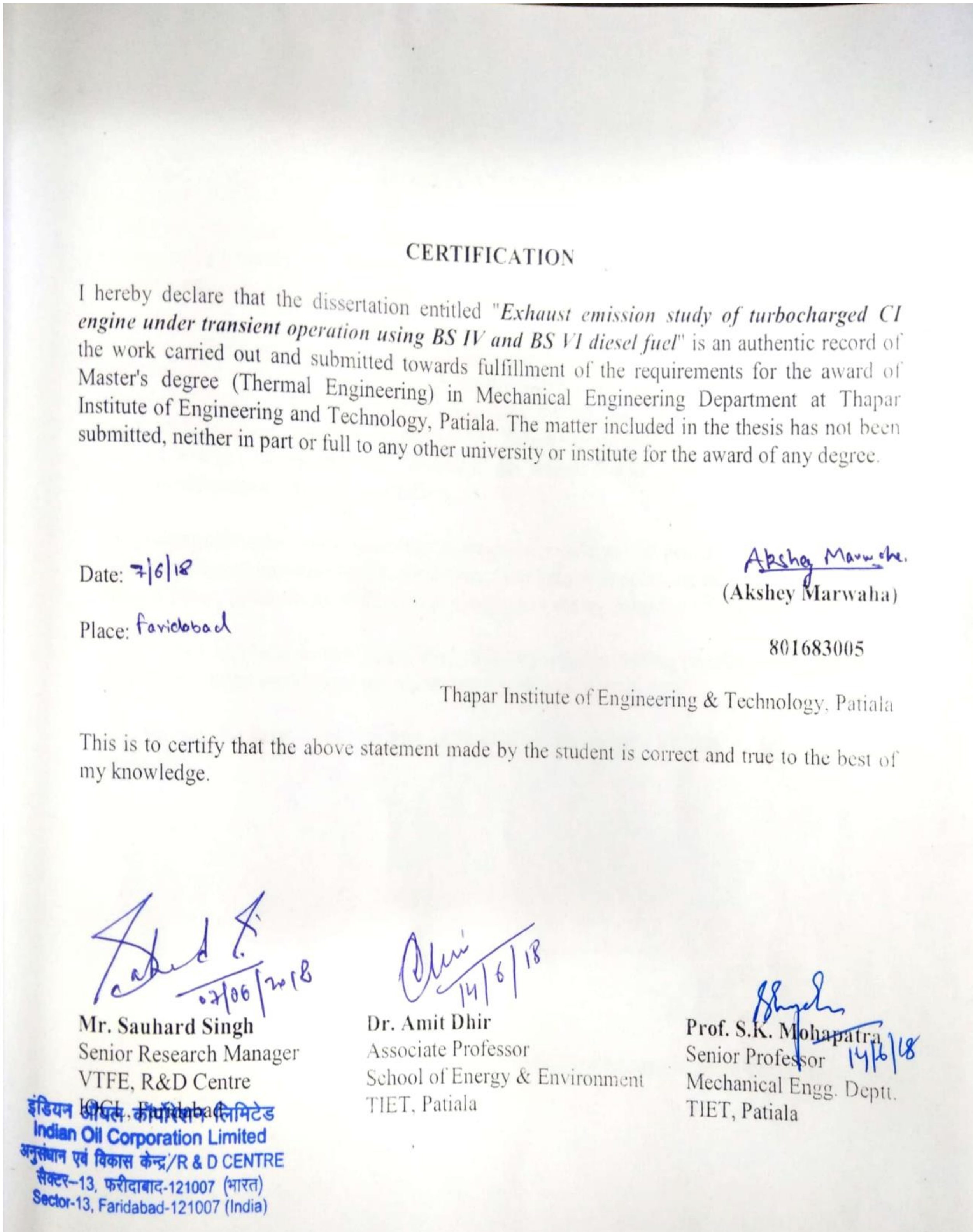

CERTIFICATION

I hereby declare that the dissertation entitled "***Exhaust emission study of turbocharged CI engine under transient operation using BS IV and BS VI diesel fuel***" is an authentic record of the work carried out and submitted towards fulfillment of the requirements for the award of Master's degree (Thermal Engineering) in Mechanical Engineering Department at Thapar Institute of Engineering and Technology, Patiala. The matter included in the thesis has not been submitted, neither in part or full to any other university or institute for the award of any degree.

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ABSTRACT

The stringent laws and regulations concerning the vehicle emissions have compelled the automotive sector and pollution boards to adapt to more advanced engine design and after treatment devices. In addition, the testing facilities have also been upgraded from time to time in order to comply with the latest emission regulations. The diesel fuel has been the prime mover of transportation and power generation sector in the world for over a century. The emission study of engine in real time is crucial to interpret the behavior and effect of fuel oil and lubricant on the engine performance and emissions. India from past few years has been following the emission regulations of Europe, that is, Euro norms, and currently Euro-4 compliant vehicles are manufactured and running all over the country.

A transient test schedule, named European Transient Cycle (ETC) was operated on the turbocharged diesel engine with use of ultra low sulfur diesel. A comparison of engine performance and emissions with Bharat Stage BS IV and BS VI diesel fuel was drawn. The concentration and mass of regulated emissions such as nitrous oxides, total hydrocarbons and carbon monoxide were calculated and compared for both the diesel fuels. Particulate matter emissions comprising of fine and ultrafine particulates were measured with full flow dilution method to calculate the particle number concentration and mass from the engine exhaust.

The BS VI diesel showed better results with improved brake specific fuel consumption, and reduced particle number (PN) emissions and particulate mass (PM) when compared to BS IV diesel fuel. Specific emissions measured in g/kWh indicate the emissions produced per kWh of electricity (work) produced by the engine.

In the following years, portable emission measurement systems (PEMS) will become more common as real time transient results can be obtained during the field trial of vehicles with portable and less bulky equipment required. As the present dilution and conditioning equipments require a very large space and investment, emission systems in the future are expected to become portable.

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NOMENCLATURE

PM	Particulate matter
ETC	European Transient Cycle
ESC	European Stationary Cycle
CNG	Compressed Natural Gas
WHTC	Worldwide Harmonized Transient Cycle
WHSC	Worldwide Harmonized Stationary Cycle
WNTE	Worldwide Harmonized Not-To-Exceed
PEMS	Portable emission measurement system
SOF	Soluble organic fraction
EGR	Exhaust gas recirculation
USLD	Ultra low sulfur diesel
PAH	Polycyclic aromatic hydrocarbons
FTIR	Fourier-transform Infrared Radioscopy
MEXA	Motor exhaust gas analyzer
VOC	Volatile organic compounds
EPA	Environmental Protection Agency
CMVR	Central motor vehicle rule
CPCB	Central Pollution Control Board
HDV	Heavy-duty vehicle
PDT	Primary dilution tunnel
UDC	Urban driving cycle

CVS	Constant volume sampler
FTP	Federal Test Procedure
SMPS	Scanning Mobility Particle Sizer
TEOM	Tapered element oscillating microbalance
DPF	Diesel particulate filter
SCR	Selective catalytic reduction
ELPI	Electrical Low Pressure Impactor
CPC	Condensation Particle Counter
ECM	Electronic Computer Module
LNT	Lean NOx Traps
PN	Particle Number
PMP	Particulate Measurement Programme
EGT	Exhaust Gas Temperature
DPM	Diesel Particulate Matter
CFV	Critical Flow Venturi
PDP	Positive Displacement Pump
VPR	Volatile Particle Remover
PNC	Particle Number Counter
PTFE	Poly Tetra Fluoro Ethylene
THC	Total Hydro Carbon
CLD	Chemiluminescence detector
NDIR	Non-dispersive Infrared Detector
FID	Flame Ionization Detector
SPCS	Solid Particle Counting System

ELR	European Load Response
GRPE	Working Party on Pollution and Energy
UNECE	United Nations Economic Commission for Europe

CHAPTER 1

INTRODUCTION

Diesel engines are in use on a wide basis with various specific applications. These engines are primary source of power in heavy-duty applications. Trucks, buses, marine propulsion, railway locomotives are some areas utilizing diesel engines. Higher compression ratio along with better fuel efficiency than gasoline engines prove to be favorable for the use of diesel injected systems. However, direct injection diesel engines are known to emit more amounts of NOx and particulate emissions than gasoline-powered engines. Therefore, it has become crucial to follow stricter emission norms imposed by the government.

Nitrogen oxides (NOx) and particulate matter (PM) are the most common and harmful pollutants emitted by diesel engines. The particulate matter includes unburnt hydrocarbons and soot. The main challenge for the improvement of diesel engine involves simultaneous reduction of both pollutants. Exhaust Gas Recirculation is most widely used technology for the reduction of NOx levels [1, 2].

The engine is loaded by a transient alternating current (AC) dynamometer in a real time emission measurement system. Generally, all over the world, the engine emission limits are specified in grams per kilowatt-hour (g/kWh).

Chassis dynamometer testing is employed for light duty vehicle emissions testing. But, for heavy-duty vehicle emissions, two cycles schedules, European Transient Cycle (ETC) and European Stationary Cycle (ESC) are performed on an engine dynamometer. Diesel heavy-duty vehicles must pass both the tests to be certified. Compressed natural gas (CNG) operated HD vehicles need not undergo the ESC test to be certified.

According to the BS VI regulation, the updated cycles, World Harmonized Transient Cycle (WHTC) and World Harmonized Stationary Cycle (WHSC) would replace the presently used ESC and ETC schedule. In addition, following the UNECE Regulation No-49, World Harmonized Not-to-Exceed (WNTE) off-cycle laboratory test would be adopted.

Figure 1.1 [3] shows the process of emission formation from internal combustion engines. Incomplete combustion in the form of black smoke and soot is observable in diesel engines because of incomplete mixture formation of air and fuel.

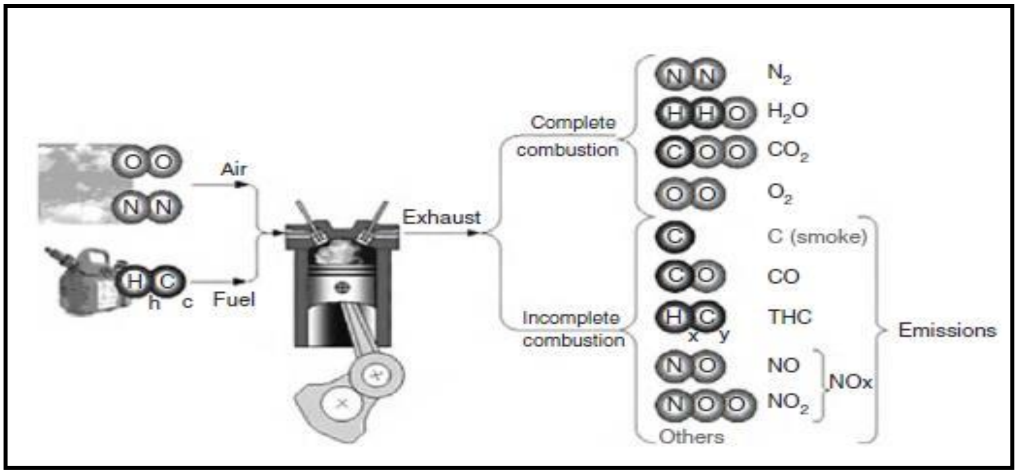


Figure 1.1 Emissions from combustion process [3]

1.1 EMISSIONS FROM DIESEL ENGINES

The design of engine and fuel composition directly affects the diesel engine emissions. The type of engine operation can also have an impact on the emission levels. The main pollutants emitted by diesel engines include the nitrogen oxides, hydrocarbons, carbon monoxide and particulate matter-PM. Among these emissions, HC and CO are produced due to incomplete combustion and unburnt fractions of liquid fuel and oil whereas high combustion temperatures above 1600°C lead to increased NOx levels (NO and NO_2). Carbon is present in form of smoke and soot emissions. PM emissions are generally caused by the agglomerated partly burned fuel particles, burned lube oil, ash content of fuel oil and cylinder lube oil [4]. Unlike the emissions from gasoline-powered engines, diesel engine operates with excess air, due to which CO emissions are not a huge problem. However, on the other hand, particulate and NOx emissions are much higher in diesel engines. Figure 1.2 [4] shows the general composition of diesel exhaust gas.

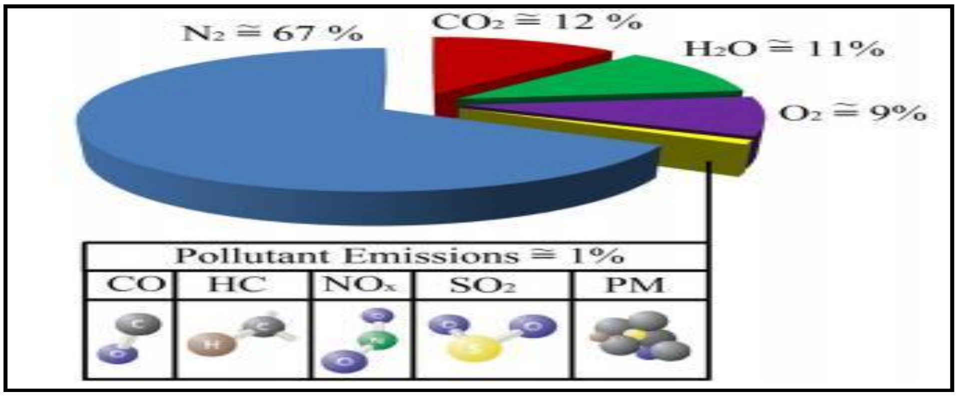


Figure 1.2 Classification of pollutant emissions [4]

According to the figure, NOx possesses highest proportion of diesel exhaust emission followed by CO2, H2O, O2 and lastly pollutant emissions. NOx emissions are easily affected by the excess air factor and maximum cylinder temperature. This has led to development and use of exhaust gas recirculation (EGR) in order to meet the latest emission standards for diesel engines. Unlike NOx, no catalytic converters are available for the elimination of sulphur dioxide. Therefore, ultra low sulfur diesel (ULSD) is becoming popular in the oil industry [4].

The emissions could be of two types, regulated and unregulated emissions. NOx, PM, HC and CO are the regulated emissions which are measured by analyzers in the motor exhaust gas analyzer (MEXA). FTIR spectrometer is used to measure the unregulated emissions including soluble organic fraction of the PM (SOF), individual hydrocarbons, ethanol, aldehydes and ketones, polycyclic aromatic hydrocarbons (PAH) and 1-nitropyrene.

The main pollutants of diesel engines have been discussed below in detail.

1.1.1 Hydrocarbons

Hydrocarbons are toxic pollutants formed because of burned or partially burned fuel. Hydrocarbons are made up of carbon and hydrogen. Oil, natural gas and pesticides have a large proportion of hydrocarbons in them. The unburned hydrocarbon could result due to two reasons: if the fuel-air mixture is too rich or too lean to ignite or to support a propagating flame inside combustion chamber of diesel engine. The hydrocarbons are main contributor of smog and its exposure may result in lung diseases.

1.1.2 Carbon monoxide

Carbon monoxide is an unwanted toxic pollutant formed due to incomplete combustion of hydrocarbons in automobiles. Transportation sector is the main contributor of CO pollutants. Long exposure to such emissions include increased risk of chest pain, headaches and impaired reaction timing. Mainly these emission may come from engines not equipped with catalytic converters. Carbon monoxide may then react with the other pollutants present in air leading to the formation of harmful ozone.

1.1.3 Oxides of nitrogen

NOx pollutants are formed when the fuel is burned at very high combustion temperatures. This brownish colored gas is a strong oxidizing agent. This is the reason it plays a huge role in atmospheric reactions with volatile organic compounds (VOC), thus producing ozone on hot summer days. Formation of nitric oxide takes place in the following order, namely, thermal NO, prompt NO, fuel NO and N_2O. In diesel engines, major fraction of NO is formed via the thermal route.

1.1.4 Particulate matter

The combination of solid soot and liquid particles found in the air result to form particulates. The formation of particulate begins with nucleation in combustion chamber by carbon soot and ash.. After this, agglomeration of nuclei mode particles takes place. Soot constitutes nearly 50% of total particulate matter produced. The formation of soot is generally observed in fuel rich regions at elevated temperatures without sufficient oxygen concentration. Particle size distribution measurement is becoming an area of great interest for the future. PM_{10}, that is, particulates with diameter less than 10µm size, have been measured by gravimetric method as according to Euro 4 emission regulation. PM can accumulate in the human respiratory system, thus resulting in lung diseases.

The particulates with size visible to the humans are called smoke. The possible source of particulates have a direct impact on the smoke colors from vehicles visible in the environment.

- Black color- soot, that is mainly carbon, making up to 95% of diesel smoke
- Blue color- hydrocarbons, noticed mainly during burning of lube oil caused to engine fault
- White color- water vapor, which may result due to condensation in cold engine or coolant leaking into combustion chamber
- Brown color- nitrogen dioxide, mainly observed in the exhaust of heavy duty engines

Ambient particulate matter can be described in four categories based on their aerodynamic diameter.

- Coarse particles- aerodynamic diameter < 10µm
- Fine particles- diameter < 2.5µm
- Ultrafine particles- diameter<0.1µm
- Nano-particles- diameter< 50nm

PM is generally regulated on a mass basis by means of filter paper and subsequent weighing by gravimetric method. The engine exhaust emissions based on mass and number over varied diameter have been shown in Figure 1.3 [5].

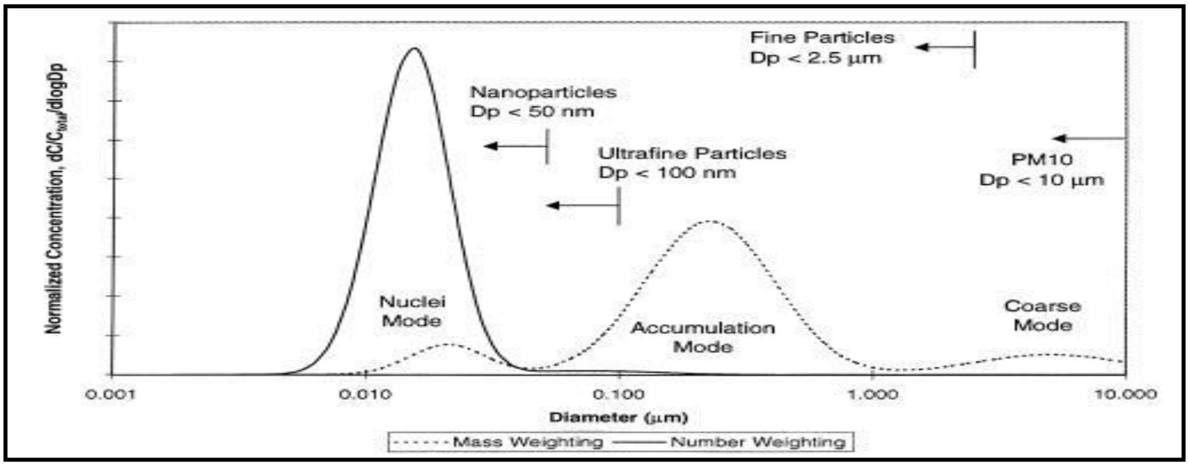


Figure 1.3 Particulate mass and number distribution [5]

The daily driving schedule involves unsteady or transient operation of the engine of vehicle. The vehicle rarely operates in true steady state, that is, at constant speed mode in cruising mode. Thus, the assumption of steady cycle mode during operation of vehicle would not give appropriate results. The transient operation demands quick changes in operating conditions with rapid engine response.

Figure 1.4 [6] shows that the real world transient operation emissions are much more dominant than steady state emissions.

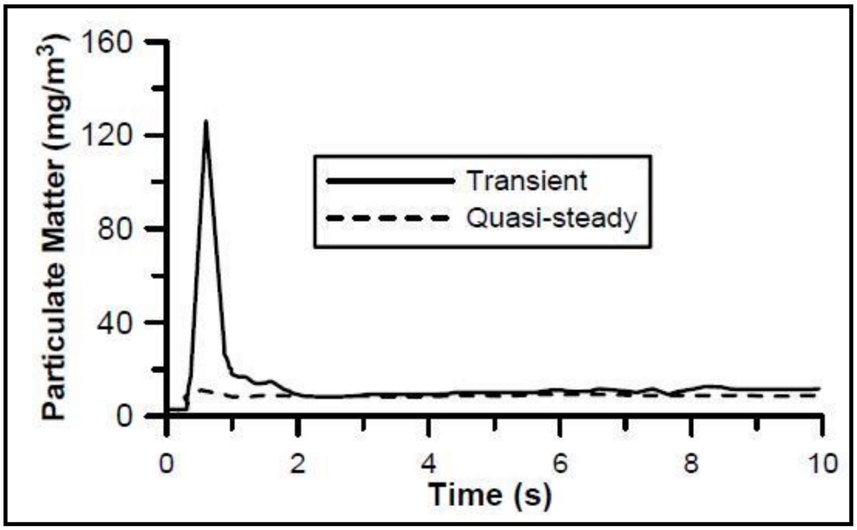


Figure 1.4 Steady state versus transient PM emissions of turbocharged diesel engine [6]

Figure 1.5 [7] shows various used for measurement of particulate matter.

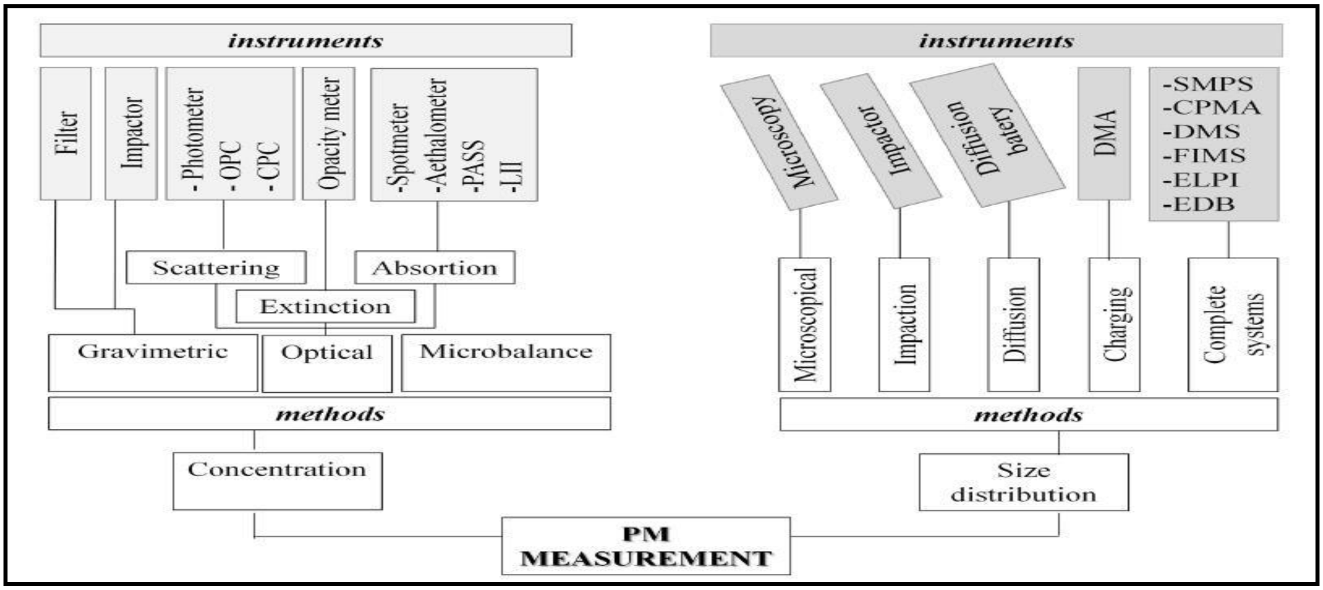


Figure 1.5 PM Measurement methods [7]

Gravimetric method is one of the most common methods of sampling which has been used from the past years in determining the particulate mass. The particulates diluted in fixed proportion are collected on a filter, whose is placed in a filter holder. The filter is then weighed on a microbalance kept in a temperature and humidity controlled chamber.

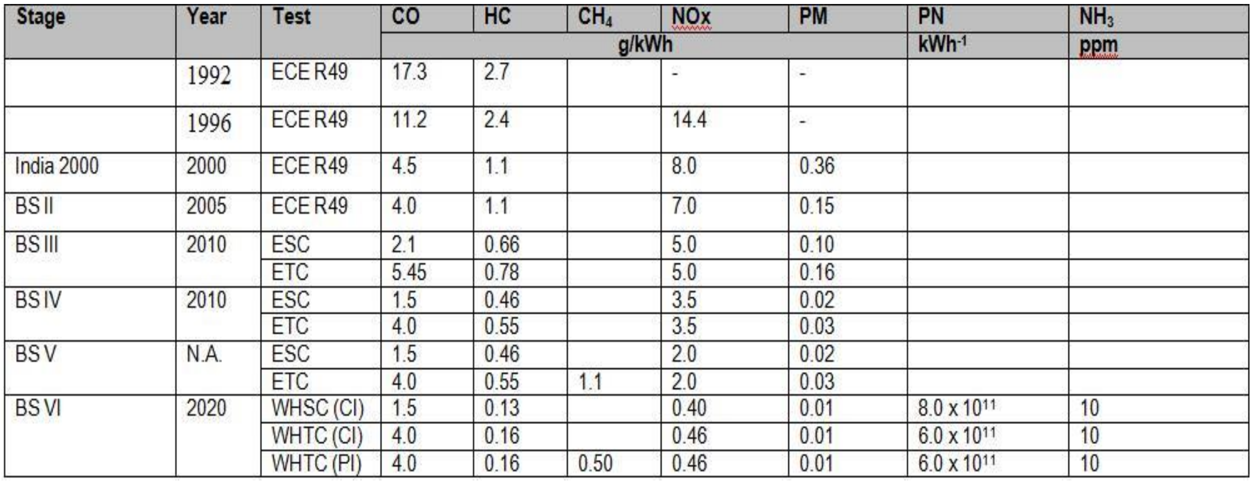
Earlier US EPA protocol, that is, before 2007, required the temperature of diluted exhaust gas at filter face to be less than or equal to 51.7°C. However, the latest protocol specifies the temperature of diluted exhaust gas to be 47°C ± 5°C.

1.1.5 Smoke emissions

Smoke is formed because of combustion, leading to a collected mixture of airborne solid, liquid particulates and gases. Smoke is made up of small particles, gases and water vapors. Black smoke is very common in heavy-duty diesel engines exhaust due to over-fueling of engine. Faulty injectors, faulty injector pump, a bad EGR valve, improper air filter or a bad turbocharger.

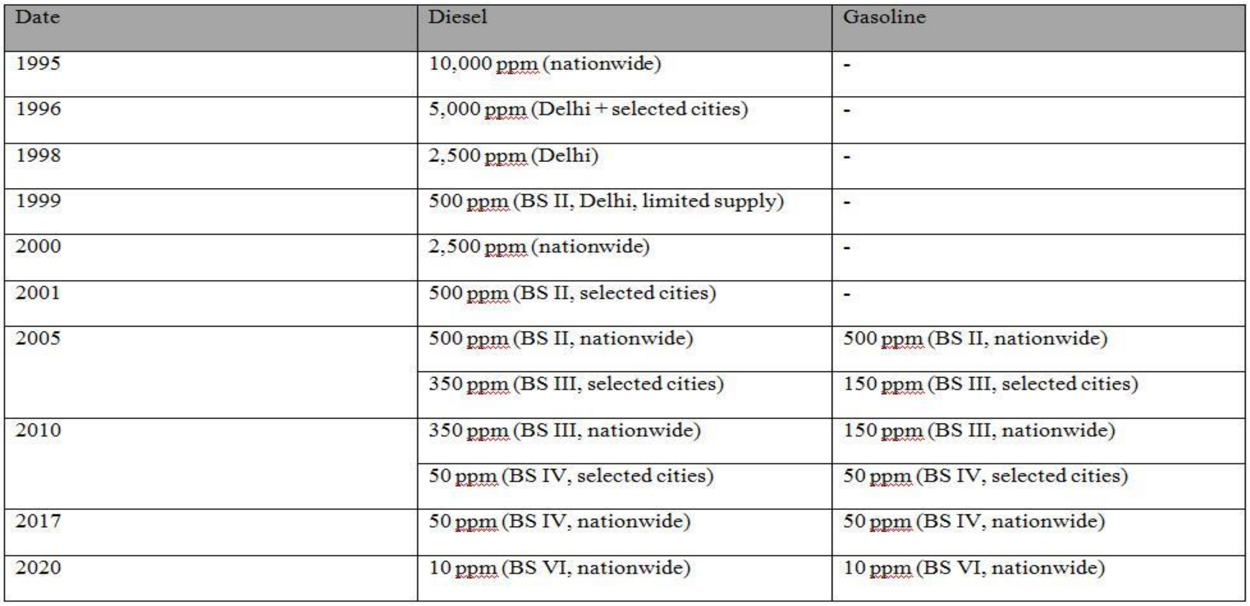
1.2 HISTORY OF BS EMISSION NORMS IN INDIA

In India for the first time, under the central motor vehicle rule (CMVR) No.15, emission regulations were made only for idling conditions. It was in the year 1991 for gasoline light duty vehicles and 1992 for diesel vehicle, that the mass emission standards were introduced for the first time. Then, India Stage-I norms were introduced from April, 2000 and since this year, India has adopted and been following the European emission and fuel regulations for four wheeled light duty and heavy duty vehicle. It was in the year 1989 that for the first time emission regulations with idle emission limits came into action. Following this, emission regulations for gasoline and diesel came into effect in the year 1991 and 1992, respectively. Presently, India is following Bharat Stage IV norms with 50ppm sulphur in diesel fuel. This number has gone down to 10 ppm sulphur with the updated BS VI diesel fuel which has introduced for use in NCT of Delhi from April 1, 2018. Earlier it was proposed to launch BS V norms in April, 2019 and BS VI norms in April, 2023. In early 2016, the Government of India decided to leapfrog BS V norms and straightaway move to BS-VI norms as the former ones were only a slight improvement over BS IV norms in terms of emissions. It is expected that BS VI fuel will be available all over the country from April, 2020. These emission standards are organized by Government of India to control the pollutants emitted by internal combustion engines. Central Pollution Control Board (CPCB) sets up the timeline and standards for successful execution of such norms. Figure 1.6 [8] shows the emission standards limits implemented in India over the few years for HD engines. Figure 1.7 [9] displays the sulfur limits enforced by government all over the country.



Stage	Year	Test	CO	HC	CH_4	NOx	PM	PN	NH_3
			g/kWh					kWh^{-1}	ppm
	1992	ECE R49	17.3	2.7		-	-		
	1996	ECE R49	11.2	2.4		14.4	-		
India 2000	2000	ECE R49	4.5	1.1		8.0	0.36		
BS II	2005	ECE R49	4.0	1.1		7.0	0.15		
BS III	2010	ESC	2.1	0.66		5.0	0.10		
		ETC	5.45	0.78		5.0	0.16		
BS IV	2010	ESC	1.5	0.46		3.5	0.02		
		ETC	4.0	0.55		3.5	0.03		
BS V	N.A.	ESC	1.5	0.46		2.0	0.02		
		ETC	4.0	0.55	1.1	2.0	0.03		
BS VI	2020	WHSC (CI)	1.5	0.13		0.40	0.01	8.0×10^{11}	10
		WHTC (CI)	4.0	0.16		0.46	0.01	6.0×10^{11}	10
		WHTC (PI)	4.0	0.16	0.50	0.46	0.01	6.0×10^{11}	10

Figure 1.6 Emission standards for heavy- duty engines [8]



Date	Diesel	Gasoline
1995	10,000 ppm (nationwide)	-
1996	5,000 ppm (Delhi + selected cities)	-
1998	2,500 ppm (Delhi)	-
1999	500 ppm (BS II, Delhi, limited supply)	-
2000	2,500 ppm (nationwide)	-
2001	500 ppm (BS II, selected cities)	-
2005	500 ppm (BS II, nationwide)	500 ppm (BS II, nationwide)
	350 ppm (BS III, selected cities)	150 ppm (BS III, selected cities)
2010	350 ppm (BS III, nationwide)	150 ppm (BS III, nationwide)
	50 ppm (BS IV, selected cities)	50 ppm (BS IV, selected cities)
2017	50 ppm (BS IV, nationwide)	50 ppm (BS IV, nationwide)
2020	10 ppm (BS VI, nationwide)	10 ppm (BS VI, nationwide)

Figure 1.7 Implementation of fuel sulfur content reductions in India [9]

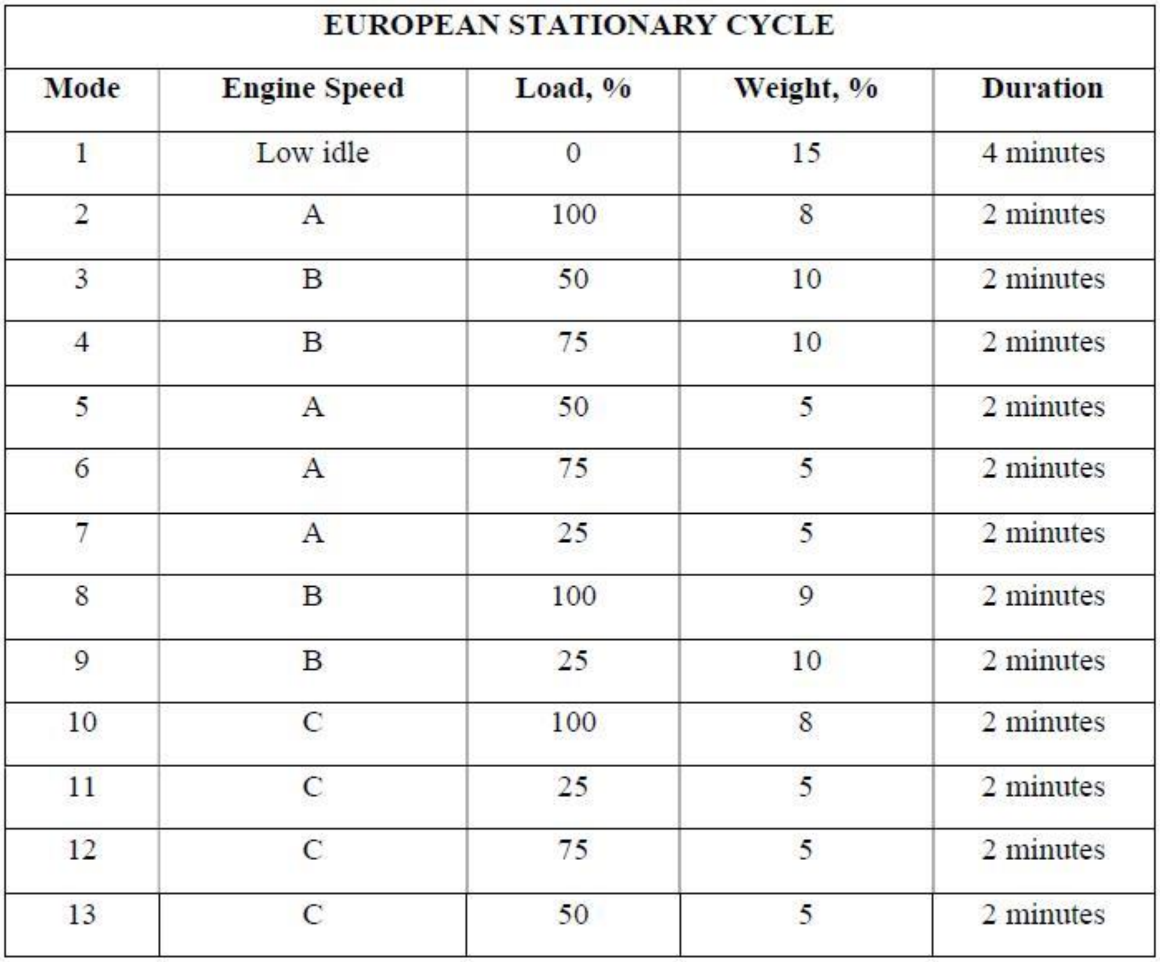
1.3 TEST CYCLES

The BS IV compliance fuel HDVs (Heavy Duty Vehicles) are tested on mainly three cycles, namely, ETC, ESC and ELR.

Whereas, the BS VI compliance fuel HDVs are tested on WHTC, WHSC and WNTE cycle.

The various cycles for transient testing are discussed below:

European Stationary Cycle- ESC procedure is a 13-mode, steady-state procedure that replaced the R-49 test. Earlier named as ACEA or OICA cycle, this test involves the engine testing on an engine dynamometer over a continuous 13 steady-state modes. The engine is run on these modes, where each mode has a fixed time. During each of the 13 modes, emissions are measured which are then averaged over the whole cycles with the use of set of weighting factors. The emission values for the cycle are specified in g/kWh. Figure 1.8 and Figure 1.9 illustrates the ESC speed and load variation at different duration of the cycle.



EUROPEAN STATIONARY CYCLE				
Mode	Engine Speed	Load, %	Weight, %	Duration
1	Low idle	0	15	4 minutes
2	A	100	8	2 minutes
3	B	50	10	2 minutes
4	B	75	10	2 minutes
5	A	50	5	2 minutes
6	A	75	5	2 minutes
7	A	25	5	2 minutes
8	B	100	9	2 minutes
9	B	25	10	2 minutes
10	C	100	8	2 minutes
11	C	25	5	2 minutes
12	C	75	5	2 minutes
13	C	50	5	2 minutes

Figure 1.8 ESC speed modes

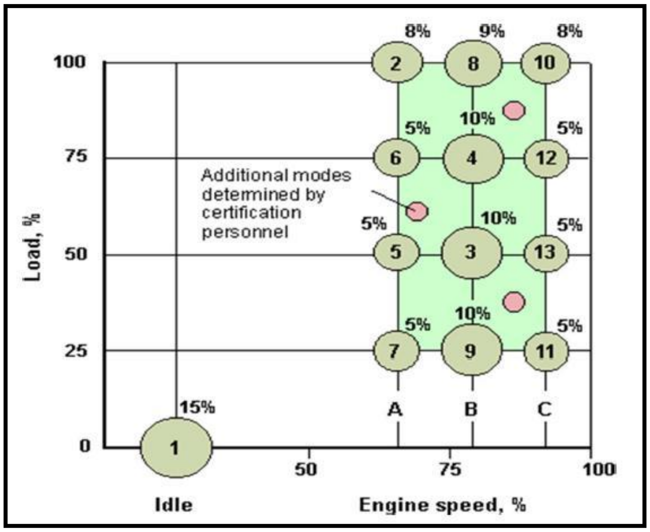


Figure 1.9 ESC speed and load variation

European Transient Cycle- ETC cycle was introduced in the year 2000 with Directive 1999/96/EC of December 13, 1999.

Earlier R-49 test was used which have now been replaced with ETC and ESC (European Stationary Cycle). The ETC cycle is divided into three equal duration parts, namely, urban, rural and motorway driving. The duration of the entire cycle is 1800s, thus each part getting a duration of 600s. Figure 1.10 shows the time schedule involved in ETC for transient engine operation.

- Urban part- This part replicates the city driving condition with engine running at maximum speed of 50 km/h with frequent starts, stops, and idling.
- Rural part- This part starts with a steep acceleration segment. The average speed achieved by the engine during this phase is about 72 km/h.
- Motorway part- This part maintains an almost constant average speed of about 88 km/h.

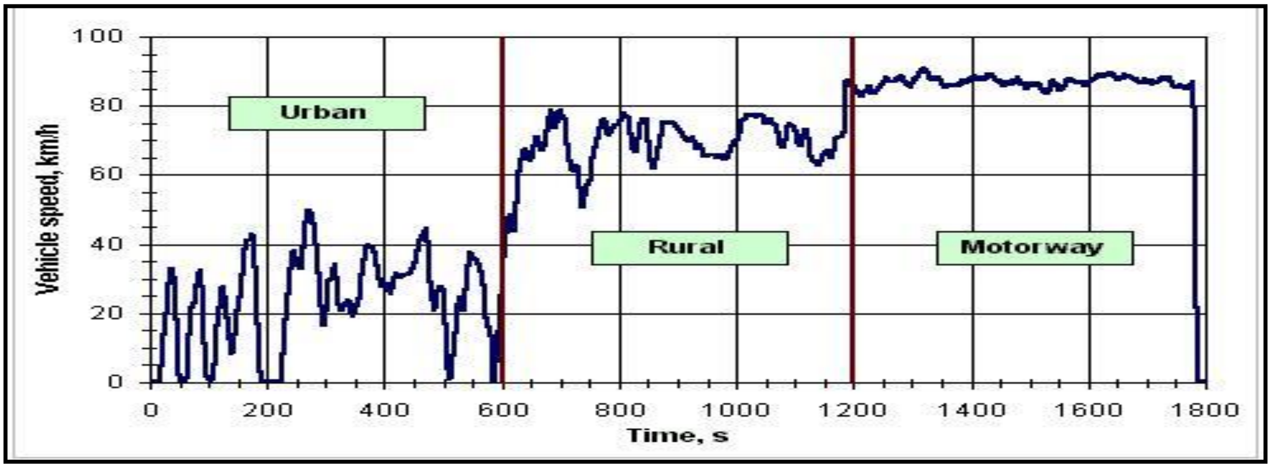


Figure 1.10 ETC time schedule

World Harmonized Transient Cycle- WHTC test schedule has been adopted by Euro VI emission regulation for HD engines, which takes into consideration the worldwide (US, EU, Japan and Australia) trend and conditions of actual HD commercial vehicle use. The cycle includes both cold and hot start requirements developed as according to the worldwide driving conditions. The WHTC is a 1800s duration transient test, with several motoring segments. Figure 1.11 shows WHTC cycle over 1800s duration with normalized speed and torque values.

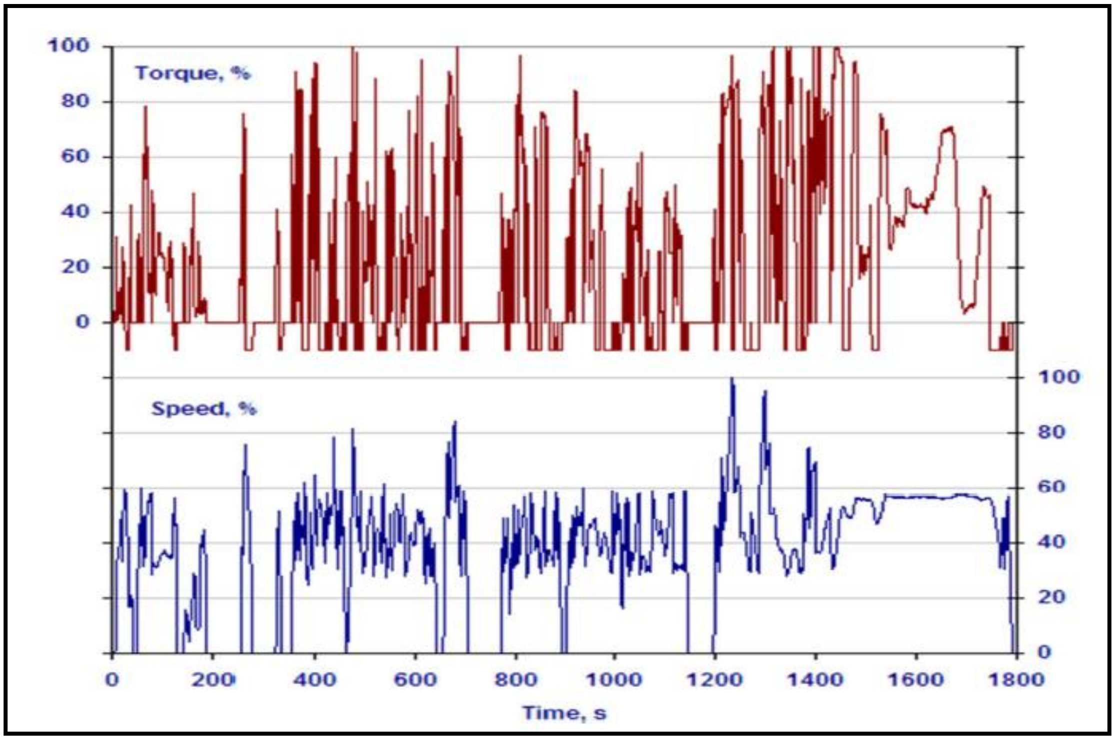
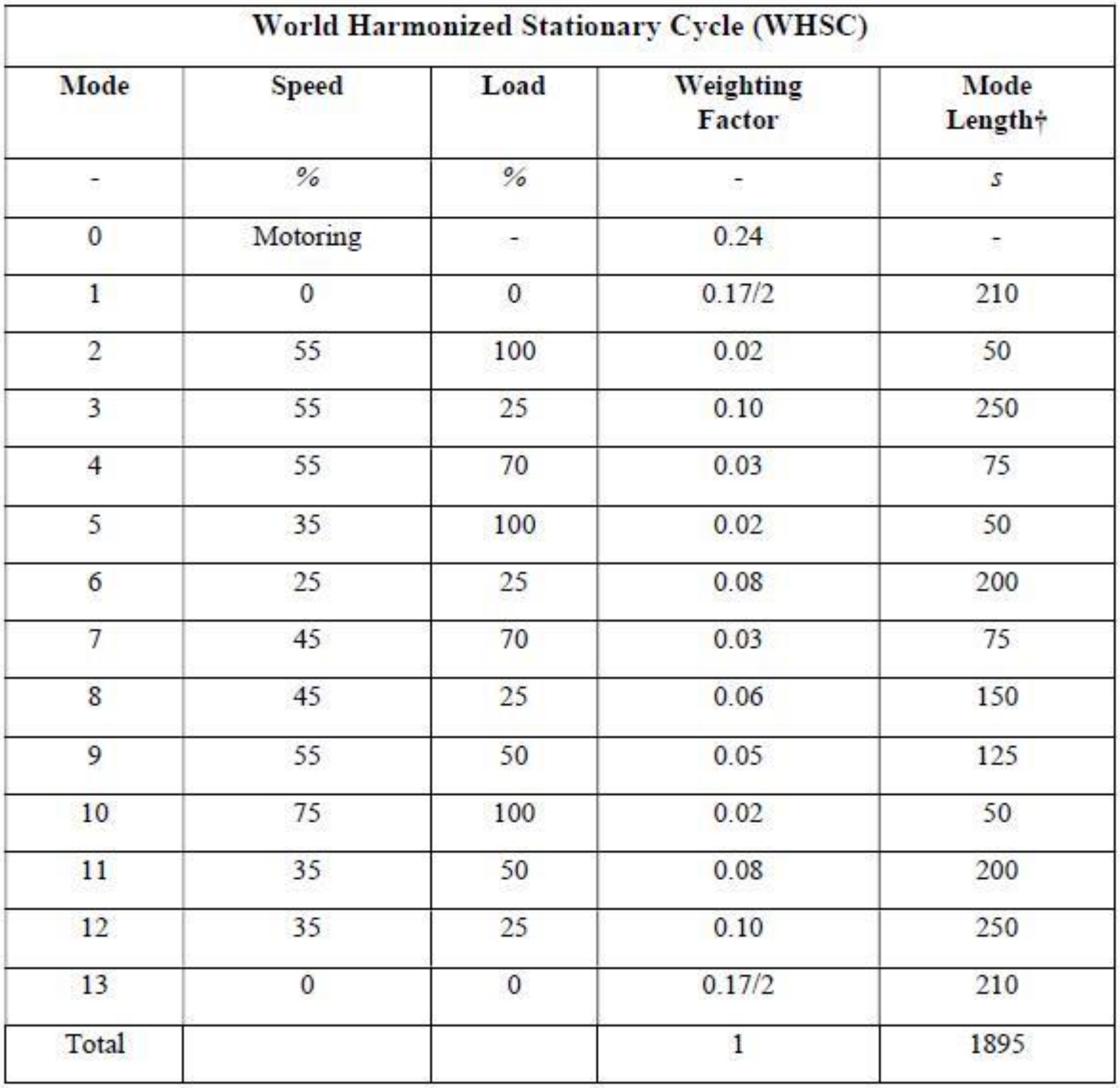


Figure 1.11 WHTC time schedule

World Harmonized Stationary Cycle**-** WHSC is a steady-state test developed by the UNECE GRPE group. This schedule includes 13 steady state modes with various speed and torque requirements at every mode and defined ramps between each of the modes. WHSC test begins from a hot start, following engine preconditioning at mode 9. The beginning of the cycle (mode 1) and end of cycle (mode 13) experience the idling of engine. Figure 1.12 enlists different parameters involved during the ESC test schedule.



World Harmonized Stationary Cycle (WHSC)				
Mode	Speed	Load	Weighting Factor	Mode Length†
-	%	%	-	s
0	Motoring	-	0.24	-
1	0	0	0.17/2	210
2	55	100	0.02	50
3	55	25	0.10	250
4	55	70	0.03	75
5	35	100	0.02	50
6	25	25	0.08	200
7	45	70	0.03	75
8	45	25	0.06	150
9	55	50	0.05	125
10	75	100	0.02	50
11	35	50	0.08	200
12	35	25	0.10	250
13	0	0	0.17/2	210
Total			1	1895

Figure 1.12 WHSC speed modes

1.4 OUTLINE OF THE THESIS

The various chapters in the thesis are organized as follows:

Chapter 1: Introduction

A brief outline has been established regarding various toxic pollutants emitted by heavy-duty diesel engines. The development and regulations of emission standards set up year by year have been mentioned and described. The procedure of testing the engines has also been discussed in detail.

Chapter 2: Literature Review

An extended literature survey on the measurement of pollutants had been done where a significant focus has been given to particulate matter emissions and their regulated measurement techniques. The cause and formation of such particulate emissions has been discussed in detail.

Chapter 3: Research gap and objectives

A few research gaps have been listed in this chapter, based on the limitations on the literature study. The noted shortcomings have not been explored to the full potential in India, and thus the need for further research was required. The objectives were prepared by keeping in mind the particulate measurement programme (PMP) for heavy-duty engines.

Chapter 4: Experimental test setup and methodology

The experimental test setup and methodology involved in order to carry out the engine testing has been explained in this chapter. The functioning of equipments with their specific roles has been discussed in detail. Also, the set of procedures and calculations with formulae involved in the emission analysis have been given accordingly.

Chapter 5: Results and discussion

In this chapter, the results collected have been analyzed in order to draw the conclusions. The comparison between BS IV and BS VI diesel has been displayed in form of column graphs and the resulting percentage improvement of performance has been evaluated. The rationale behind the data attained has been provided to interpret the results assuredly.

Chapter 6: Conclusion and future scope

The possible conclusions have been drawn keeping in mind the result data accquired from experimental tests. The rundown and bottom-line is presented in the final section to develop the hypothesis. In addition, future scope of the concerned area has also been discussed in detail.

CHAPTER 2

LITERATURE REVIEW

Transient operation of diesel engine is difficult due to the continuous speed and load changes of engine with respect to time. The particulate matter composition is thus influenced by the changing air-fuel ratio and the in-cylinder temperature. Because of the transient conditions, the accurate particulate matter measurement requires the use of sophisticated real-time automation and control.

In contrast to the larger particles, smaller particles posses higher surface area per unit particle mass, thereby offering more surface area for condensation/adsorption of toxins such as VOC's and PAH's. Thus, the smaller particles tend to become more lethal to the health of humans.

Ushakov et al. [10] revealed a correlation observed between sulfur content in marine fuels with particulate mass and number concentrations. The sulfur content had negligible effect on accumulation mode particles (consisting of soot agglomerates), which vary with speed and load conditions. Nucleation mode particles were highly influenced with sulfur content in fuel. Similar effect was observed for size distributions being affected by primary dilution tunnel (PDT). The particulate mass was observed to increase with high sulfur fuel.

Kittelson [11] surveyed the various nanoparticle emissions thrown out by diesel engines. Diesel engine emitted particulate matter can be categorized into three size ranges: nuclei mode, accumulation mode and coarse mode. Unlike mass, particle number is not conserved and can be varied by coalgulation and nucleation, which may lead to change in particle size and inaccurate results and measurements.

Ushakov et al. [12] investigated the particulate matter size distributions from a HD CI engine running on a low sulphur marine diesel fuel. SMPS and ELPI used for measuring particle number size distributions gave similar results that were in agreement with each other. Accumulation mode particles with diameter ranged at 55-65 nm were observed at maximum engine speed. The increase of Primary Dilution air Temperature (PDT) from 30°C to 400°C resulted in reduction of particle number.

Yokoi et al. [13] studied the effect of dilution factor, dilution air conditions (humidity, temperature) and engine preconditioning on the particle number size distributions emitted at the engine tailpipe. The results revealed that diluted air parameters must be kept constant in order to obtain steady measurement values.

Burtscher [14] emphasized on volatile materials that initially are in gaseous phase, but condense in solid particle form resulting in more number of particle concentrations. The nucleation effect is therefore prevented by diluting the exhaust gas in a full flow dilution based CVS system. The design of sampling and dilution system is a crucial aspect of exhaust emission measurement affecting the particle number concentrations.

Arregle et al. [15] studied the performance of a 4 cylinder, turbocharged diesel engine to measure gaseous emissions in real time with engine operating at transient condition. The particulate mass was obtained based on the measurement values of smoke opacity and hydrocarbon emissions. The mass procured by this method was validated with standard gravimetric method. The application of this method was applied on a light duty diesel engine running on UDC, and the results confirmed the method to be efficient for transient engine operation.

Bermudez et al. [16] investigated the capability of optical methods to predict soot and particle emissions and compared the results with gravimetric method during the engine transient operation. Opacimeters with fast response time measured continuous particle emissions in real time. The expressions obtained to estimate total particle emissions over-predicted the measured emissions. The study indicated a 4% factor for hydrocarbon emission to the obtained particulate mass but it is not possible to compute universal factor predicting correct contribution of hydrocarbons in soluble organic fraction (SOF).

Kinsey et al. [17] carried out a comparison study on different particulate matter mass and number measuring instruments on two turbocharged engines. TEOM with fast response time gave the best results in correlation with gravimetric filter method for particulate mass measurement. SMPS and ELPI presented a similar behavior in measuring particle number distributions.

Wang et al. [18] tested a No.2 certification fuel and a low sulphur diesel (BP-15) on a 5.9 liter turbocharged diesel engine equipped with EGR over FTP test cycle. The test results revealed average particle number concentration of 1.2e8/cm^3 using certification fuel, which was four times that for BP-15 fuel. Such high concentration resulted from high speed, torque and acceleration included in the test cycle. The diesel NOx absorbers with active regenerations were successful in minimizing the formation of particle emissions.

Mohr et al. [19] highlighted various particle mass measurement methods consisting of both mass based and non-mass based techniques in order to analyze and compare their effectiveness (based on sensitivity, repeatability, limit of detection) in measuring particulate emissions on a Euro 3 compliant 6 cylinder, Volvo make turbocharged engine. The non-mass based methods (CPC, ELPI, light scattering, diffusion charger, and diffusion battery) show better sensitivity in measuring particle emissions. Better and updated emission measurement devices may lead to difficulty in comparing particle emission of past technology, but will be significant in effective measuring the particulate matter of very low concentration.

Srivastava et al. [20] carried out an investigation to study the effect of engine load on particle matter number and size distribution from a Kirloskar make diesel engine. Temperature increased with larger load leading to more formation of soot. The results were computed for load varying from no load to full load (applied by a resistive load bank) at constant engine speed. At no load, particles in size range of 20-25 nm dominated the number concentration, whereas with increase of load, 20-25 nm size ranged particles had highest concentration. Figure 2.1 depicts that on further increasing the load on engine, 60-70 nm size ranged particles dominated the concentration.

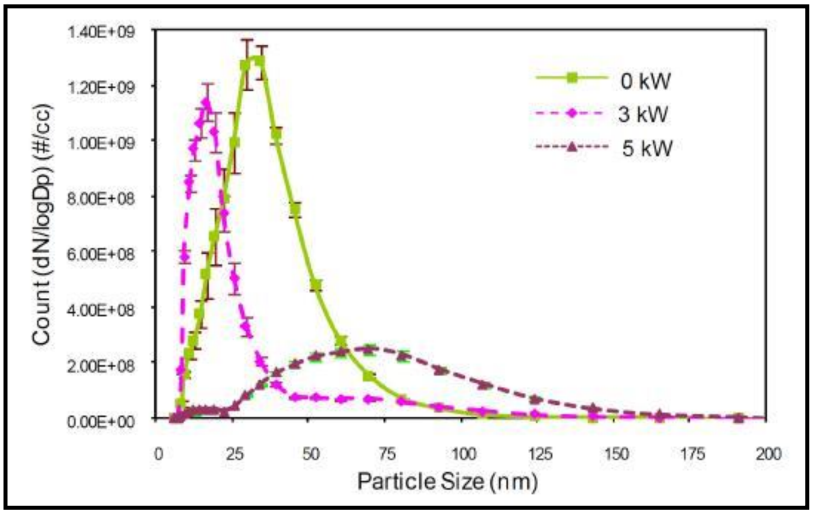


Figure 2.1 Effect of engine load on particle number and size

Giakoumis and Alafouzos [21] carried out a study to compare exhaust emissions of a turbocharged diesel engine operating on ETC, FTP and WHTC schedule. The simulation procedure used to compare the three cycles was based on steady state experimental study of engine to compute power, nitrous oxides, fueling and soot corresponding to speed and torque of engine. ETC was observed to be the most dynamic cycle with abrupt changes in load and speed resulting in increased emissions. The urban part segment in ETC with frequent stops is mainly responsible for soot generation.

Myung et al. [22] emphasized on calculating nano-particle mass and concentrations of HD diesel engine equipped with DPF operating on European and Worldwide Transient test cycles. The particle number concentrations (#/kWh) for WHTC, WHSC, ETC and ESC were 4.783E+11, 6.087E+10, 4.596E+10 and 3.389E+12. The particle mass observed in the study ranged from 0.0011 g/kWh for WHSC to 0.0031 g/kWh for ESC.

Yum et al. [23] performed an experimental study to investigate the effects of cyclic transient loads towards NOx emissions and fuel economy on a turbocharged diesel engine. The quasi-steady mapping method used in the study predicted fuel consumption accurately except at low load with high frequency conditions.

Huai at al. [24] analyzed the performance of heavy duty diesel truck to measured the emissions. The NOx emission rate (ton per day) were calculated at different speed modes: idle, creep, transient and cruise. On-board Electronic Computer Modules (ECM) periodically collect engine operating data with parameters including engine speed and load. This data collection method records vehicle operation data for over entire lifetime of vehicle unlike the traditional method.

Johnson [25] evaluated the regulations concerning heavy duty diesel vehicle emissions and their respective control strategies. SCR is an after treatment technology for NOx control, which requires further developments in performance of zeolite SCR catalysts in low temperature regimes LNTs being effective upto 70-80 percent deNOx efficiency. Diesel Particulate Filter (DPF) is another effective technology which may be used to avoid the release of harmful particulates.

Bischof [26] reflected on some past developments giving an insight on legislations controlling measurement of particulate emissions. In addition to particulate mass measurements, particle number (PN) has been added as an additional emission parameter. Unlike the former parameters, solid particle number method is more sensitive in recording the performance of after-treatment devices such as DPF. Particulate Measurement Programme (PMP) recognizes measurement of solid particle with size above 23nm threshold to avoid variability in emission measurement results.

Giakoumis and Alafouzos [27] generated an engine mapping-based methodology and a comparative analysis for all three parts of ETC schedule were performed which led to conclusion that urban driving part results in major amount of emissions (in g and g/kWh) due to most abrupt and frequent load and speed changes. The mapping technique can easily determine the effect of after treatment devices in terms of improvement in emissions.

Watson et al. [28] carried experimental study to obtain results for suspended particulate matter from gravimetric analysis method. Aerosol sampling by passing diluted exhaust air through the filter is mostly used to determine $PM_{2.5}$ and PM_{10} concentrations. However, a precisely temperature and humidity controlled environment is necessary for error free filter weighing.

Liu et al. [29] inspected PM number emissions during transient operation of old and modern diesel engine. The nuclei mode (diameter of particle < 30nm) PM emissions from both engines increased with suplhur content of fuel, whereas higher primary dilution ratios led to increase in total nuclei-mode PM emissions. The acceleration of engine leads to high Exhaust Gas Temperature (EGT) and high soot concentrations resulting in decrease of nuclei mode particle formation, where deceleration leads to the opposite.

Saiyasitpanich et al. [30] discovered an increase of diesel particulate matter (DPM) as a result of increased sulfur content and applied loads on a non road diesel generator. An empirican relation for DPM prediction was developed involving engine load and sulfur content as independent variables. More than 50% reduction in DPM was achievable with decrease of sulfur content from 3,700 ppm to 500 ppm.

Liu et al. [31] studied the various size distribution of particulate matter emitted by diesel engines under transient conditions. Almost 90% of the particle emissions are in the nuclei mode range (D_p<50nm), but due to their very small size constitute only 20% of the mass. The larger diameters of accumulation mode range (50nm<Dp<500nm) particles results in their largest share in mass percentage of emissions.

Petrović et al. [32] carried out study to measure particulate emissions in a dilution system along with CFV flow measuring device. The tunnel with single dilution was designed for full automatisation of emissions measurement testing. Analytical analyzers were used for measuring gaseous emissions such as CO, HC and NOx. For the measurement of particulates, gravimetric method was employed for collection of particles using filters.

CHAPTER 3

RESEARCH GAP AND OBJECTIVES

The emission analysis and control studies conducted in the past have led to further advancements in procedures and regulations in limiting the toxic emission from vehicles. India, in particular lags behind other nations in the world, in terms of minimizing the emission levels due to the unregulated law and regulations. This means that the older technologies are still prevalent in the country, which has resulted in pollution problems in many areas. Heavy-duty diesel vehicles are one of the primary carriers of materials and resources in the country. Regulated emissions such as nitrous oxides, carbon monoxide and hydrocarbons are more observed in diesel engines. In addition, the area of particulate emissions requires more attention due to its detrimental effect on human health.

An extensive literature survey was carried out to search for gaps in literature and subsequently construct the possible objectives for research.

3.1 RESEARCH GAPS

Many research studies have been performed in order to determine the regulated emissions from gasoline and diesel engines. However, a limited experimental study has been done in measuring the fine particulates escaping the engine tailpipe in real time conditions. The transient operation of engine simulates the real time operation of the vehicle. Till the Euro 4 emission standards, gravimetric method was being used to measure PM_{10}, that is, particulates with diameter less than 10µm(Dp<10 µm). The gravimetric method is not capable of capturing ultrafine and nano particulates having the diameter size of less than 0.3 µm. The measurement of fine (Dp<2.5 µm), ultrafine (Dp<0.1 µm) and nano particulates (Dp<50nm) is an area on which insufficient study has been done. The literature lacks the testing and analysis of ultra low sulfur diesel (USLD) in CI engines. Also, in India, ULSD is not available all over the country, except the National Capital Territory (NCT), that is New Delhi. Therefore, the effect and influence of low sulfur diesel on presently running vehicles in the country is crucial in order to observe the improvement in emissions and engine performance.

3.2 RESEARCH OBJECTIVES

The objectives as identified from the literature study are given as follows:

- Evaluating the brake power, brake specific fuel consumption, torque and speed variations with time in a transient test cycle schedule, that is European Transient Cycle (ETC) using BS VI diesel fuel

- Calculation of specific gas emissions (nitrous oxides, carbon monoxide and hydrocarbons) from engine exhaust using BS IV and BS VI diesel

- Calculation and comparison of specific particulate emissions, specific particle number (PN) emissions.

CHAPTER 4

EXPERIMENTAL TEST SETUP AND METHODOLOGY

4.1 INTRODUCTION

The measurement of particulate emissions requires dilution of exhaust gas with air in a dilution tunnel, where the sample is continuously collected from the diluted gas and filtered to collect particulate matter. The dilution can be achieved either by a full flow dilution double dilution system or a partial flow dilution system. The full flow dilution systems generally require more space and thus are more costly than partial flow systems. The temperature of the dilution air must be higher than 288K when entering the dilution tunnel. The determination of particulate mass requires particulate sampling filters, particulate sampling system, microgram balance, and a humidity and temperature controlled chamber. The mass of collected PM is measured to determine specific PM emissions in terms of g/km or g/kWh.

As the diluted exhaust gas flows at constant flow rate controlled by CVS system, the particles (solid and liquid) are deposited on the filter. The liquid mist or droplets are present as they condense at high temperatures of around 45-52°C.

The disadvantage of such collecting methods is that they can only provide an average result over a given cycle. Any outcome during transient phase, that is, during acceleration cannot be analyzed specifically.

4.2 EQUIPMENT FOR LOAD SIMULATION AND EMISSION MEASUREMENT

4.2.1 CI Turbocharged engine

Ashok Leyland make, a 4-stroke, 6-cylinder, turbocharged-intercooled direct injection Hino series heavy-duty diesel engine was used for testing and emission purpose as shown in Figure 4.1.

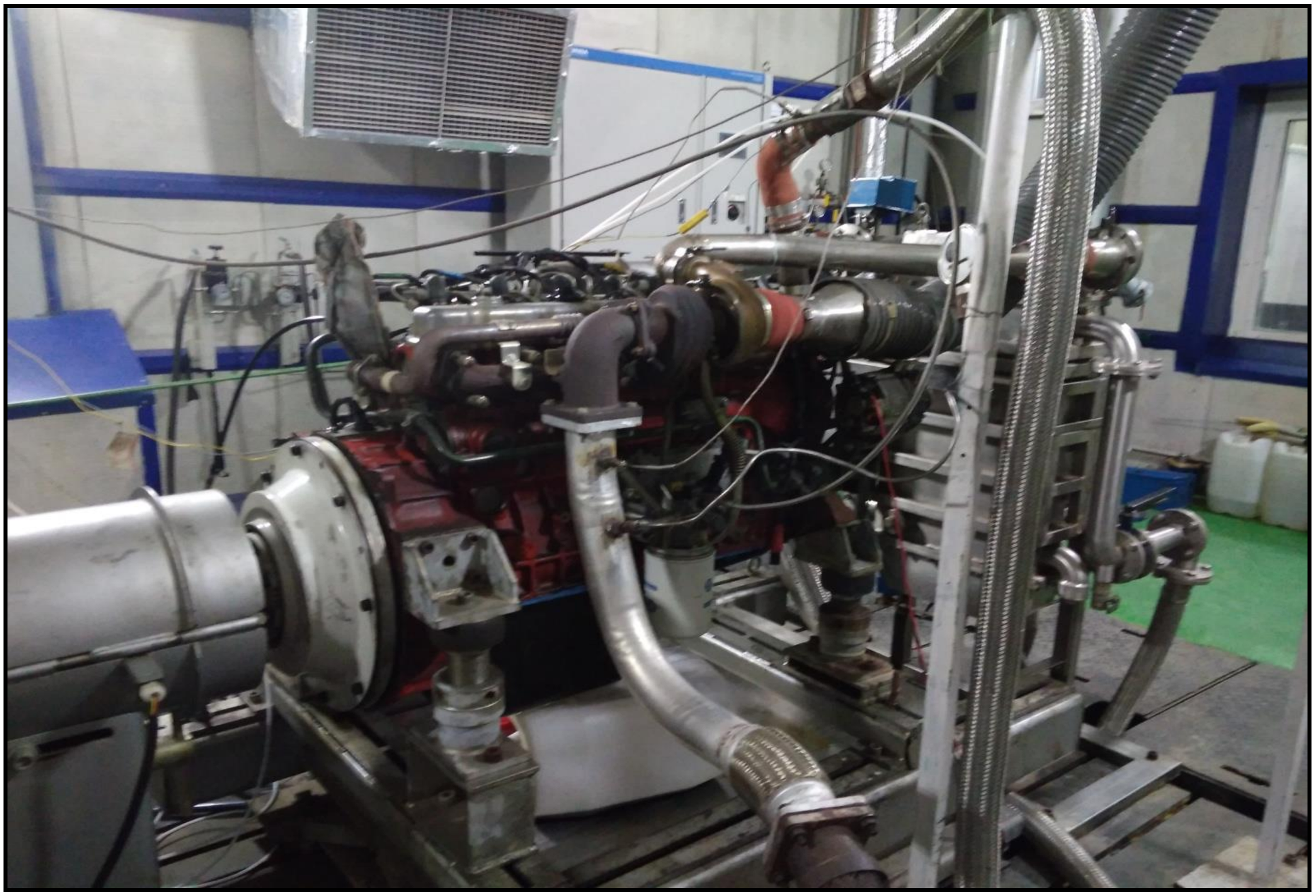


Figure 4.1 CI Turbocharged Engine

Table 4.1: Technical details of the engine

Make	**Ashok Leyland 225 HP H6E4ED162**
Certification level	Euro 4
Bore	104 mm
Stroke	113 mm
Engine capacity (Displacement)	5759 cc
Number of cylinders	6
Rated speed	2400 rpm
Rated torque	660 Nm
Rated power	225 HP
Engine technology	Turbocharged and inter cooled with EGR

4.2.2 AC transient engine asynchronous dynamometer

The transient engine dynamometer model, shown in Figure 4.2 is DynaS3 HD 460 kW from Horiba, Japan. The load and drive units DynaS3 are specifically developed for use on engine test stands/driveline test stands. They form units comprising an asynchronous motor, frequency converter with a test stand control and safety module, which have been specifically tuned to each other and tested. They can be used for all types of development and function test stands. Their application range covers simple stationary test stands through to dynamic test stands. The unit is controlled via the test stand controller SPARC. The torque signal of the measuring flange and the speed signal are prepared by the evaluation unit and processed by the test stand controller. The evaluation unit provides the frequency converter with a second torque signal. These type of dynamometers are used to control the engine through speed-torque cycle. The power is dissipated with help of water-cooling. AC dynamometers are the most suitable to perform transient tests, but are usually expensive and require full control of hardware for operation.

Figure 4.2 Transient AC asynchronous dynamometer

4.2.3 Combustion air handling unit

Sierra instruments make, Combustion air handling unit (CAHU) is a system used for supplying conditioned air to the engine intake, as shown in Figure 4.3. Controlled by CADET V14 software, the CAHU completely governs precise control temperature, humidity and pressure as according to the specific requirements of the engine. In simpler terms, this unit simulates the real world ambient air condition for combustion in engine. Such control of conditions is mandatory for emission testing of engine in fast response transient environment.

Figure 4.3 Combustion air handling unit

4.2.4 Fuel flow-measuring unit

Horiba make, FQ-2200CR fuel measuring system can be used in precise measurement of mass flow rate of fuel in the range of 0.2 kg/h to 108 kg/h. The unit shown in Figure 4.4 consists of Coriolis flow meter using Coriolis effect causes laterally vibrating tube to distort. The fuel-conditioning unit consisting of integrated pumps and temperature control systems ensure a constant temperature level for fuel in the engine fuel circuit. The fuel temperature could be controlled with supply of cooling water in the range of 5°C to 40°C. The density measuring range of the unit is between 0.6 g/cm^3 to 1 g/cm^3.

Figure 4.4 Fuel flow measuring and conditioning unit

4.2.5 Dilution system

The exhaust pipe as shown in Figure 4.5 must have:

- A maximum length of 10 m going from the after treatment device (EGR) to the dilution tunnel
- Insulation of connection tubing with glass wool

Generally, the exhaust pipe length from the turbocharger exit or exhaust manifold to the dilution tunnel is about 10 meters or lesser. In cases, where this length is greater than 4 meters, the tubing must be insulated. Here, the engine exhaust is led to silencer or muffler, designed in such a way that it cancels out the sound waves produced by exhaust, thus leading to reduction in noise level.

Figure 4.5 Engine exhaust pipe

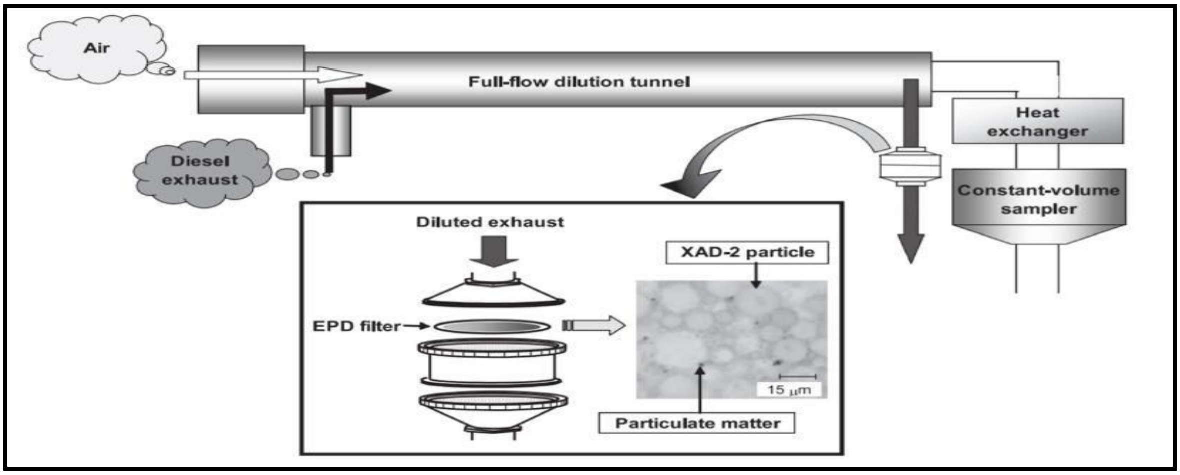


Figure 4.6 Dilution system

Figure 4.6 depicts the full flow dilution procedure for measurement of particulates.

At the tailpipe region of the vehicle, exhaust gas temperature as well as particle-vapor concentrations are very high. This requires dilution of cool ambient air to lower down the particle concentration and cool down the exhaust. Thus, the purpose of dilution of exhaust gas with ambient air is to avoid the occurrence of condensation of water in the air mixture, with air mixture temperature being less than 52°C. This helps in duplicating the real world driving process where hot exhaust gas coming out of the tailpipe is mixed with cooler ambient air. A blower or pump is used to supply the mixture through the system at relatively constant combined volumetric flow rate. In this way, the system would operate at a variable dilution ratio, wherein as the vehicle would produce more exhaust gas, a lesser ambient air will be required to mix eventually to maintain constant flow rate. For this purpose, a metering device is employed in the bulk stream to determine the flow rate. Generally, there are two types of CVS (Constant Volume Sampler): the CFV (Critical Flow Venturi) and Positive Displacement Pump (PDP). Such computer-controlled technologies help in lowering the process cost and improve the precision.

Figure 4.7 Dilution Tunnel

The nominal length of dilution tunnel as shown in Figure 4.7 is generally about 10 times the diameter of the tunnel.

Dilution of sample could be done in two ways: Single dilution and Double dilution. Single dilution process involves direct collection of small sample of gas from dilution tunnel passed through the filter to collect the particulate matter sample. But, if the sample is diluted once more in a secondary dilution tunnel, then it is referred to as double dilution.

The entire dilution process takes place in the following steps:

1. Dilution of the exhaust gas with ambient air in the dilution tunnel duct
2. Recording of the gas stream temperature in dilution tunnel,
3. With use of microbalance, weighing of the filter, before and after the sampling in a chamber of controlled temperature humidity
4. Continuous measurement of the flow rate of diluted exhaust gas passing through the filter during the sample period

Units of mass per power time [g/kWh] or mass per brake horsepower-hour [g/bhph] for engine tests and mass per distance [g/km] for chassis tests are used for PM measurement.

Double dilution is considered when the filter temperature requirement cannot be met with single dilution method.

4.2.6 Continuous solid particle counting system

Horiba make, MEXA-2000SPCS, shown in Figure 4.8 is used for test procedure for Euro 5/6, latest regulations in Europe.

Figure 4.8 MEXA 2000 SPCS

For transient testing of heavy-duty diesel engine emission, particle counting system measure the emissions connected to full flow dilution tunnel. The measurement of particulate emissions in the latest comes under the PMP (Particulate Measurement Programme) which includes:

- measurement of only non-volatile particles
- only particles >23 nm (cut point)
- use of PNC (Particle Number Counter)

Figure 4.9 shows the complete system configuration required as per the Euro 5 and Euro 6 norms.

As shown in the Figure 4.9**,** the probe will collect the diluted exhaust gas from full flow dilution tunnel, through a pre-classifier, which cuts off the particles ranging between 2.5 and 10µm size range. From here, the hot diluter (PND1) will dilute the incoming exhaust gas with high temperature, ranging from 150 °C to 400 °C, in order to avoid the presence of volatile particles consisting of SOF (Soluble Organic Fraction) and sulphur compounds. Such volatile particles that have been generated, are then vaporized in evaporation tube with temperature range of 300-400°C.

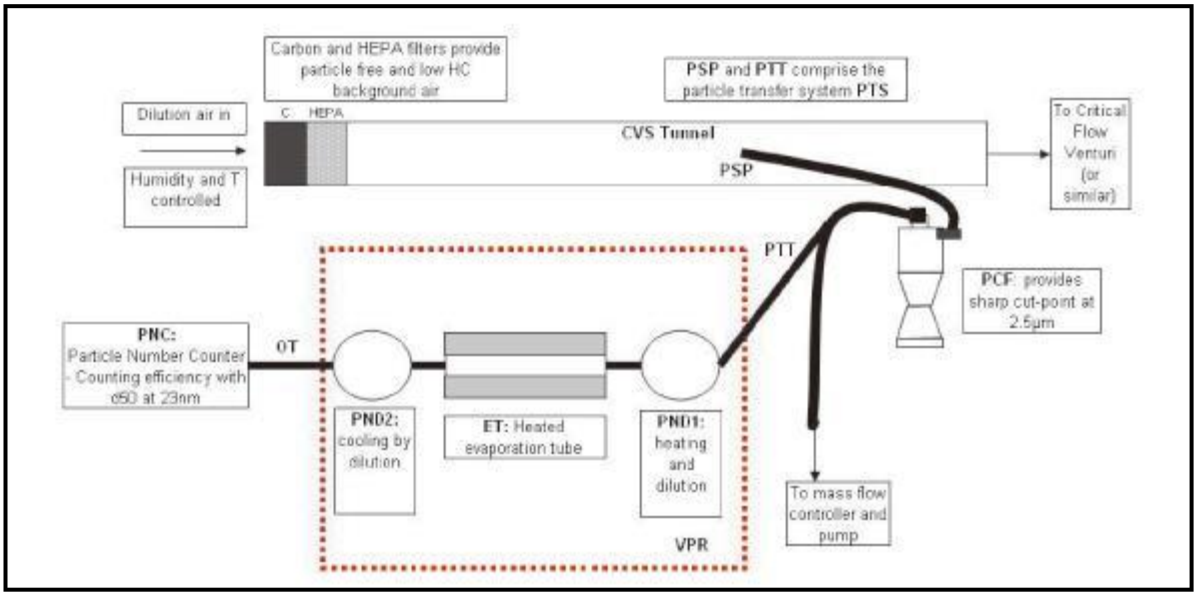


Figure 4.9 Particulate sampling system

Then, the sample gas is further cooled down to 35°C in cold diluter (PND2), in order to prevent re-condensation that may lead to particle formation. Such mechanism is followed in VPR (Volatile Particle Remover), to allow only solid particles to enter into particle number counter.

4.2.7 Sampling filter

Pallflex make filters (Emfab filters), shown in Figure 4.10, are preferred filters for diesel exhaust and stack emission testing. These borosilicate microfibers reinforced with woven glass cloth and bonded with PTFE (Polytetrafluoroethylene) were used for mass determination of particulates. The filter element is placed in a filter cartridge, which is then fitted into a filter holder.

Figure 4.10 Filter paper

Table 4.2: Specifications of sampling filter

Diameter	47 mm
Thickness	178 µm
Filter weight	5.0 mg/cm^2
Maximum operating temperature	260°C

Sampling of diluted exhaust gas is done by making it pass through a pair of filters placed in series, that is, primary and back up (bypass) filter. The bypass filter is then placed around 100 mm below the primary filter.

4.3.8 Filter holders

The filters are placed in the ambient and main line (hot and cold) filter holders as shown in Figure 4.11 and Figure 4.12. The ambient and dilute exhaust flow passes through these lines, and subsequently particulates in the flow are deposited on the filter.

Figure 4.11 Ambient air filter holder

Figure 4.12 Main line filter holder

4.2.9 Constant Volume Sampler (CVS)

CVS is a device used in emission tests to measure the mass of exhaust emissions. CFV (Critical Flow Venturi) type CVS system of Horiba make, Japan, model-7400T, as shown in Figure 4.13**,** was used for sampling of exhaust gas. The exhaust gas is diluted with ambient air passed through HEPA (High Efficiency Particulate Air) filter. In this way, the total exact volume of mixed ambient air and exhaust gas is measured and a proportional sample of mixed air is collected simultaneously in sampling bags and dilution air bag for further analysis. CVS bags are generally made up of PTFE (Poly Tetra Fluoro Ethylene) so that no pollutants are exposed to the diluted mixture of gases. Figure 4.14 depicts the dilution process within the CVS unit taking place.

Figure 4.13 Constant Volume Sampler

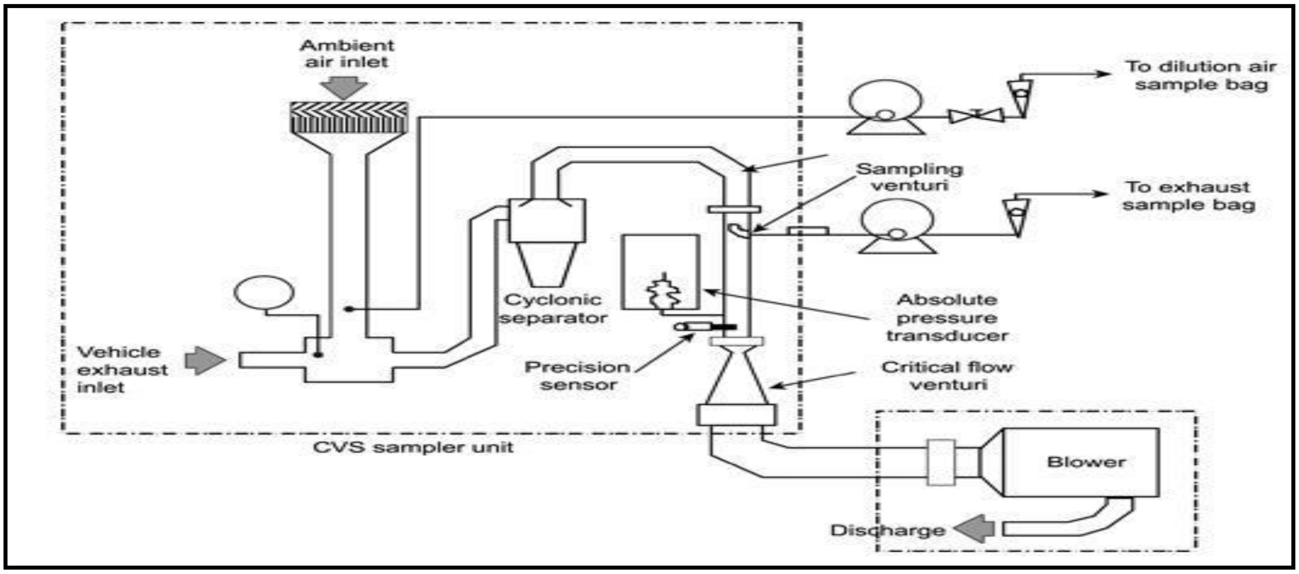


Figure 4.14 Dilution process

The whole process flow is shown in Figure 4.15.

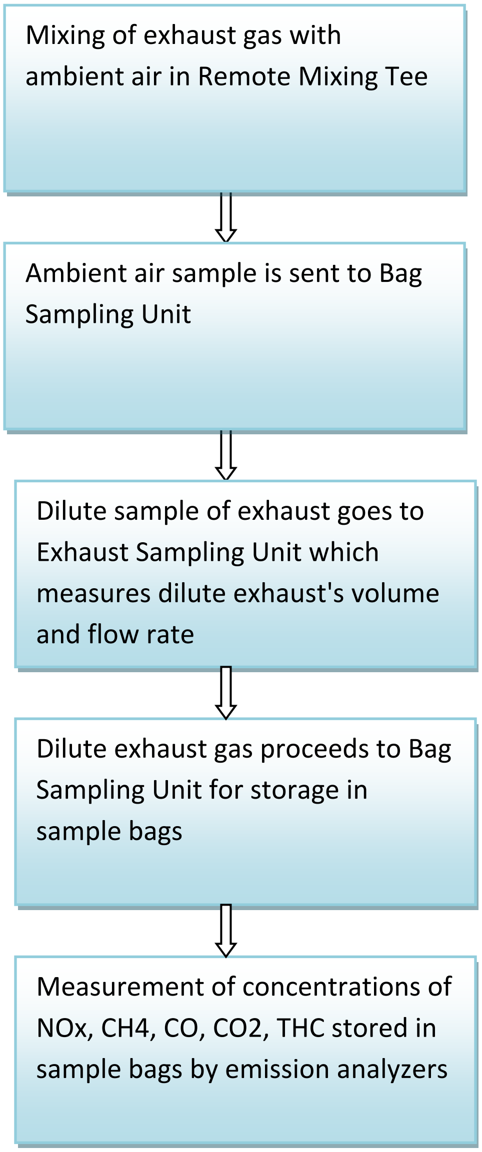


Figure 4.15 Flow diagram of CVS process

Dilution of emission exhaust gas with ambient filter air is done to simulate the real world condition of exhaust escaping the vehicles through tailpipe. In real conditions, the hot exhaust upon being released by the vehicle mix with cool ambient air, leading to condensation of volatile particles to small solid particles in the atmosphere.

Figure 4.16 [33] represents the Exhaust sampling process from start to end.

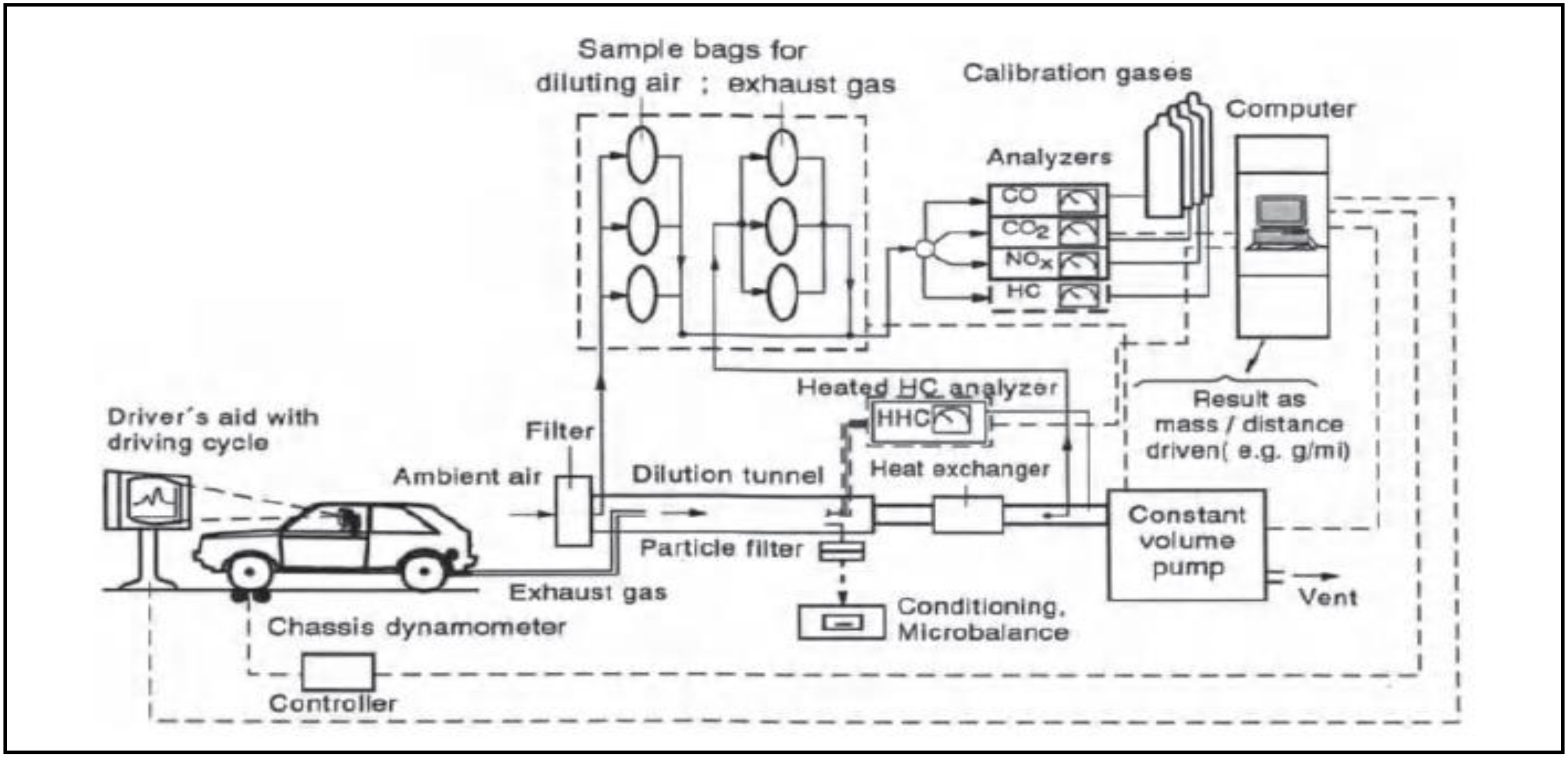


Figure 4.16 Exhaust sampling process [33]

4.2.10 Motor Exhaust Gas Analyzer (MEXA)

Horiba make, MEXA-7400DEGR, as shown in Figure 4.17 is a testing device equipped with different analyzers to measure the concentrations of direct and dilute lines. Chemiluminescence detector (CLD), flame ionisation detector (FID) and non-dispersive infrared detector (NDIR) are the analyzer used to measure concentrations of nitrous oxides, hydrocarbons and carbon monoxide, respectively.

Figure 4.17 Motor Exhaust Gas Analyzer

Table 4.3: Methods of measuring various emissions

Component	Detection principle
NO, NOx	Heated dual-CLD
CO,CO2	Heated NDIR
THC	Heated FID
PM	Gravimetric method

4.2.11 Chamber and Micro Balance

Horiba make, clean chamber CHAM-1000, shown in Figure 4.18 is humidity and temperature controlled chamber for accurate measuring of filter weight.

The temperature of the chamber (or room) in which the particulate filters are conditioned and weighed shall be maintained to within ± 6K of set point between 293 and 303 K (20°C and 30°C) during all filter conditioning and weighing. The relative humidity shall be maintained to within ± 10% relative humidity of a set point between 35% and 55 %.

The chamber must be free from atmospheric contaminants such as dirt and dust to determine the best results. If average weight of the reference filter changes between sample filter weighing by more than ± 6% of the recommended minimum filter loading ,then all sample filters discarded and the emission tests repeated.

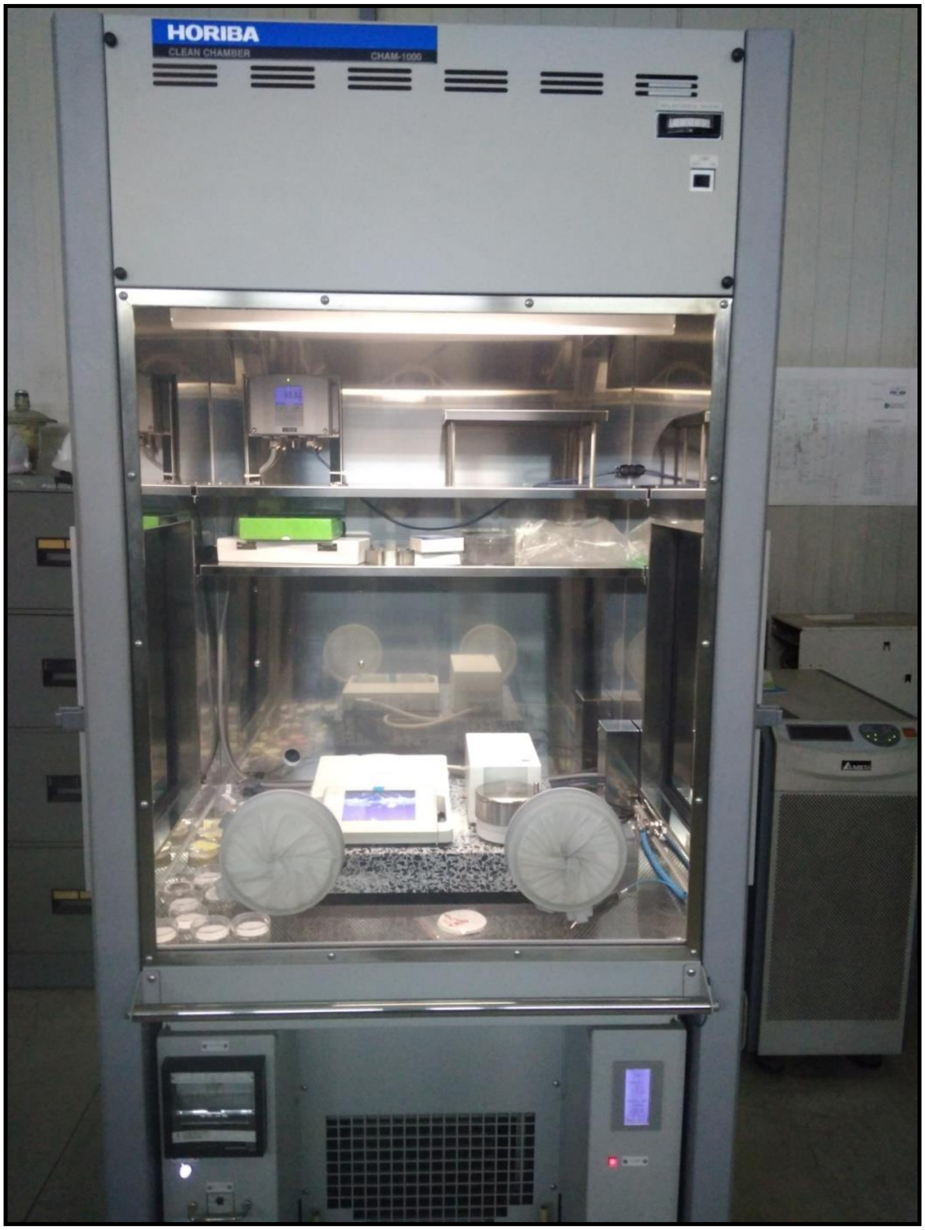


Figure 4.18 Condition controlled chamber

4.3 METHODOLOGY

4.3.1 Engine mapping procedure for European Transient Cycle

Prior to the testing of the engine on any cycle, the engine requires to be mapped in order to determine the speed versus torque curve. For this purpose, the minimum and maximum mapping speeds are required which are calculated as given below:

$$\boldsymbol{Minimum\ mapping\ speed} = idle\ speed \quad (4.1)$$

Thus, in this case, minimum mapping speed is 600rpm.

$$\boldsymbol{Maximum\ mapping\ speed} = 1.02 * nhi \quad (4.2)$$

where, n_{hi} is highest engine speed (where 70% of declared maximum power occurs)

Thus, maximum mapping speed= 1.02*2422.24 = 2470.68 rpm

The performance curves can be plotted manually or can be computer generated, thus giving an idea about the response of the engine when subjected to a change in the following parameter:

- Speed
- Ignition timing
- Air-fuel ratio
- Load (throttle opening)
- Engine temperature and ambient temperature

Engine power map

Prior to the engine power map performance, the engine is stabilized by warming up at its maximum power. Engine map is performed in the following manner:

1. Unloaded engine operated at idle speed
2. Operation of engine at full load setting of injection pump at minimum mapping speed
3. Increase of the engine speed from its minimum to maximum mapping speed at average speed rate of 8±1 rpm/s.

The engine speed and torque is obtained at various data points, thus forming performance torque curve. The actual torque values are then calculated by de-normalizing the normalized torque values.

4.3.2 Determination of actual speed and torque

The de-normalization procedure involves determination of actual speed and torque values.

The actual speed is determined from the following formula

$$\boldsymbol{Actual\ speed} = \frac{(\text{reference speed} - \text{idle speed})}{100} \tag{4.3}$$

In the above equation (4.3), the reference speed (N_{ref}) corresponds to the 100% speed values specified in the engine dynamometer schedule.

$$\mathbf{N_{ref}} = \mathrm{N_{lo}} + 95\% \, (\mathrm{N_{hi}} - \mathrm{N_{lo}}) \tag{4.4}$$

In equation (4.4), N_{lo} is the lowest engine speed, where 50% of the maximum power (specified by manufacturer) occurs.

N_{hi} is the highest engine speed, where 70% of the maximum power (specified by manufacturer) occurs.

Similarly, the torque normalized to maximum torque at respective speed is un-normalized using the mapping curve determined from the following formula:

$$\boldsymbol{Actual\ torque} = \frac{\%torque * max\ torque}{100} \tag{4.5}$$

The maximum torque value can be found out from the respective engine-mapping curve.

4.3.3 Preparation of emission test run

4.3.3.1 Weighing of sampling filter

Prior to the test run, each filter should be weighed where the tare weight is recorded. The filter paper is then put into the sampling holder for particulate measurement.

4.3.3.2 Dilution system

The warm up of the engine and dilution system is performed so that all the necessary temperatures and pressures are stabilized at maximum power as specified by the manufacturer.

4.3.3.3 Checking of Analyzers

Before beginning the test procedure, the emission analyzers are set at zero and spanned. If the sample bags are to be used, they shall be evacuated.

4.3.4 Emission gas measurement

4.3.4.1 Raw exhaust measurement

The measurement starts by analyzing the raw exhaust gas concentrations. The gaseous emission concentrations and mass flow rates of HC, NOx and CO are recorded and stored with at least 2 Hz on the computer system. The usual system response time is of 10 seconds. The data is recorded with a sample rate of at least 1 Hz.

4.3.4.2 Diluted exhaust measurement

Diluted exhaust is measured after the collecting and mixing of engine exhaust and filtered dilution air. In the full flow dilution system measurement, Constant Volume Sampler (CVS) measures the amount of diluted exhaust gas at specified temperature and pressure. The measurement of HC and NOx is done in the dilution tunnel only with a frequency of 2Hz. The average concentrations are then determined by integrating the analyzer signals over the test cycle. CO, CO2, NMHC and CH4 concentrations are determined by integration or by analyzing the concentrations in the sample bag, collected over the cycle. The concentrations of gaseous pollutants in the dilution air can be determined by integrating or by collecting into the background bag. All the other values are recorded with a minimum of one measurement per second (1Hz).

Figure 4.19 shows the process flow chart explaining the systematic procedure for particulate mass measurement by gravimetric method.

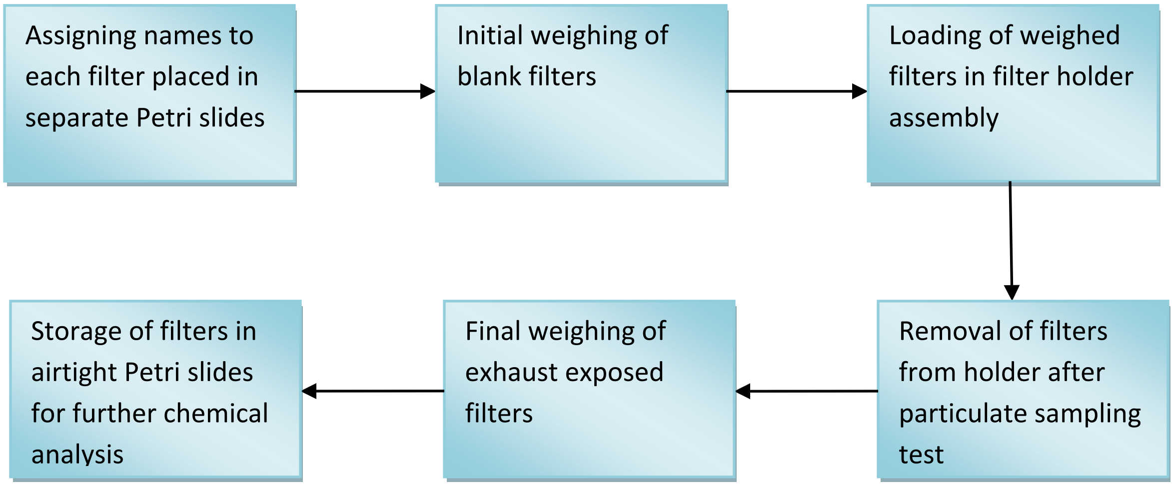


Figure 4.19 Flow diagram of gravimetric analysis procedure

4.3.5 Calculation Procedure

$$\boldsymbol{NOx\ correction\ factor}, K_{h,D} = \frac{1}{1 - 0.0182\ (\mathrm{H_a} - 10.71) + 0.0045\ (\mathrm{T_a} - 298)} \quad (4.6)$$

where, H_a is humidity of intake air, g water/kg dry air

T_a is intake air temperature, Kelvin

$$\boldsymbol{Stoichiometric\ factor}, F_s = 100 \text{ x } \frac{1}{1 + \frac{\alpha}{2} + 3.76\ (1 + \frac{\alpha}{4} - \frac{\varepsilon}{2})} \quad (4.7)$$

where, α, ε are molar ratios corresponding to diesel fuel $CH_{\alpha}O_{\varepsilon}$

$$\boldsymbol{Background\ corrected\ net\ concentration}, c = c_e - c_d(1 - \frac{1}{D}) \quad (4.8)$$

where, c is net exhaust concentration, ppm

c_e is concentration in dilute exhaust gas, ppm

c_d is concentration in dilution air, ppm

D is dilution factor

$$\boldsymbol{Exhaust\ emissions\ mass}, m_{gas} = u_{gas} c_{gas} K_{h,d}\, m_{ed} \qquad (4.9)$$

where, u_{gas} is ratio between density of exhaust component and density of exhaust gas

$$\boldsymbol{Specific\ gaseous\ emission} = m_{exhaust\ gas}/W_{cycle} \qquad (4.10)$$

where, $m_{exhaust\ gas}$ is mass of exhaust gas, grams

W_{cycle} is work done during test cycle, kWh

$$\boldsymbol{Dilution\ Factor}, DF = \frac{\mathrm{F_s}}{\mathrm{C_{CO_2}} + (\mathrm{C_{HC}} + \mathrm{C_{CO}})\mathrm{x}\ 10^{-4}} \qquad (4.11)$$

where, C_{CO2},C_{HC}, C_{CO} are concentrations of CO_2, HC and CO, ppm

$$\boldsymbol{Volumetric\ flow\ rate}, Q_a = Q_{std}\ \frac{P_{std}}{P_a}\ \frac{\mathrm{T_a}}{T_{std}} \qquad (4.12)$$

where, Q_{std} is standard volume flow rate, L/min

P_{std} is standard barometric pressure, bar

P_a is ambient barometric pressure, bar

Ta is ambient temperature, Kelvin

T_{std} is standard temperature, Kelvin

For TSI instruments, standard conditions are 21.1°C temperature & 101.3kPa pressure

A standard flow rate of 100 L/min will be taken into consideration.

$$\boldsymbol{Volume\ of\ air\ sampled}, V_a = Q_a t \qquad (4.13)$$

where, Q_a is volumetric flow rate, L/min

t is sampling time, min

$$\boldsymbol{PM\ mass\ concentration}, c = \frac{\mathrm{M_f} - \mathrm{M_i}}{V_\mathrm{a}} \qquad (4.14)$$

where, c is PM mass concentration, $\mu g/m^3$

M_i is blank filter weight, mg

M_f is exposed filter weight, mg

V_a is volume of air sampled, m^3

$$\boldsymbol{Specific\ PM\ emissions} = \frac{m_{PT}}{W_{cyclic}} \qquad (4.15)$$

where, m_{PT} is particulate mass per test, grams

$W_{cyclic}$is cyclic work, kWh

$$\boldsymbol{Specific\ PN\ emissions} = \frac{PN}{W_{cyclic}} \qquad (4.16)$$

where, PN is particle number emission

W_{cyclic} is cyclic work done, kWh

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 TRANSIENT ENGINE TEST SCHEDULE PERFORMANCE

For European Transient Cycle, normalized speed and torque value graphs were obtained which were then converted into actual values to be plotted below for better understanding of the engine behavior.

The plots of actual speed (revolutions per minute), actual torque (Newton meter), actual brake power (kilowatt) and actual fuel consumption (kilogram per hour) with respect to time (seconds) have been depicted below.

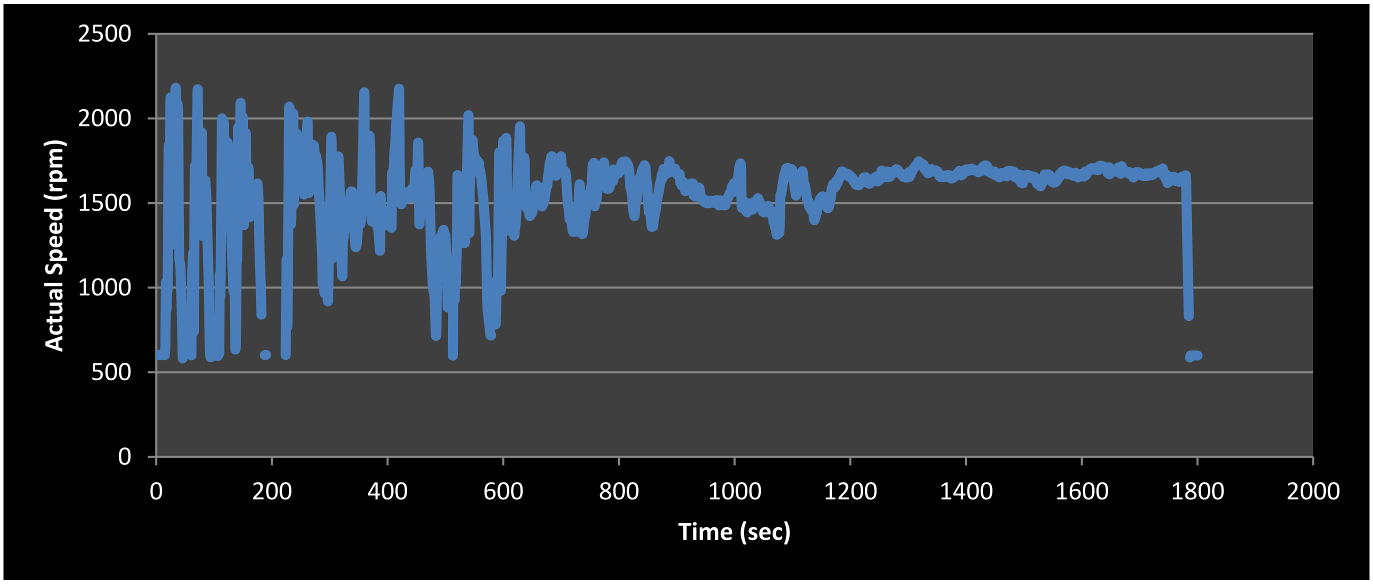


Figure 5.1 Time versus speed plot

Figure 5.1 represents the 1800 second time schedule of transient test involving sudden changes in load and speed. In the first 600 second segment, the speed varies very abruptly in a continuous manner, which suggests maximum contribution to emissions. In the second segment speed variation is less with respect to the time. In the last segment, speed becomes almost constant with time which is observed during motoring of the vehicle.

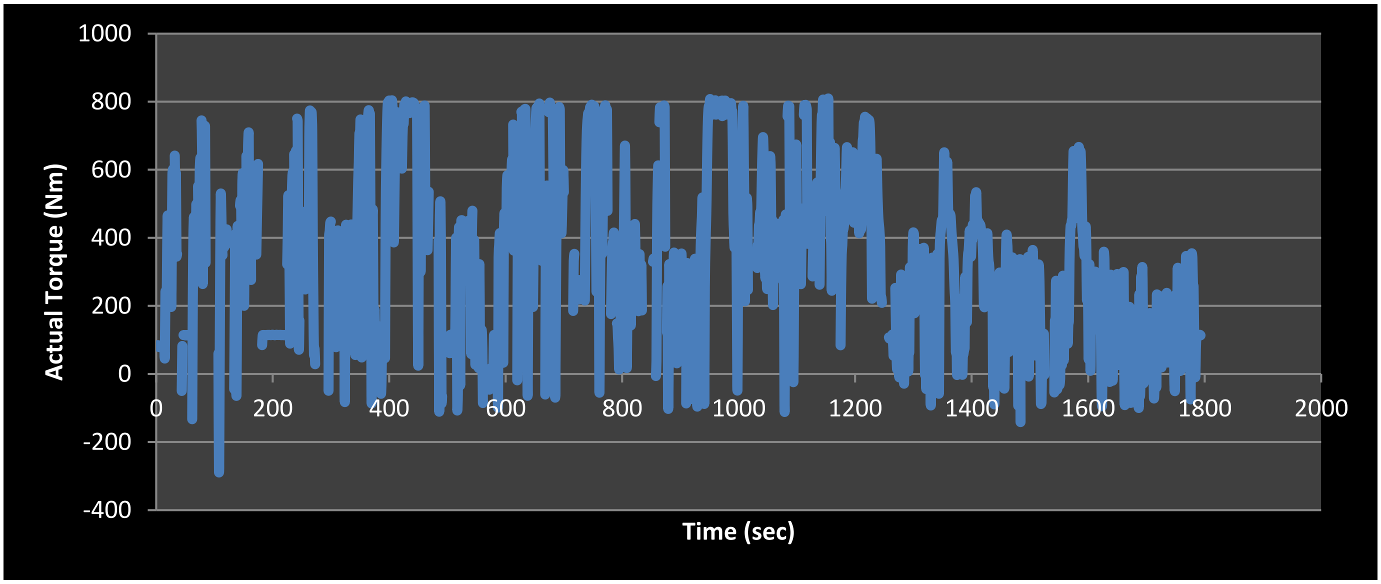


Figure 5.2 Time versus torque plot

The time-torque plot shown in Figure 5.2 reveals continuous changes in torque. The motorway segment shows lower torque due to increased friction in engine parts when engine is running at constant high speed.

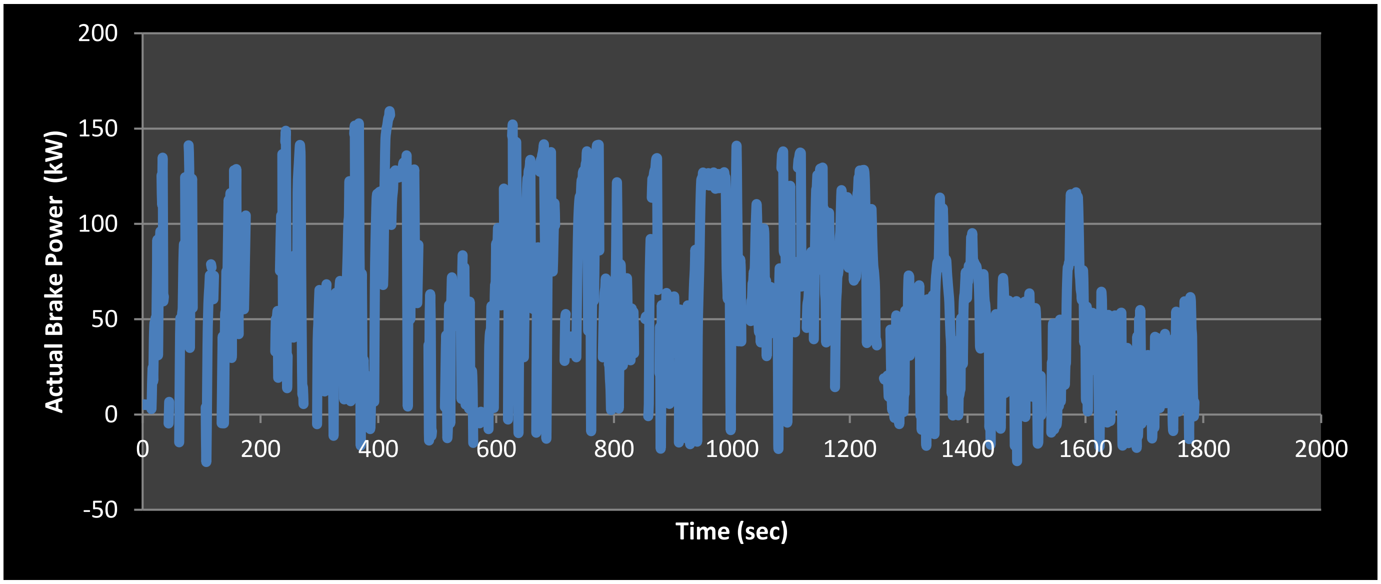


Figure 5.3 Time versus brake power plot

The time versus brake power plot shown in Figure 5.3 reveals that a maximum power of about 160kW is achievable during the transient testing of the engine.

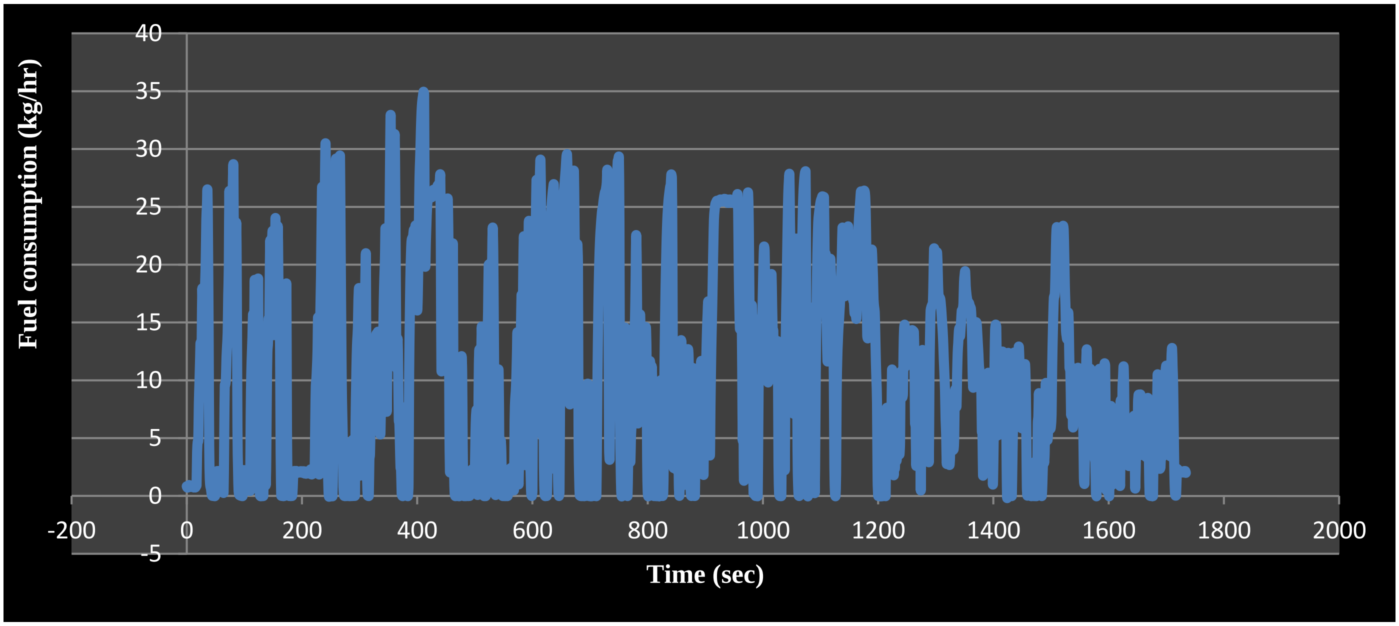


Figure 5.4 Time versus fuel consumption plot

Figure 5.4 show that the fuel consumption reaches the maximum value of 35 kg/hr in the urban (first) segment of the cycle. During the motorway part of cycle, the fuel consumed begins to decrease at slow rate.

5.2 BS IV FUEL CALCULATIONS

CFV type CVS measures the total mass of exhaust, which is diluted.

For BS IV fuel, mass of diluted exhaust= 2200 kg/test

From equation (4.6), NOx correction factor

$$K_{h,D} = \frac{1}{1 - 0.0182\,(14.67 - 10.71) + 0.0045\,(298 - 298)}$$

$$= 1.078$$

From equation (4.7), stoichiometric factor

$$F_s = 100 \text{ x } \frac{1}{1 + \frac{12}{2} + 3.76\ (1 + \frac{12}{4} - \frac{0}{2})}$$

$$= 4.537$$

From equation (4.8), gas concentrations

$$c_{NOx} = 37.65 - 0.21\left(1 - \frac{1}{18.414}\right)$$

$$= 37.452 \text{ ppm}$$

$$c_{CO} = 46.94 - 44.33(1 - \frac{1}{18.414})$$

$$= 5.02 \text{ ppm}$$

$$c_{HC} = 7.41 - 6.41\left(1 - \frac{1}{18.414}\right)$$

$$= 1.35 \text{ ppm}$$

From equation (4.9), mass of exhaust emissions

$$m_{NOx} = 0.001587 * 37.452 * 1.078 * 2200$$

$$= 140.959 \text{ g}$$

$$m_{CO} = 0.000966 * 5.02 * 1.078 * 2200$$

$$= 9.409 \text{ g}$$

$$m_{HC} = 0.000479 * 1.35 \ * 1.078 * 2200$$

$$= 1.533 \text{ g}$$

From equation (4.10), specific gaseous emission

$$sge_{NOX} = 140.959/21.05$$

$$= 6.696 \text{ g/kWh}$$

$$sge_{CO} = 9.409 /21.05$$

$$= 0.546 \text{ g/kWh}$$

$$sge_{HC} = 1.533 /21.05$$

$$= 0.072 \text{ g/kWh}$$

Stoichiometric factor is assumed as $F_s = 13.4$

From equation (4.11), dilution factor

$$DF \quad = \frac{13.4}{0.723 + (9 + 38.9) \text{x } 10^{-4}}$$

$$= 18.414$$

From equation (4.12),

$$\mathrm{Q_a} = 100 * \frac{273.15 + 30}{273.15 + 21.11} * \frac{101.3}{117}$$

= 89.19 L/min

From equation (4.13),

$$V_a = 89.11 \frac{L}{min} \text{ x } 30 \text{ min}$$

$$= 2.6733 \text{ m}^3$$

Determination of Particulates

BS IV Diesel tests on ETC cycle

Table 5.1: BS IV diesel particulate mass Trial 1

	Primary line		**Ambient Air**	
	Main	**Bypass**	**Main**	**Bypass**
Initial	76.4301	76.5197	77.3285	77.9177
Final	76.7960	76.5539	77.3486	78.0296

A total PM emissions of 288.5 mg were observed in trial 1.

Cyclic work in trial 1 cycle = 21.05 kWh

PN emissions in trial 1 cycle = 7.42E+14 #/test

Before sample, filter weight= 76.4301mg

After sample, weight= 76.7960 mg

Therefore, PM weight= 0.365 mg

From equation (4.14),

$$c = \frac{76.7960 - 76.4301}{2.6733}$$

$$= 136.87\ \mu g/m^3$$

From equation (4.15),

$$Specific\ PM\ emissions = \frac{0.2885}{21.05}$$

$$= 0.0137\ g/kWh$$

From equation (4.16),

$$Specific\ PN\ emissions = \frac{7.42E + 14}{21.05}$$

$$= 3.53E+13\ \#/kWh$$

Table 5.2: BS IV diesel particulate mass Trial 2

	Primary line		**Ambient Air**	
	Main	**Bypass**	**Main**	**Bypass**
Initial	75.6763	76.1726	76.0033	76.2056
Final	76.1726	76.2416	76.0092	76.2812

A total PM emissions of 498.2 mg were observed in trial 2.

Cyclic work in trial 2 cycle = 21.22 kWh

PN emissions in trial 2 cycle = 1.35E+15 #/test

Before sample, filter weight= 75.6763 mg

After sample, weight= 76.1726 mg

Therefore, PM weight= 0.496 mg

From equation (4.14),

$$c = \frac{76.1726 - 75.6763}{2.6733}$$

$$= 185.53\ \mu g/m^3$$

From equation (4.15),

$$Specific\ PM\ emissions = \frac{0.4982}{21.22}$$

$$= 0.0234\ g/kWh$$

From equation (4.16),

$$Specific\ PN\ emissions = \frac{1.35E + 15}{21.22}$$

$$= 6.34E{+}13\ \#/kWh$$

Table 5.3: BS IV diesel particulate mass Trial 3

	Primary line		**Ambient Air**	
	Main	**Bypass**	**Main**	**Bypass**
Initial	77.5292	77.3438	76.5534	76.3882
Final	77.9340	77.3842	76.5674	76.4501

A total PM emissions of 385.8 mg were observed in trial 2.

Cyclic work in trial 2 cycle = 21.10 kWh

PN emissions in trial 2 cycle = 9.97E+14 #/test

Before sample, filter weight= 77.5292 mg

After sample, weight= 77.9340 mg

Therefore, PM weight= 0.404 mg

From equation (4.14),

$$c = \frac{77.9340 - 77.5292}{2.6733}$$

$$= 151.49\ \mu g/m^3$$

From equation (4.15),

$$Specific\ PM\ emissions = \frac{0.3858}{21.10}$$

$$= 0.0182\ g/kWh$$

From equation (4.16),

$$Specific\ PN\ emissions = \frac{9.97E + 14}{21.10}$$

$$= 4.72E{+}13\ \#/kWh$$

Table 5.4: BS IV diesel averaged results

	Total PM emissions averaged (mg/test)	Dilute line PM mass difference (mg)	PM 2.5 mass concentration ($\mu g/m^3$)	Specific PM emissions (g/kWh)	Specific PN emissions (#/kWh)
Trial 1	288.5	0.365	136.87	0.0137	3.53E+13
Trial 2	498.2	0.497	185.91	0.0234	6.34E+13
Trial 3	385.8	0.405	151.49	0.0182	4.72E+13
Averaged values	390.83	0.422	158.09	0.0184	4.86E+13

5.3 BS VI FUEL CALCULATIONS

CFV type CVS measures the total mass of exhaust that is diluted.

For BS IV fuel, mass of diluted exhaust= 2200 kg/test

From equation (4.6), NOx correction factor

$$K_{h,D} = \frac{1}{1 - 0.0182\ (12.8 - 10.71) + 0.0045\ (298 - \ 298)}$$

= 1.039

From equation (4.7), stoichiometric factor

$$F_s = 100 \text{ x } \frac{1}{1 + \frac{12}{2} + 3.76\ (1 + \frac{12}{4} - \frac{0}{2})}$$

= 4.537

From equation (4.8), gas concentrations

$$c_{NOx} = 22.9 - 0.3\left(1 - \frac{1}{18.414}\right)$$

= 22.61 ppm

$$c_{CO} = 45.2 - 44.1(1 - \frac{1}{18.414})$$

= 3.5 ppm

$$c_{HC} = 6.9 - 6.3\left(1 - \frac{1}{18.414}\right)$$

= 0.943 ppm

From equation (4.9), mass of exhaust emissions

$$m_{NOx} = 0.001587 * 22.61 * 1.039 * 2200$$

= 82.019 g

$$m_{CO} = 0.000966 * 3.5 * 1.039 * 2200$$

= 7.728 g

$$m_{HC} = 0.000479 * 0.943 * 1.039 * 2200$$

= 1.032 g

From equation (4.10), specific gaseous emission

$$sge_{NOX} = 82.019/23.85$$

= 3.438 g/kWh

$$sge_{CO} = 7.728\ /23.85$$

= 0.324 g/kWh

$$sge_{HC} = 1.032\ /23.85$$

= 0.043 g/kWh

Stoichiometric factor is assumed as F_s = 13.4

From equation (4.11), dilution factor

$$DF \quad = \frac{13.4}{0.723 + (9 + 38.9)\text{x}\ 10^{-4}}$$

= 18.414

From equation (4.12),

$$\mathrm{Q_a} = 100 * \frac{273.15 + 30}{273.15 + 21.11} * \frac{101.3}{117}$$

= 89.19 L/min

From equation (4.13),

$$V_a = 89.11\ \frac{L}{min}\ \text{x}\ 30\ \text{min}$$

$$= 2.6733\ \text{m}^3$$

Determination of Particulates

BS VI Diesel tests on ETC cycle

Table 5.5: BS VI diesel particulate mass Trial 1

	Primary line		**Ambient Air**	
	Main	**Bypass**	**Main**	**Bypass**
Initial	76.5480	76.4058	76.2613	77.4522
Final	76.5730	76.4075	76.4860	77.4850

A total PM emissions of 117.37 mg were observed in trial 1.

Cyclic work in trial 1 cycle = 23.85 kWh

PN emissions in trial 1 cycle = 7.56E+13 #/test

Before sample, filter weight= 76.5480 mg

After sample, weight= 76.5730 mg

Therefore, PM weight= 0.025 mg

From equation (4.14),

$$c = \frac{76.5730 - 76.5480}{2.6733}$$

$$= 9.351\ \mu g/m^3$$

From equation (4.15),

$$Specific\ PM\ emissions = \frac{0.1173}{23.85}$$

$$= 0.0049\ g/kWh$$

From equation (4.16),

$$Specific\ PN\ emissions = \frac{7.56\mathrm{E}+13}{23.85}$$

= 3.17E+12 #/kWh

Table 5.6: BS VI diesel particulate mass Trial 2

	Primary line		**Ambient Air**	
	Main	**Bypass**	**Main**	**Bypass**
Initial	76.5326	76.6424	77.8450	76.3059
Final	76.5431	76.6271	77.8434	76.4256

A total PM emissions of 104.49mg were observed in trial 2.

Cyclic work in trial 2 cycle= 24.22 kWh

PN emissions in trial 2 cycle = 7.107E+13

Before sample, filter weight= 76.5326 mg

After sample, weight= 76.5431 mg

Therefore, PM weight= 0.010 mg

From equation (4.14),

$$c = \frac{76.5431 - 76.5326}{2.6733}$$

= 3.927 µg/m^3

From equation (4.15),

$$Specific\ PM\ emissions = \frac{0.1044}{24.22}$$

= 0.0043 g/kWh

From equation (4.16),

$$Specific\ PN\ emissions = \frac{7.107\mathrm{E} + 13}{24.22}$$

= 2.935E+12 #/kWh

Table 5.7: BS VI diesel particulate mass Trial 3

	Primary line		**Ambient Air**	
	Main	**Bypass**	**Main**	**Bypass**
Initial	76.8330	76.9890	76.3776	76.3105
Final	76.8943	76.9939	76.3841	76.3886

A total PM emissions of 198.88mg were observed in trial 3.

Cyclic work in trial 3 cycle = 24.08 kWh

PN emissions in trial 3 cycle = 4.088E+ 14

Before sample, filter weight= 76.8330 mg

After sample, weight= 76.8943 mg

Therefore, PM weight= 0.061 mg

From equation (4.14),

$$c = \frac{76.8943 - 76.8330}{2.6733}$$

= 22.93 μg/m^3

From equation (4.15),

$$Specific\ PM\ emissions = \frac{0.1988}{24.08}$$

= 0.0082 g/kWh

From equation (4.16)

$$Specific\ PN\ emissions = \frac{4.088E + 14}{24.08}$$

= 1.697E+ 13 #/kWh

Table 5.8: BS VI diesel averaged values

	Total PM emissions averaged (mg/test)	**Dilute line PM mass difference (mg)**	**PM 2.5 mass concentration (μg/m^3)**	**Specific PM emissions (g/kWh)**	**Specific PN emissions (#/kWh)**
Trial 1	117.37	0.025	9.351	0.0049	3.17E+12
Trial 2	104.49	0.089	3.927	0.0043	2.935E+12
Trial 3	198.88	0.061	22.93	0.0082	1.697E+13
Averaged values	140.24	0.032	12.069	0.0058	7.69E+12

Total PM mass emissions of BS VI diesel (averaged) = 140.24 mg

Specific PM emissions for BS VI diesel (averaged) = 0.0058 g/kWh

Table 5.9: BS IV and BS VI diesel specific emissions

Pollutants	Specific emissions (g/kWh)		Emission limits (g/kWh)
	BS IV	BS VI	
NOx	6.696	3.438	3.50
CO	0.546	0.324	4.00
THC	0.072	0.043	-
PM	0.0184	0.0058	0.03
PN	4.86E+13	7.69E+12	-

Table 5.9 indicates that all the specific emission values were well within the limits except for BS IV diesel for which NOx levels exceeded the limits. This could be due to increased temperatures in the engine leading to oxidation of some nitrogen in the intake air to form more NOx gases. The percentage difference in emissions with BS IV and BS VI diesel have been shown below in the next section.

5.4 RESULT COMPARISON BY GRAPHS

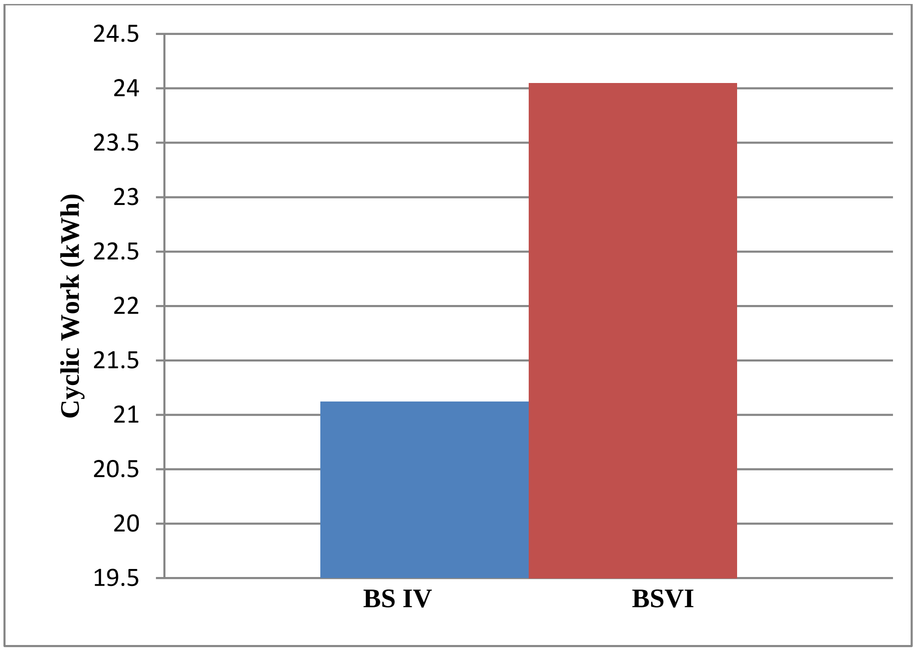


Figure 5.5 Cyclic work (kWh)

The cyclic work (kWh) showed a 13.87% increase with BS VI diesel fuel. This could mean that due to cleaner composition and no contaminants, BS VI fuel performs better than BS IV diesel.

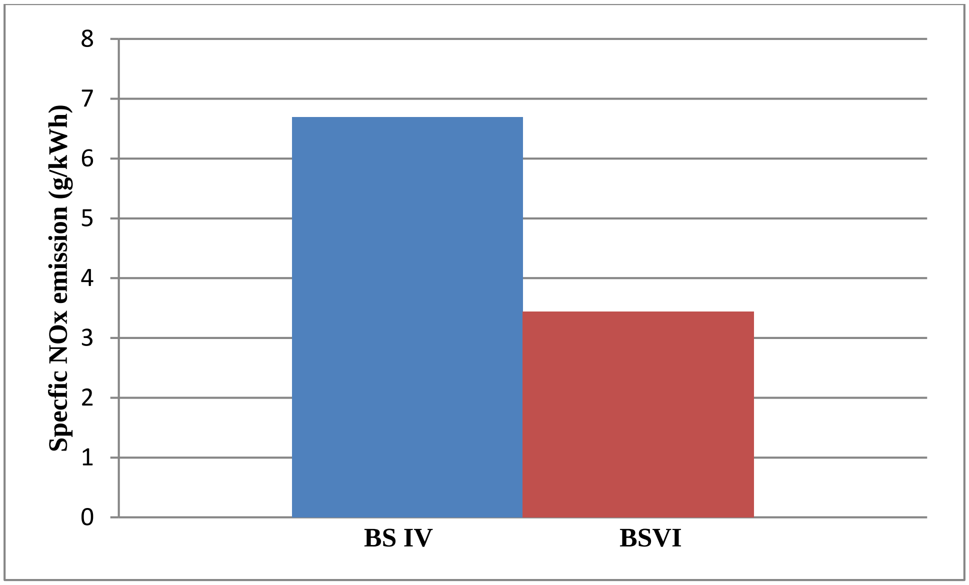


Figure 5.6 Specific NOx emission (g/kWh)

For the BS IV fuel, nitrogen oxide emissions were beyond the specified limits of 3.50 g/kWh. The reason for such high levels could be attributed to very high temperature in the engine caused due to ineffective cooling of chilled air over the engine. The NOx emissions measured by CLD showed a 48.65% decrease, when calculated in specific emission terms (g/kWh), shown in Figure 5.6.

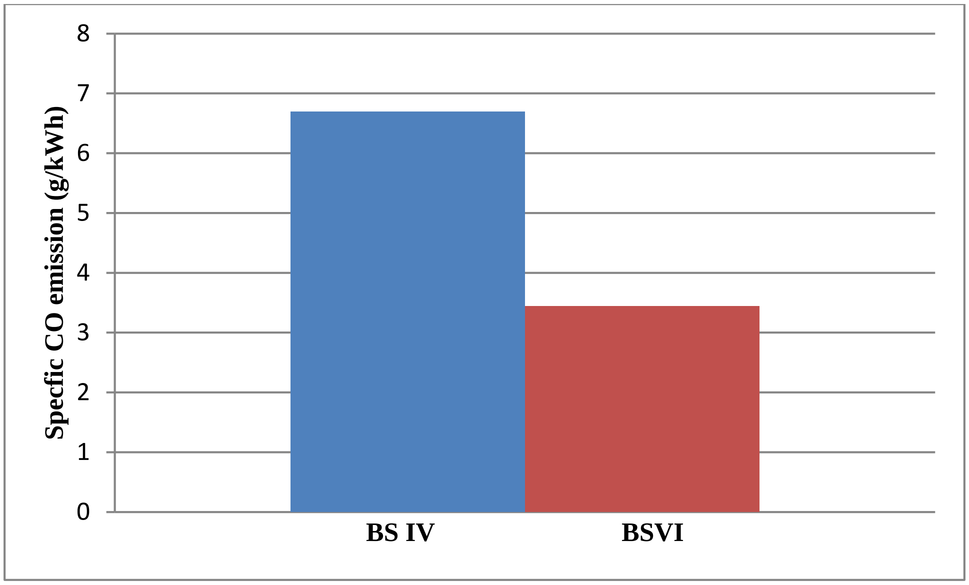


Figure 5.7 Specific CO emission (g/kWh)

Figure 5.7 reveals a 40.65% decrease in specific CO emissions with use of BS VI diesel in place of BS IV fuel. The decrease reveals that the incomplete combustion of carbon monoxide decreases with use of cleaner (ultra low sulfur) fuel, that is, BS VI fuel.

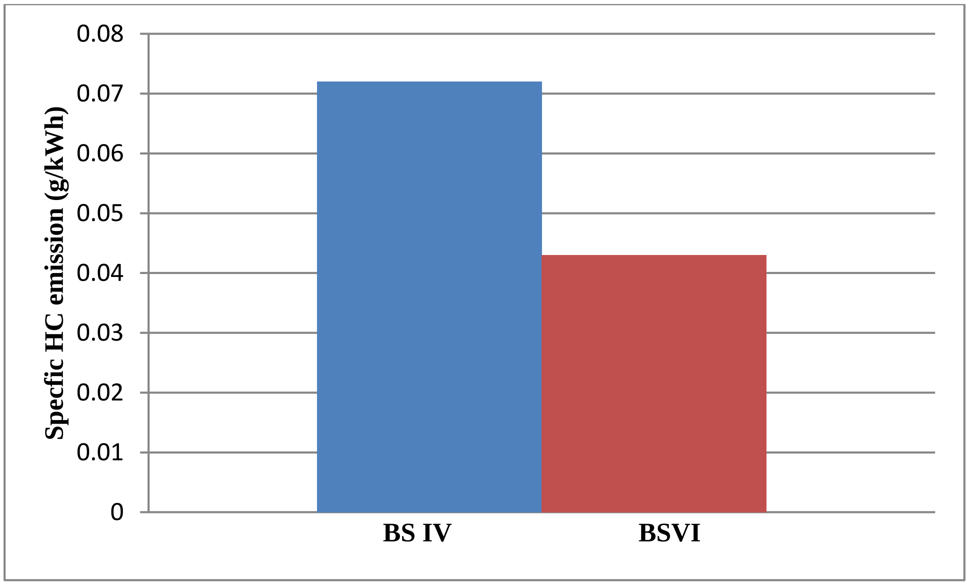


Figure 5.8 Specific HC emission (g/kWh)

Figure 5.8 shows similar reduction pattern for hydrocarbon with 40.27 % decrease as observed for carbon monoxide. In this case also, incomplete combustion phenomenon takes place due to partially burned fuel, but decreases with use of BS VI fuel.

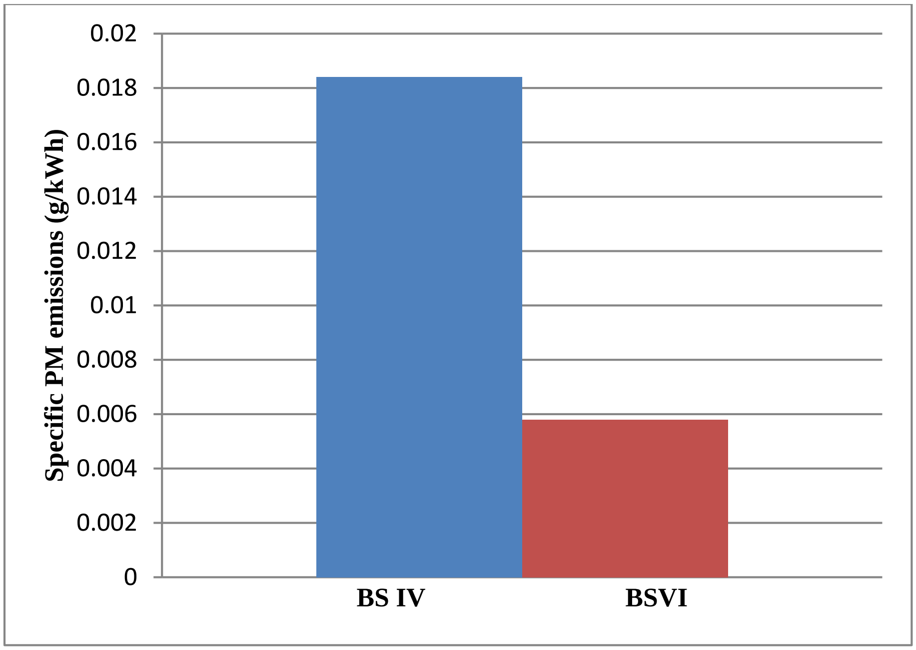


Figure 5.9 Specific PM emission (g/kWh)

Specific PM emissions witness a large reduction of 68.47% as compared with the use of BS IV fuel. The minimal sulfur content in ULSD reduced the PM emissions as sulfur in diesel fuel is associated with particulate matter. The decrease can also be attributed to increased cyclic work when BS VI was used in the engine.

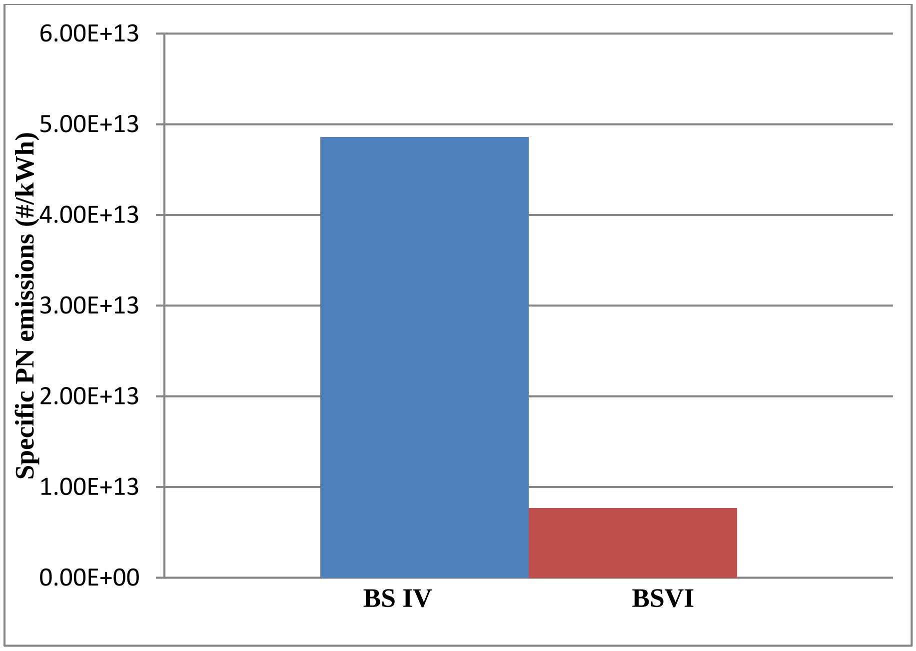


Figure 5.10 Specific PN emission (#/kWh)

A very high reduction of 84.17% in specific PN emissions is observed when the fuel was changed from BS IV to BS VI diesel. This decrease is caused due to almost 80 percent reduced sulfur content in BS VI fuel.

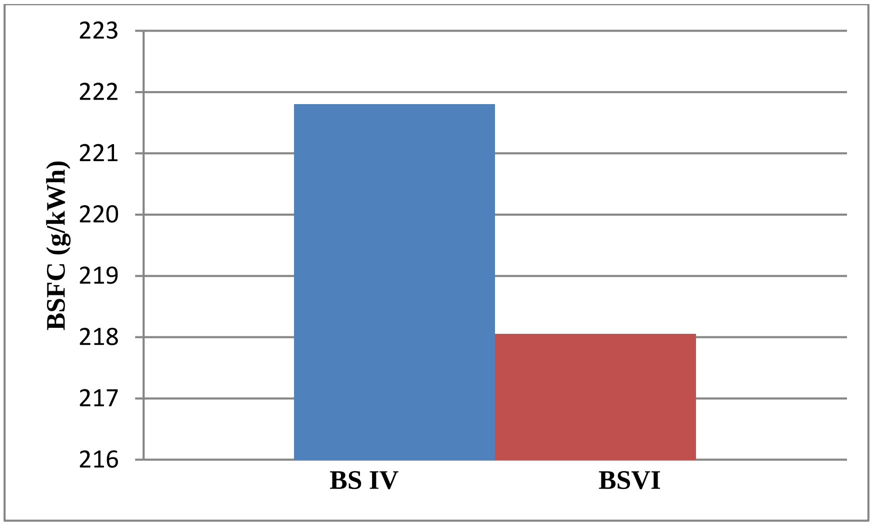


Figure 5.11 BSFC (g/kWh)

A minimal decrease of 1.66% was observed in BSFC values when BS VI fuel was used. This means that for 1kWh of electricity produced, lesser fuel will be consumed when BS VI is used instead of BS IV diesel.

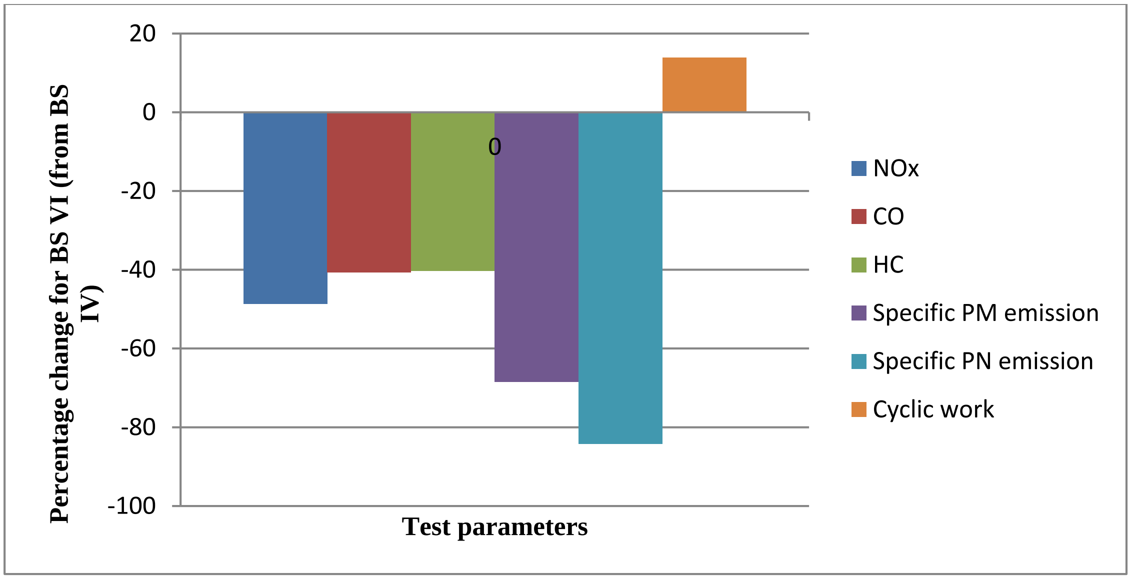


Figure 5.12 Percentage change for BS VI from BS IV value

Figure 5.12 shows the percentage change computed and observed for various test parameters while testing BS IV and BS VI fuels. As can be seen from the figure, maximum changes in specific PM emission and PN emission (above 60%) were observed when shifting to BS VI diesel. Carbon monoxide and hydrocarbons showed a similar reduction whereas nitrogen oxides decreased to more than 40% of the previous value.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 CONCLUSIONS

The research study focused on evaluating the behavior of engine under transient operation. European Transient Cycle was chosen to operate the engine with abrupt changes in speed and load and thus record the emission results.

Based on the collected results, the following conclusions have been drawn:

6.1.1 Engine performance

The engine response with test parameters was recorded in form of plots with respect to time variable.

- Torque- The rural segment (middle segment- 600 to 1200 seconds) attained maximum torque values (above 800Nm) which started to decrease in motoring segment due to high speed and thus increased friction in engine parts
- Brake power- The motorway segment with constant speed of about 1650 rpm resulted in decreased power obtained at the engine shaft
- Fuel consumption- Due to the aggressive speed and load changes, the fuel requirement reached the highest at 35kg/hr in urban segment of test schedule, which then decreased to lower values with time

6.1.2 Emission measurements

The gaseous emissions (NOx, HC, CO) as well as particulate emissions for BS IV and BS VI diesel were evaluated in specific emission (g/kWh) terms in order to analyze the emission quantity produced per kilowatt-hour of electricity generated by the engine shaft.

- The specific NOx emission levels revealed a 48.65% decrease when BS VI fuel was used instead of BS IV fuel.

- A 40.65% reduction in specific CO emission levels was observed when BS IV was replaced with BS VI fuel.
- A 40.27% decrease in specific hydrocarbon emissions was noticed with the use of BS VI diesel fuel.
- With 24.05kWh for BS VI fuel, the cyclic work showed a 13.87% increase.
- A 68.47% decrease in specific particulate matter emissions (g/kWh) was observed with use of BS VI fuel
- Specific particle number emissions (#/kWh) revealed a huge difference with 84.17% decrease when fuel was changed from BS IV to BS VI diesel
- The particle concentration (µg/m^3) signifies the particle mass collected over a volume of 1m^3. Particle concentration of 158.09 µg/m^3 and 12.069 µg/m^3 was obtained on filter sample using BS IV and BS VI fuel, respectively.

6.2 FUTURE SCOPE

Instead of creating real world driving conditions, vehicle and in specific terms, engine emission testing industry can foresee the usage of portable emissions measurement system (PEMS) to become more common. Such a setup would require lesser work force resulting in emission testing in reduced time. In addition, the variables added to simulate the real driving conditions would not be required and hence a more predictable and realistic results could be obtained. Although, since long time, the mobile emissions have been in use since 1990s but the major challenges involved in on-road emission testing are the size, weight and power consumption of emission analyzing instruments which should as minimum as possible. European Union (EU) has included real driving standards (RDE) standard, thereby, promoting light and portable low cost equipment. Furthermore, the system components are required to possess excellent resistance to shocks, vibrations, and temperature variations, which are normally expected in real world driving conditions. Integrated PEMS equipment kits are becoming popular but are to receive certification in many countries.

The soot and PM are major concerns in diesel engines, thus the real time measurement of these emissions is crucial. The further developments in portable gravimetric measurement system would be beneficent in interpreting the phenomenon of abnormal or incomplete combustion in heavy-duty diesel vehicles.

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