Investigation on the Effects of Quadruple Injection Strategy on Noise, Performance and Emission Characteristics of the Automotive Diesel Engine

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STATEMENT OF ORGINALITY

I, **Sanjoy Biswas**, registered on 1st April 2015 do hereby declare that this thesis entitled, "**Investigation on the Effects of Quadruple Injection strategy on Noise, Performance and Emission Characteristics of the Automotive Diesel Engine**" contains literature survey and original research work done by the undersigned candidate as a part of Doctoral Studies.

All the information in this thesis have been obtained and presented in accordance with existing academic rules and ethical conduct. I declare that, as required by these rules and conduct, I have fully cited and referred all materials and results that are not original to this work.

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CERTIFICATE FROM THE SUPERVISOR/S

This is to certify that the thesis entitled **"Investigation on the Effects of Quadruple Injection Strategy on Noise, Performance and Emission characteristics of the Automotive Diesel Engine"** submitted by Sanjoy Biswas who got his name registered on 1st April 2015 for the award of Ph.D. (Engineering) degree of Jadavpur University is absolutely based upon his own work under the supervision of Prof. Achintya Mukhopadhyay and that neither his thesis nor any part of the thesis has been submitted for any degree/ diploma or any other academic award anywhere before.

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Dedicated to my Mother, Beloved Wife and Parent -in- law

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Abstract

Internal Combustion engine (ICE) emissions, noise and fuel economy have a significant impact on environmental pollution especially with on road or automotive ICE. Thus, the challenges are multi-fold for engine developer/research engineer (R&D), especially for a diesel engine as they need to deal with stringent emissions norms [Example- BS-IV, BS-VI or Real driving emission (RDE)] in line with mandated fuel economy norms as per applicability [for example, heavy-duty fuel economy (HDFE) or corporate average fuel efficiency/economy (CAFE)]. Fuel economy norms are targeted towards reduction of carbon footprint or CO_2 emissions (in gm/km) to control global warming by improvement of fuel consumption over last norms. Diesel or Compression ignition (CI) engine is a very popular automotive power source (on road and off -road) due to its mileage, part load efficiency and durability though it has some inherent problem like combustion noise and soot emissions. Currently, diesel engine combustion noise (CN/radiation) has also gained significant attention, as it is associated with the passengers and pedestrians' discomfort along with noise pollution. Exhaust After treatment system has big role to meet the emission regulation but it has much less effect on fuel efficiency other performance like torque or brake thermal efficiency [BTE] and combustion noise (CN). Here, In-Cylinder emission reduction techniques plays the significant role on combustion characteristics. Thus, combustion characteristics influence the efficiency and pollutant formation level of engine simultaneously. Furthermore, combustion characteristics of diesel engines depends on several factors like – design of combustion chamber, turbocharger, Exhaust gas circulation (EGR)**,** Injector Nozzle , fuel injection strategy and its parameters (e.g.- Fuel injection Pressure (FIP), Injection Timing, Start of injection (SOI), Injection Dwell, Rate shaping, Fuel Quantity). Here, EGR is a proven in-cylinder NOx reduction methodology but reverse effect on Soot emission. Higher EGR percentage depending on engine size with suitable measures (e.g. - fuel injection characteristic, compression ratio, Air intake) is the simplest method to achieve low temperature combustion (LTC) which may give simultaneous reduction in NO_x, and Particulate emissions.

The Multiple fuel injections are nothing but splitting the total injected fuel quantity of each cycle to multiple pulses, to achive better control on the spatial fuel delivery to improve the air usage in the combustion chamber (Figure 2.1). In Multiple injections, mainly three types of injection pulses are there namely a) pre-injections (or pilot injections), b) main injection and c) post/After-injections, as shown in Figure 2.1. It is well-known that a DI diesel engine combustion process are divided into four phases namely – ingnition delay , pre-mixed burning, diffusion/mixing conrolled combustion and late burning. The multiple injections plays key role in combustion processes which utimately control

igintion delay, premixed and diffusion control phases. Lastly, it control the combustion chamber inside heat realease rate (HRR) , combustion pressure, bulk gas temperature. These are the enablers to control BSFC, Torque, emissions and combustion noise.

Therefore, fuel injection strategy plays a key role in the simultaneous reduction of emissions and noise without penalizing fuel economy due to its better control on the combustion process. Fuel injection strategy in combination with common rail direct injection (CRDI) technology and heavy or high EGR is also a promising low-temperature combustion (LTC) methodology. The CRDI technology provides flexibility to experiment with various injection strategies based on parameters, such as injection pressure, fuel quantity and injection timing, which are influential to engine combustion management.

The major research in the domain of direct injection Compression engine with different injection strategies, Injection parameters, alternative fuels, EGR- LTC and predictive combustion models mainly to reduce emissions and improve performance. Many of them were in combination with EGR and multiple injection Strategies to achieve the same. It also revealed that adoption of multiple injections along with suitable EGR rate [i.e.- Low (<30%) or Medium (>30%- <45%) or High (>45% - <60%) or Heavy(>60%)] on the basis engine size/configuration appears to be an encouraging technique to take care of Thermal efficiency, Performance (BSFC or fuel economy) and emissions to meet the regulatory norms. Adoptation of EGR specially high or heavy percentage allows to achive low teamperature combustion (LTC) condition. However, all these researches give limited insights on quadruple injections strategy consisting of double pilots (early and pilot or ep) and one-post injection pulse in combination with high EGR-LTC on diesel engine. Studies of the influence of multiple injection strategies upon vehicle level fuel economy and noise performance have not been reported yet.

Considering these research gaps, we have focused on the comprehensive assessment of multiple injections, including the newest quadruple injection. This thesis deals with study on the effects or potentialities of quadruple injection schedules over three triple injections, two double injections on a classic six-cylinder heavy-duty CRDI engine at different operating conditions (loads and speeds (low-to-high)) and injection parameters (Injection Timing , Post injection Dwell) using design of experiments (DoE) approach. The study is further sub divided into 5 key researches; namely (i) Assessment of multiple injections (Double, Triple, Quadruple) over single injection (Main) at full load; (ii) Comparison and optimization of quadruple injection strategy (epMa) over Triple injections (pilot-main-after; pMa) with variable main injection timing ; (iii) Comparative Analysis of quadruple injection strategy (epMa) over baseline Triple injections (pilot-main-after; pMa) and double injection (Pilot-Main; pM) with fixed e main injection timing (SOI Main), (iv) Assessment of the quadruple injection strategy (epMa) over three different Triple injections (early-main-after [eMa], early- pilot- main [epM] and pilot-main-after [pMa]) with fixed main injection timing; and (v) Effect of the quadruple injection strategy with different pilot and post injection timing. Fuel efficiency, Torque and Brake thermal efficiency (BTE) are considered under performance evaluation. Brake specific fuel consumption (BSFC) measured in all the studies. In addition, Vehicle level fuel economy has been evaluated as a requirement of HDFE norms in one of study. In few of the investigations, Pass by noise (PBN) at vehicle are captured along with Rig level noise (Nearby Noise; NBN) performance. One of unique focus of this research is to evaluate the outcome in real time or vehicle application.

The study shows that Quadruple injection strategy is superior in providing optimum results in emissions (NOx, PM, THC, CO) and combustion noise (CN)[@Rig level and @ Vehicle level Pass by Noise (PBN)]. This gives the optimum results in BSFC, CSFC (contestant speed fuel consumption), Torque and brake thermal efficiency (BTE) performance w.r.t other combinations and base triple injections (pMa). Also, the comparative study shown that Quadruple (epMa) injection strategy is superior to provide optimum (BSFC, overall emissions) results in comparison to Triple and Double injection strategies for all aspects. Smoke level is marginally higher at lower speed range for Quadruple injection scheduling whereas NOx emission level is lowest among the injection strategies

Further, Quadruple injection strategy with retarded early and advanced pilot and advanced post injection dwell timing is superior in providing optimum results in emissions and combustion noise (CN)[both Rig level and Vehicle level Pass by Noise (PBN)]. This gives the best results in brake specific fuel consumption (BSFC), Torque and brake thermal efficiency (BTE) performance w.r.t other Quadruple injection combinations (timing of ep and DtA) and base triple injections (pMa). In contrary, the quadruple injection strategy having advanced double pilots with delayed post injection dwell; shows the best CN reduction. Best smoke results found with the combination of retarded pilots and advanced post injection dwell. This study shows the importance of injection timing specially the twin pilots (early, pilot) along with post injection dwell and SOI main. Furthermore, it indicates the potentiality of newest Quadruple injection strategy (epMa) over Triple, double and single injection.

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Abbreviations/Nomenclature/Symbols

TDC	Top dead Centre;
CA	crank angle
Ai	main injection advance w.r.t TDC;
AiE	early injection advance w.r.t TDC,
AiP	pilot injection advance w.r.t TDC;
AiA	After injection w.r.t TDC;
p	Pilot injection or Pilot injection 2;
e	Pilot injection 1 or early pilot injection;
EtE	early injection duration;
EtP	pilot injection duration;
DtA	After injection Dwell,
qpf	quantity of fuel at pilot or early pilot injection,
qaf	quantity of fuel at after or post injection
bmep	brake mean effective pressure
CR	Compression ratio
CA	crank angle
CA BTDC	crank angle before top dead centre
eM	early–main
epM /ppM	early–pilot–main /pilot-pilot -main
epMa /ppMa	early–pilot–main-after /pilot-pilot –main-after
GHRR	gross heat release rate
NOx	Nitrogen oxides
PM	pilot–main / particulate matter
THC	total hydrocarbon
ETC	European Transient Cycle
ESC	European Stationary Cycle
FSN	Filter Smoke Number
ms	milli sec
dBA	Decibel A-weighted
SoI	start of injection,
EoI	end of injection;
SoC	Start of combustion,
EoC	end of combustion,
RoHR/ HRR	Rate of heat release / heat release rate
HRL	Heat relate line
FFR	Fuel flow rate
BSFC/bsfc	brake specific fuel consumption
CSFC	Constant speed fuel economy
BTE	Brake Thermal Efficiency
HDFE	Heavy-duty fuel Economy
CAFE	Corporate average fuel economy
CN	Combustion Noise
PBN	Pass by Noise
NBN	Near by Noise
RAR	Rear Axle Ratio
DoE /DOE	Design of Experiments

SYMBOL	**UNIT**	
g	m/s2	Acceleration due to gravity
ma	kg/s	Air mass flow rate
Ø	-	Air excess ratio
N	rpm	Crankshaft rotational speed /Engine Speed
r	kg/m3	Density
m EGR	kg/s	EGR mass flow rate
Pb	kW	Engine brake power
Tb	Nm	Engine brake torque
mf	kg/s	Fuel mass flow rate
F	-	Fuel-to-air equivalence ratio
V	cm3	Instantaneous volume of the engine cylinder
p	bar	In-cylinder pressure
qdelay	deg	Ignition delay
K	joules	Kinetic energy
pmax	bar	Peak in-cylinder pressure
pdrop	bar	Pressure drop
g	-	Ratio of specific heats
Rswirl	-	Swirl ratio
t	s	Time
m_{Total}	kg/s	Total air mass flow rate
R	J/mol. K	Universal gas constant
V	V	Voltage signal
ϕ	-	Equivalence ratio

Chapter -1

Introduction

Introduction

1.1 Preamble

The German engineer Rudolf Diesel has patented the first compression ignition (CI or Diesel) engine in 1892 with his concept permitted a doubling of efficiency in comparison to other internal combustion engines. The diesel engine has been used in numerous applications such as power generators, ships, aircrafts, submarines, tanks, trains, tractors, trucks and bus. It is being widely used in high-duty vehicles and marine propulsion due its higher efficiency in comparison with SI engines. The main reason behind this is the use of lean air/fuel mixture under higher compression ratios, and without throttling losses during part load. Thus, Diesel consumption is around 70% for transport application and its demand has increases by near 7-10% automotive segment in last few decades even though it emits more hazardous pollutants compared to SI engines. Below sub-sections are covering various aspects of Diesel engine including emission norms, combustion process, emission formation mechanism and emission control technologies.

1.1.1 Progression of Diesel engine emission Norms

The stringent emissions regulations (e.g. – BS-IV, BS-IV, Real driving emissions [RDE]) are mandated or optimum fuel economy requirements (e.g.- heavy-duty fuel economy [HDFE] and Corporate Average Fuel Efficiency/Economy [CAFÉ]) are mandated in India like other developed countries [1, 3-7] with different time frame. At the same time, combustion noise (radiated) from Diesel engine [16-18, 28-29] has drawn significant attention along with strict emission norms and sustainable fuel economy requirement. In vehicle level Pass by Noise (PBN) and in-Cab Noise, Engine is the key contributor. Among the engine noise, key contributor are combustion/radiated noise (CN), piston slap noise and fan belt noise [15, 18]. These are the key inputs for the R&D researchers/engineers to develop Diesel engine for automotive or transport application.

Table 1.1: - Steady State cycle emission limits for heavy diesel truck and buses [1, 3]

Pollutant	BS-III Limits (g/kWh	BS-IV Limits (g/kWh)	BS-V Limits (g/kWh)	BS VI Limits (g/kWh)	Reduction % w.r.t BS-IV
PM	0.10	0.02	0.02	0.01	50%
Nox	5.0	3.5	2	0.40	89%
HC	0.66	0.46	0.46	0.13	72%
CO	2.1	1.5	1.5	1.5	-
Nation Wide	Year 2010	Year 2017	Skipped	Year 2020	RDE plan on 2023

Table 1.2: - Transient cycle emission limits for heavy diesel truck and buses [1, 3]

Pollutant	BS-III Limits (g/kWh)	BS-IV Limits (g/kWh)	BS-V Limits (g/kWh)	BS VI Limits (g/kWh)	Reduction % w.r.t BS-IV
PM	0.16	0.03	0.03	0.01	67%
Nox	5.0	3.5	2	0.46	87%
HC	0.78	0.55	0.55	0.16	71%
CO	5.45	4	4	4	-
Nation wide	Year 2010	Year 2017	Skipped	Year 2020	RDE plan on 2023

Similarly, European counties and major developed countries worldwide follow the European emission standards which is called as EURO standards.

Table 1.3: - Implementation timeline of emission Standards for Diesel Truck and Bus Engines [1,3]

Standard	Reference	Year	Region
India 2000	Euro 1	2000	Nationwide
BS-II	Euro 2	2001	NCR, Mumbai, Kolkata, Chennai
		2003	NCR, 13 Cities
		2005	Nationwide
BS-III	Euro 3	2005	NCR, 13 Cities
		2010	Nationwide
BS-IV	Euro 4	2010	NCR, 13 Cities
		April, 2017	Nationwide
BS-V	Euro 5	(Skipped)	-
BS-VI	Euro 6	April, 2018	Delhi NCR (BS VI Fuel only)
		January, 2019	13 Cities (BS VI Fuel only)
		April, 2020	Nationwide (Both BS Fuel & Compliant vehicles)

Indian emissions standards based on vehicle class, its implementation time line and emission reduction values are shown in the above tables (Table 1.1, Table 1.2 and Table 1.3). Here mainly focus given for heavy vehicle (GVW > 3.5T) engine which is majorly applicable for truck and bus usages. The emissions regulation indicates the importance of drastic reduction target of pollutants level by European Union (Fig 1.2 and Fig.1.3) as well as India (Table 1.1, Table 1.2 and Table 1.3) for heavy diesel engines. To achieve such kind emission level one requires adequate research and development on diesel engine combustion and emission technologies [5, 7].

1.1.2 Diesel engine combustion, emission formation mechanism and its control technologies

This section consists of brief of diesel engine combustion, emission formation and emission control technologies vide different sub heading and sub-sub heading sequentially.

1.1.2.1 Diesel engine Combustion

This sub section is covering diesel engine combustion process vide two sub-sub sections namely combustion mechanism (1.1.2.1.1) and combustion models (1.1.2.1.2).

1.1.2.1.1:- Combustion Mechanism

A complete combustion cycle of compression ignition or diesel engine or 4-stroke ICE has duration of 720° crank angle (CA). Generally, the timing indicates in °CA relative to the piston position at TDC prior to the combustion stroke. Thus, Crank angles are expressed in °CA BTDC (before TDC) or °CA ATDC (after TDC) as per the requirement. Diesel combustion is one of complex process combination of several sub-processes [10]. Fuel is injected into the cylinder towards end of compression stroke where the inducted charge has been compressed. Usually, the liquid fuel injected at high velocity as one or more jets through small orifices or nozzles injector. The fuel jet then breaks up into droplets which evaporates and mixed with the surrounding high temperature and high-pressure cylinder air. At this stage, temperature and pressure of Cylinder air is more than the fuel's ignition point. Reactions start within the mixture and eventually combustion occurs and quickly spreads throughout the cylinder where combustible mixtures are available. The time between the start of injection until combustion occurs is called the ignition delay period and the subsequent combustion is called the premixed combustion phase. Following this is a mixing-controlled phase where the combustion stabilizes and starts at an almost constant distance downstream the injector nozzle, at the so called lift-off length, and the combustion process remains steady until the end of injection. The last phase is called the late combustion phase. In this phase, the fuel sprays no longer dominate the in-cylinder gas-motion. Instead, effects of intake charge motion e.g. swirl and tumble, are more prominent.

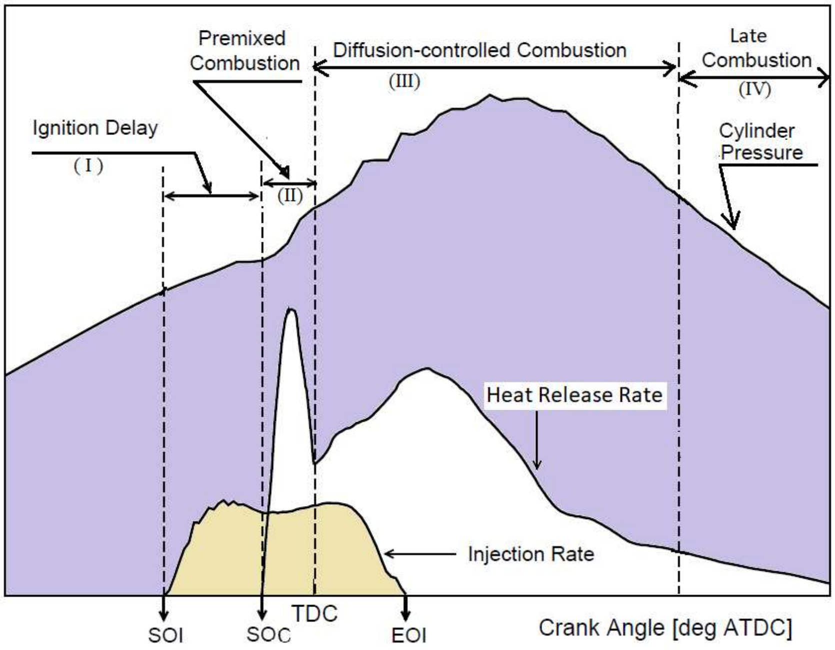


Figure 1.1:- Typical Diesel engine combustion curves with heat release rate, injection rate and cylinder pressure at different combustion phases [Source 9, 10, and 11].

The four stages are illustrated on typical heat release diagram as represented in Figure 1.1. In this Figure, four stages are identified as a. Ignition delay (I) b. Premixed or Rapid combustion phase (II), c. Mixed-controlled Combustion phase (III) and d. late combustion phase (IV).

Depending on design of combustion chamber, diesel engines are categories as - a. Direct Injection (DI) and b. Indirect Injection (IDI) diesel engine. Direct injection diesel engines have single open combustion chamber into which fuel is injected directly. On other hand, combustion chamber is divided into two regions in indirect injection engines and hence, fuel is injected into pre-chamber, which is connected to main chamber by means of a nozzle or one or more orifices.

1.1.2.1.2:- Combustion Models

Diesel engine combustion simulation models [19] are classified as a. Zero-dimensional (0 D), single-zone models, b. Quasi-dimensional (1D), multi-zone models and c. Multidimensional models (computational fluid dynamics [CFD]) respectively depending on the various factors. Zero-dimensional, single-zone models are simplest model based on thermodynamic analysis where the cylinder charge is assumed as uniform in both composition and temperature, at all time during the cycle. On the other hand, multidimensional models (or CFD), solve the space of the cylinder on a fine grid, thus provides a formidable amount of special information and its required high computational support.

Quasi-dimensional, multi-zone models or phenomenological models are intermediate among zero-dimensional and multi-dimensional models, and this model combines some of the advantages of zero-dimensional models and multi-dimensional models [20].

1.1.2.2 Diesel engine emission formation mechanism

Diesel engine exhaust gases consist of large number of organic, inorganic solid, liquid and gaseous chemical species [7, 9]. Among these NOx and PM (soot) are the main concern for diesel engine. In diesel engines, combustion process begins with a premixed phase ignition and develops with diffusive behavior. The combustion ignition delay is affected by the rate of fuel injected; particularly, the duration of the premixed and mixing-controlled combustion phases. It is well recognized that combustion characteristics extremely influence the engine efficiency and pollutant formation [9,12]. Specifically, the formation of nitrogen oxides (NOx) happens during the course of high temperature burned gases formed behind the flame by chemical reactions. It involves nitrogen and oxygen atoms and molecules, which do not reach chemical equilibrium condition [10]. The higher the temperature of the burned gas, the higher is the rate of NO, which impact upon NOx formation. As combustion reaches high temperatures, this mixture is heated and compressed and accordingly, the premixed phase formed. During the expansion stroke, as the burned gases cool, the reaction comprising NO freezes and leaves NO concentrations faraway in excess of the estimated levels at equilibrium and exhaust conditions. Soot is generated largely in the spray core area and adjacent to nozzle orifice and it is characterized by a fuel–air rich mixture [10]. The diffusive combustion duration decreases as the temperature during the diffusive phase of combustion increases. It improves soot oxidation processes. Therefore, soot concentration at the exhaust is significantly lesser than the soot levels in the cylinder during combustion. Total hydrocarbons (THC) result from in cylinder zones are categorized by an air–fuel ratio lower than the combustion limits. Unburned fuel, fuel decomposition products, and partial oxidation products are present in these zones. Therefore, the quantity of aforesaid products leaving from combustion chamber strongly depends on duration of ignition delay. As longer the ignition delays, higher are the THC emissions [10].

NO formation: -

Applicable three different ways of nitric oxide (NO) forming mechanism are important for diesel engine combustion. Those are namely a) Thermal NO b) Prompt NO and c) N2O- Intermediate respectively.

a) Thermal NO –In 1946 Zeldovich [21] proposed this thermal mechanism for NO formation, and later stage, it was extended by Lavoie et al. [22], by inclusion of third reaction. This is called as the extended Zeldovich mechanism and is given by the following three reactions:

$$O + N_2 \rightleftharpoons NO + N \tag{1.1}$$

$$N + O_2 \rightleftharpoons NO + O \tag{1.2}$$

$$N + OH \rightleftharpoons NO + H \tag{1.3}$$

The reaction (1.1) is slower in comparison with reactions (1.5) and (1.6) due to its comparatively large activation energy (318 kJ/mol). Thus, this mechanism becomes significant at higher temperature (> 1800 K, hence, the name appeared as “Thermal”). The reaction rate is expressed by an Arrhenius-type expression:

$$k_1 = A_1 \exp[-\frac{E_{a,1}}{RT}] \tag{1.4}$$

From above further express as

$$\frac{dk_1}{k_1} = \frac{E_{a,1}}{R}\frac{dT}{T^2} \tag{1.5}$$

Here, $E_{a,1}$ /K =38370K suggests the high temperature sensitivity. For example, at 2000 K, an increase in temperature of 1% causes an increase of the reaction rate of around 20%, i.e. NO formation rate. It is widely acknowledged as dominant NO formation mechanisms. Thermal NO is formed in the post-flame hot combustion products resulting from the diffusion flame.

b) Prompt NO formation –This is also denoted as the Fenimore mechanism [23]. NO formation by the prompt-NO mechanism, happens in fuel-rich flames in the presence of hydrocarbon radicals, which react with N2 to form HCN (hydrocyanic acid). HCN oxidise to N atoms by different steps and subsequently reacts as per equation 1.1 and 1.2. The name “prompt” creates based on the fact that NO is formed so rapid which appears in or nearer to the flame front.

$$CH + N_2 \rightleftharpoons HCN + N \tag{1.6}$$

c) NO formation via N_2O-intermediate pathway – In 1972 Wolfrum [24] postulated the N_2O-intermediate pathway. It defines the NO formation process via N2O as intermediate species, which are formed due to attack of N2 by atomic oxygen and a third-body molecule M . This mechanism has low activation energy (76 kJ/mol) comparatively. Thus, it is important for low temperature and high-pressure combustion cases like EGR. Prompt NO and thermal NO are become less significant for this condition.

$$N_2 + O + M \rightleftharpoons N_2O + M \tag{1.7}$$

$$N_2O + O \rightleftharpoons 2NO \tag{1.8}$$

Soot formation: -

In diesel engine, Soot is produced during premixed or diffusion combustion of fuel rich mixtures. High concentration of soot in the exhaust is manifested as visible black smoke emissions. Fuel composition also plays important role in soot formation, but this factor is not considered in present carried-out analysis. The factors that affect soot formation and oxidation also influence smoke. Engine power rating and maximum brake mean effective pressure is limited by the permissible smoke emissions. Smoke value can be measured in terms of opacity or FSN (Filter Smoke Number) or HSU (Hartridge Smoke Unit) or BSU (*Bosch Smoke Unit*). All these units have correlation among also with PM (particulate matter) and in this study FSN unit is used for smoke measurement. Particulate matter is basically combination of soot and unburned hydrocarbons absorbed on soot of exhaust. Hence, Soot content can be roughly estimated from smoke measurement using the developed correlations with different level of accuracy [134-137]. Particulate Matter (PM) is a regulated diesel engine emission norms but understanding the soot formation model is very important. Soot is quantification of the insoluble, carbonaceous part of the total PM. The widely accepted phenomenology of soot formation process as below [25]

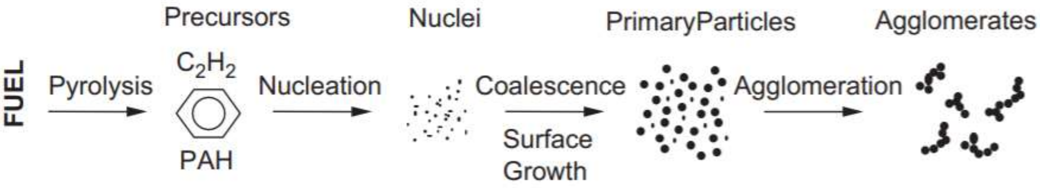


Figure 1.2:- Schematic representation of phenomenology of soot formation process [25].

The soot formation mechanism consists of following steps /parallel process namely (i) Molecular precursors by fuel pyrolysis; (ii) Particle nucleation; (iii) Surface growth; (iv) coalescence and agglomeration; and (V)Particle oxidation

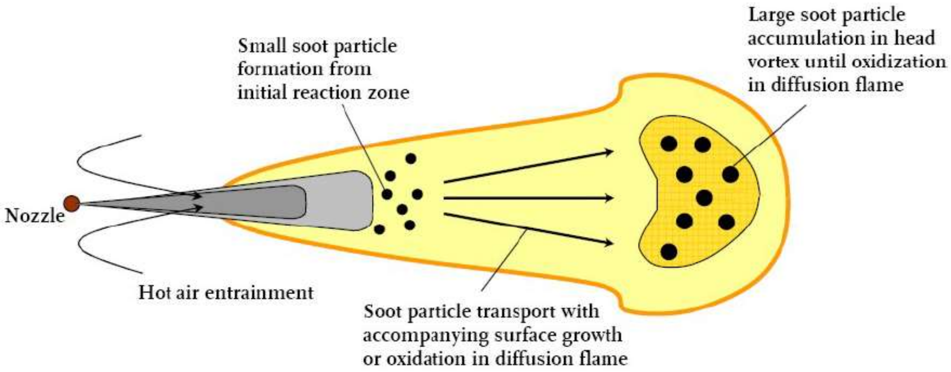


Figure 1.3:- Chronology of a soot particle in a diesel spray combustion-event [25].

The phenomenology of soot formation has been illustrated in Figure 1.2 for the combusting diesel fuel spray. Here, at downstream of liquid length and at the rich premixed reaction zone, the Initial fuel pyrolysis happens. The combustion products of the rich initial reaction cover high concentration of unburned fuel elements with the increase of equivalence ratio of the initial reaction zone. This outcome in higher level of soot particle inception just downstream of the initial reaction zone where small soot particles are seen. Then, theses small particles move towards the head vortex and start grow in size by surface growth and coagulation process. Oxidation (soot particles) occurs when they travel close to or by the diffusion flame formed nearby the periphery of the fuel spray. In this zone, the particles are exposed to high temperatures and oxygen attack.

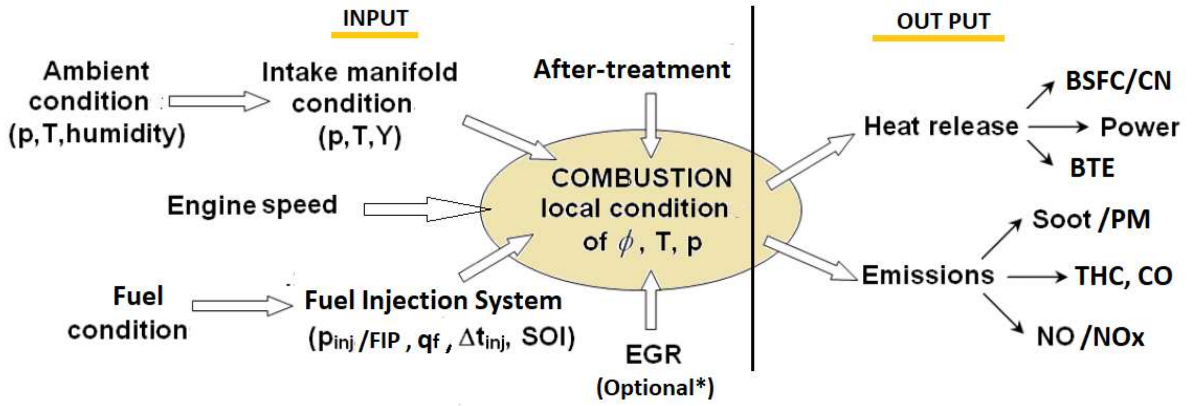


Figure 1.4:- Overview of input factors influencing the local in-cylinder conditions defining the combustion progression and subsequent outputs of the combustion [Source 2].

The combustion process is influenced by different variables, as shown in Figure 1.4. Not all diesel engine is equipped with EGR and hence, it is marked as optional. All these input factors affect the emissions and heat release rate (HRR) but the combined effect influences the three main aspects of the combustion process, namely (1) the local availability of oxygen and fuel (2) the local temperature, which encourages chemical reaction and (3) the time availability for combustion. The influence of fuel availability, local temperature and oxygen level, is precisely illustrated in Figure 1.5, using the ϕ-T map.

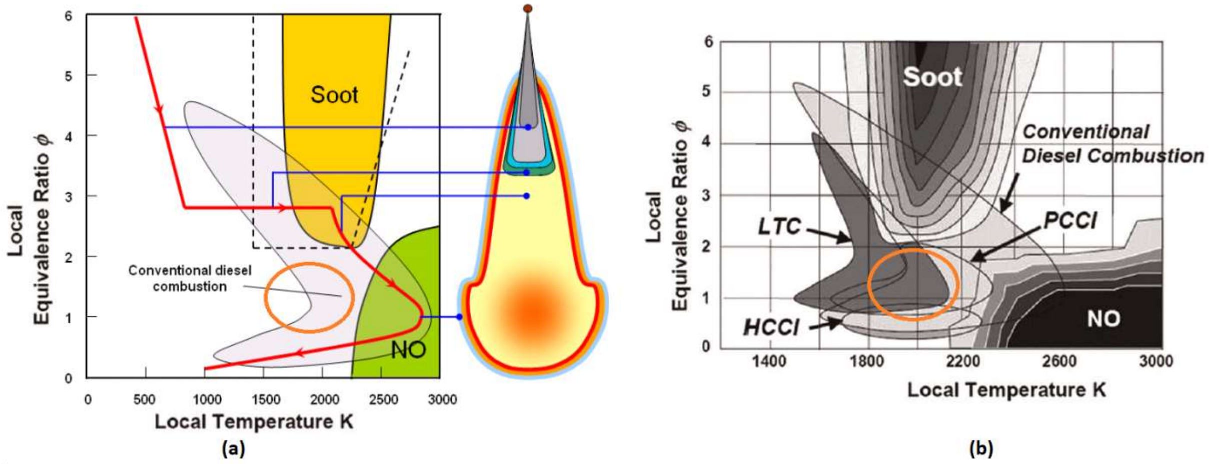


Figure 1.5:-
(a) ϕ-T map with main regions of NO_x and soot formation. Pressure = 60 bar, 0% EGR, Residence time = 1.0 ms [Source 26].
(b) Equivalence ratio versus temperature plot showing NOx and soot formation zones [Source 27]

The influence of local equivalence ratio, local temperature on soot and NO formation are well explained in Fig 1.5. Tradeoff of between NOx and Particulate /soot is the key focus area without compromising of BSFC. This figure indicates that equivalence ratio-ϕ of around ~ 1.5 and local temperature range of 1800-2200K may favorable condition to achieve LTC or near HCCI combustion mode. The dashed line represents soot formation region of Kitamura et al. [27] in Fig 1.5 (a). The shaded region indicates the ϕ-T region for conventional diesel combustion. The solid line represents an example of a typical ϕ-T-route occurring in the quasi-steady burning fuel spray.

1.1.2.3 Diesel engine emission control Technologies

Diesel engine offers better fuel economy, benefit of CO2 emissions reduction and durability in comparison to gasoline engines. However, the PM and NOx emissions are become very critical subject to legislative norms due to their adverse effects on environment and human health specially the unburned soot /PM emission. There have been significant developments in engine research domain to enhance both engine combustion process and after treatment system to achieve desired level of emissions reduction. Figure 1.6 and Figure 1.7 are shows the different ways of NOx and PM reduction from diesel engine exhaust.

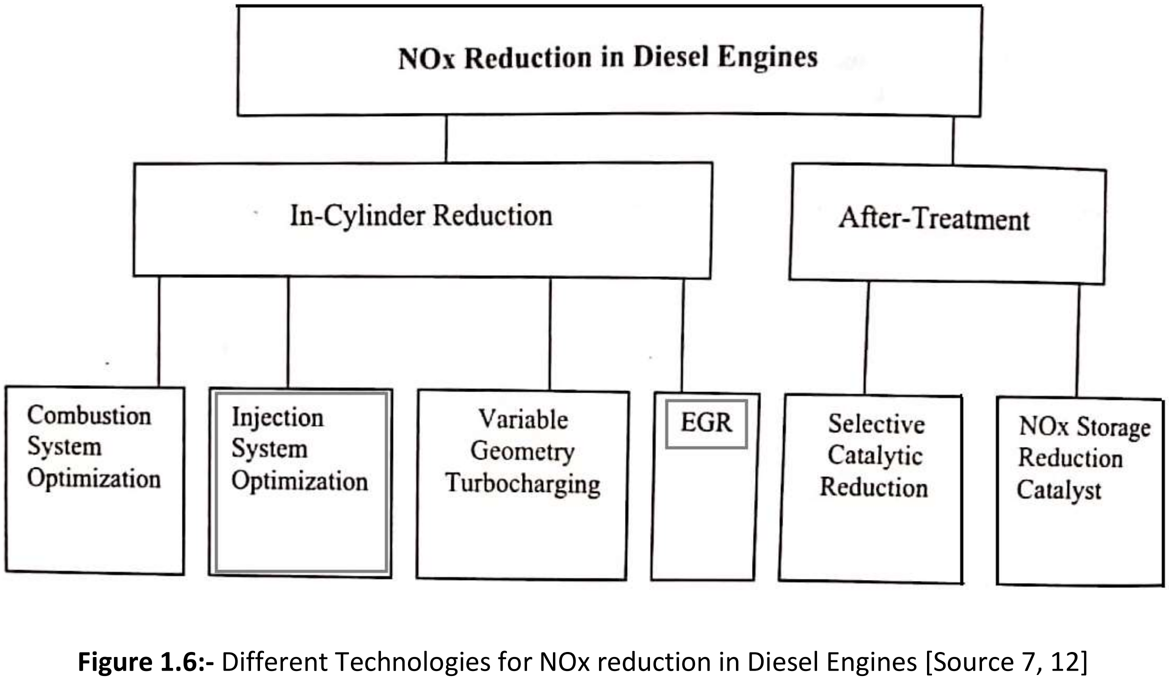


Figure 1.6:- Different Technologies for NOx reduction in Diesel Engines [Source 7, 12]

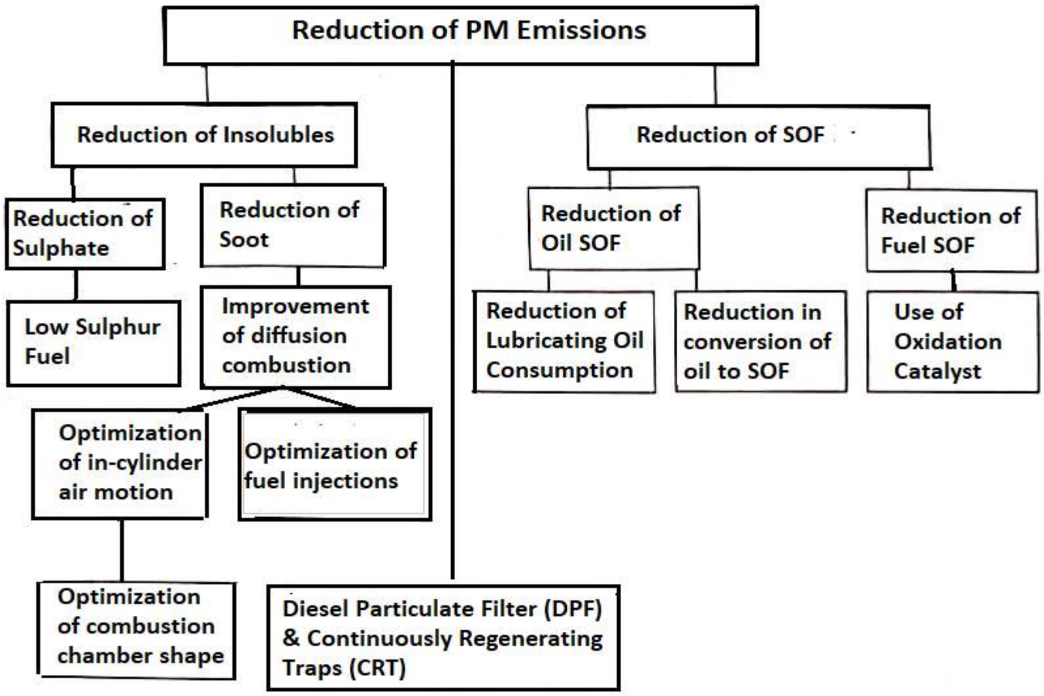


Figure 1.7:- Different Technologies for PM reduction in Diesel Engines [Source 7, 12]

From the above figures, it is clear that fuel injection system has key influences in reduction of NOx and PM (soot) emission of diesel engine by improvement of combustion process. Among the in-cylinder technologies, EGR (exhaust Gas recirculation), VGT (variable geometry turbocharging) and electronic injection system are widely used. EGR may not be necessary for all application due to the advancement of Selective Catalytic Reduction (SCR) technology. However, sometime both the technologies are used combined specially foe heavy diesel engine. The SCR is cost effective and fuel-efficient technology.

Also, the oxidation catalyst/filters for diesel after treatment system are DOC (Diesel Oxidation Catalyst), POC (Particulate Oxidation Catalyst), DPF (Diesel Particulate filter) , LNT **(**Lean NOx Trap) / NOx Adsorbers , CTR (Continuously Regenerating Trap) are popular and used in different combination.

Exhaust Gas recirculation (EGR*)* -

EGR is a useful and proven method for reduction of NOx formation in the combustion chamber. While a portion of this exhaust gas is re-circulated to the combustion chamber, it acts as diluent to the combusting mixture. This recirculation can be achieved either internally with the proper valve timing, or externally with some kind of piping. This also reduces the concentration of O2 in the combustion chamber. As the specific heat of the EGR is much higher than fresh air, it increases the heat capacity (specific heat) of the intake charge, thus decreasing the temperature rise for the same heat release in the combustion chamber. Based on the temperature, configuration and pressure, it can be classified into different types. EGR rate, its cooling and configuration (Short or long route) has significant impact on emissions and fuel economy [31-33].

$$\%EGR = \frac{\text{volume of EGR}}{\text{total intake charge into the cyclinder}} \times 100 \qquad \text{……………………………………………} (1.9)$$

Kohketsu et al [31] have studied through comprehensive experiments to understand the effect of EGR on NOx, BSFC, smoke at different operating condition such as load. Hountalas et al [32] exhibited from their study that EGR cooling is promising with the benefits of low NOx emissions without compromising the engine efficiency significantly. The requirement for EGR cooling is more obvious at high EGR rates and low engine speeds to prevent soot emissions.

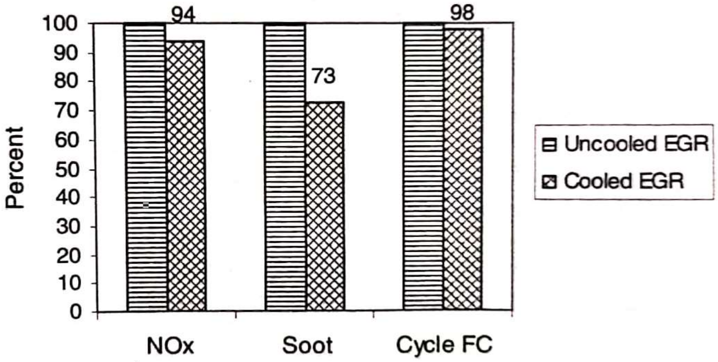


Figure 1.8: Effect of EGR cooling on emission and Fuel consumption [32]

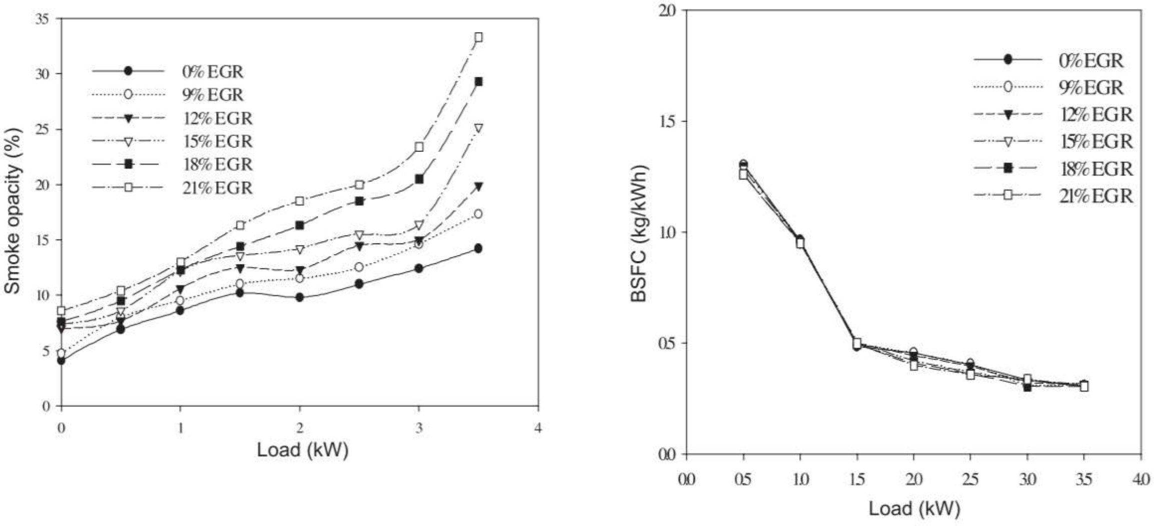


Figure 1.9: - Effect of EGR rate on Smoke opacity and BSFC at different load on Diesel engine [33]

According to Agarwal et al [33], BSFC are not affected significantly by EGR though PM emission in the exhaust increases which observed from the smoke opacity results.

1.1.3- Overview of fuel injection system

The previous section is clearly indicating that there are two possible methods used for the purpose of emission control either by the engine design changes or by treating in the exhaust using after treatment techniques. To achieve meet both fuel economy and emissions goals, both in-cylinder and after treatment techniques are adopted simultaneously. Fuel injection system optimization is one of attractive techniques to achieve desired combustion process improvement with major changes in engine design. Modern electronic fuel injection system is the key enables to achieve desired combustion environment so the combustion management can be done for required outcome. Among the injection types (1. Inline Type, 2. Distributer or rotary type, 3. Unit injection type (EUI) and 4. Common rail type (CRDI)), Common rail direct injection is superior. The CRDI technology provides flexibility to experiment with various injection strategies based on parameters, such as injection pressure, fuel quantity and injection timing [35], which are linked to engine combustion management. A CRDI system works at constant pressure all over the period of injection and the control of injection timing is made independent of Engine speed [34,36]. A common rail injection system consists of high-pressure supply pump, common-rail, injectors, fuel metering, various sensors and an ECM/ECU (electronic control unit) to map/ control the different engine components as shown in Fig.2.1.

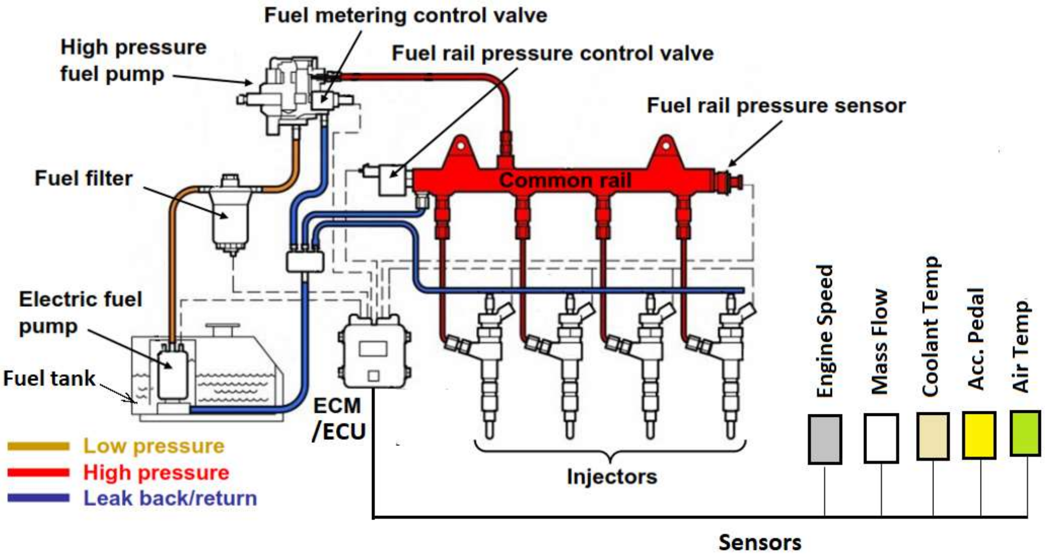


Figure 1.10:- Common Rail Diesel fuel injection System [Source Bosh]

The inline and distributor (rotary) type are most common and conventional fuel injection system (PLI-Pump inline injector) of DI diesel engine. These types of system generate fuel pressure for each injection repeatedly. In case of unit injection system, pump and nozzle are combined in single housing. Each cylinder is provided with one of this injector. Fuel brought up into the injector using low pressure pump and at proper time rocker arm activates the plunger at proper time so that fuel inject into the cylinder. In CRDI, Fuel injection pressure is not dependent on engine speeds [36] like other type of injection system.

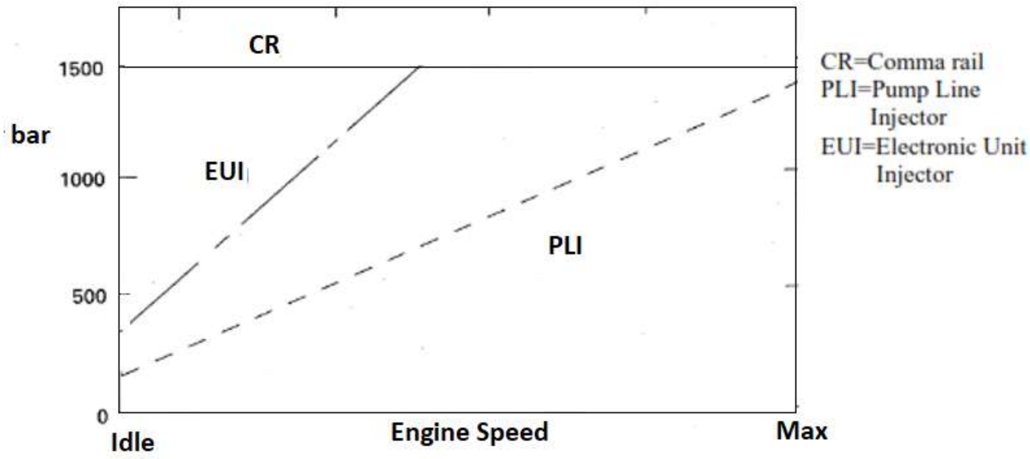


Figure 1.11:- Rail Pressure variation with speeds in different Fuel Injection Systems [36]

The increase in fuel injection pressure enhances the atomization quality and air entrainment in combustion process, and as a consequence, there is an enhancement in fuel consumption level and a reduction in soot formation. However, it increases the injection rate as well which ultimately increases the rapid burning premixed combustion phase. This leads to an increase of NOx emissions and high peak pressure inside the combustion chamber, which is transformed as high combustion noise. Primarily, a common rail direct injection system has the following injection parameters

1. Fuel Injection Pressure (FIP)
2. Injection timing (SOI, Dwell, Energizing time)
3. Injector parameters like nozzle hole diameter, position, no of holes
4. Injection rate shaping
5. Number of injection pulse (single /Multiple/Split injection)

The fuel injection strategy/system and its parameters have significant impact on combustion mechanism which affect emissions and performance of DI diesel engines. Few of key research are discussed in brief in forthcoming section (Chapter -2).

As mentioned earlier, Diesel or Compression ignition (CI) engine is a very popular automotive power source (on road and off –road) due to its high mileage, part load efficiency and durability though it has some inherent problem like combustion noise (CN) and soot emissions. The current stringent emissions regulations (e.g. - BS-IV, BS-IV, Real driving emissions [RDE]) and mandated or optimum fuel economy requirements (e.g.- heavy-duty fuel economy [HDFE] and Corporate Average Fuel Efficiency/Economy [CAFÉ]) are the key inputs to the research and development activities of internal combustion engine (ICE) for automotive application. Exhaust After treatment system has a big role to meet the emission regulation but it has minimal impact on fuel efficiency and other performance parameters like torque or brake thermal efficiency [BTE] and combustion noise. Here, In-Cylinder emission reduction techniques plays the significant role on combustion characteristics. Thus, combustion characteristics simultaneously influence the efficiency and pollutant formation level of engine.

Furthermore, Combustion characteristic of diesel engines depends on several factors like – design of combustion chamber, turbocharger, Injector Nozzle, fuel injection strategy and its parameters (e.g- Fuel injection Pressure (FIP), Injection Timing, Start of injection (SOI), Injection Dwell, Rate shaping, Fuel Quantity). Exhaust gas circulation (EGR) is also proven in-cylinder NOx reduction methodology. Among these, Fuel injection strategy and its parameters play a vital role in combustion characteristics for trade-off between pollution and performance specially with multiple injections. Engine calibration is also an important part to ensure consistency in output. The CRDI (common rail direct injection) technology is the enabler and provides the flexibility to play with different fuel injection strategies along with the injection parameters like injection pressure, fuel quantity, injection timing etc. which are connected with engine combustion management. High EGR % depending on engine size with suitable measures (e.g. - fuel injection characteristic, compression ratio, Air intake) is the simplest method to achieve low temperature combustion (LTC) which may give simultaneous reduction in NO_x, and particulate emissions though with some drawbacks.

Thus, multiple fuel injection strategy in combination with suitable (high/heavy) exhaust gas recirculation (EGR) is a promising method to achieve low temperature combustion regime in present CRDI diesel engine. This helps in simultaneous reduction of NOx and PM or Soot to meet the stringent emission standards without penalizing the fuel efficiency and overcomes the downsides of high EGR-LTC. This thesis is dealing with the study on the effect of newest Quadruple injection (early-pilot-main-after; epMa) startegy in association with high EGR , on performance, emissions and noise with different injection parameters on an on-road CRDI inline 6 cylinder diesel engine at extensive operating conditions (Speeds and Loads). Real time or vehicle level perforamnce like pass by noise (PBN), Constant speed fuel consumption (CSFC) are also part of this research. Furthermore, an effort given to development and validation of phenomenological or low order combustion model for newest Quadrupole injection strategy.

1.2 Thesis outline

Chapter 1 covers the introduction and thesis outline concisely.

Chapter 2 reviews the scientific literatures on diesel engine cycles, combustion basic, brief of combustion models, emission and fuel economy norms, emission-control technologies, and fuel injection strategies. After that, research gap-analysis and research objectives are presented.

Chapter 3 focuses on the experimental setup, procedure, engine specification, instrumentation details, vehicle details and noise measurement schematic and method. This also shows the uncertainty analysis of measurement. All the information provided in this chapter is applicable for all the experimental investigation.

Chapter 4 focuses on the experimental assessment 5 different multiple injection strategies with single injection at full load and different speeds. The assessment done for soot /smoke emission, BSFC, torque and combustion noise

Chapter 5 evaluate the effectiveness of quadruple injections over triple injection with different SOI Main injection timing experimentally at wide operating conditions.

Chapter 6 presents the comparative evaluation of quadruple, triple and double injections (consisting of at least one pilot injection event) in terms of emission, performance and combustion noise at three loads and five speeds.

Chapter 7 represents an comprehensive assessment of quadruple injection strategy (epMa) over three different (pMa, epM, eMa) triple injections at fixed main injection timing (SOI) and wide operating condition on Rig and vehicle level for Fuel economy, emissions and noise.

Chapter 8 compares the baseline triple injection (pMa) with quadruple injection (epMa) with different injection timing combination of pilots (early /pilot1, Pilot or Pilot 2) and post injection dwell. This to evaluate the effectiveness of injection timing with quadruple injection experimentally.

Chapter 9 summarizes the dissertation and indicates the further scope of work.

Chapter -2

Literature Review

2.1: - Influence of Fuel Injection Strategy

The fuel injection strategy and its parameters have substantial impact on combustion process of Diesel engine which effects the emissions and performance of DI diesel engines. The CRDI provides the flexibility to play with different fuel injection parameters which helps in finalization of engine calibration strategy. Fuel injection strategy is sub-set of engine calibration strategy.

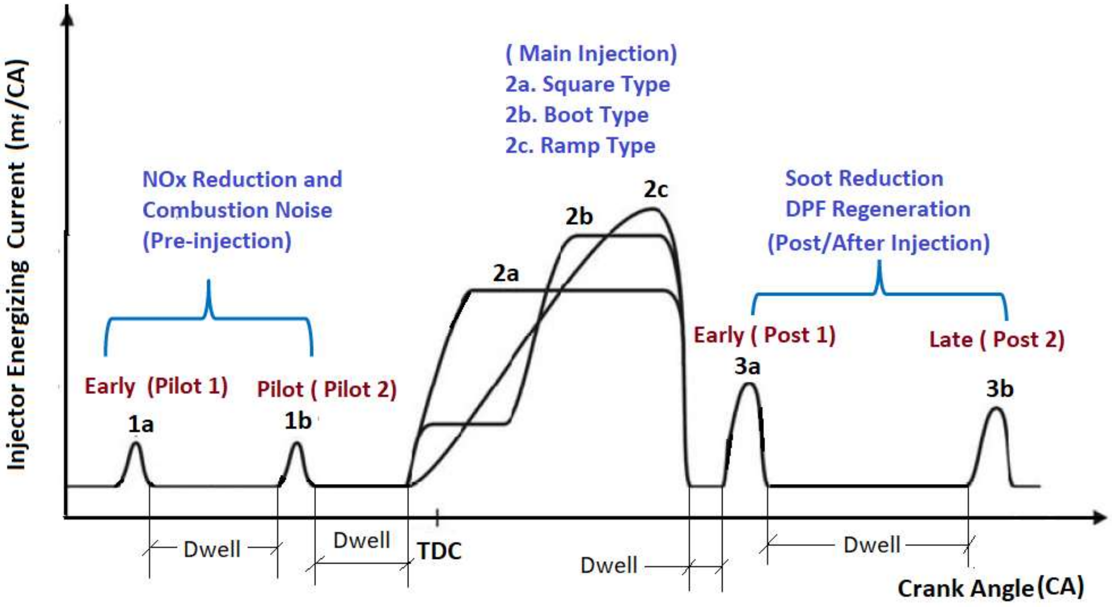


Figure-2.1:- Schematic of multiple /split fuel injections scheme

The multiple fuel injections are nothing but splitting the total injected fuel quantity of each cycle to multiple pulses, to achive better control on the spatial fuel delivery to improve the air usage in the combustion chamber (refer Fig. 2.1). In Multiple injections, mainly three types of injection pulses are there namely a) pre-injections (or pilot injections), b) main injection and c) post/After-injections, as shown in Figure 2.1. According to Badami et al [37], pilot injections are helpful to decrease the combustion noise, while post-injections reduce the soot emissions. It is known that a DI diesel engine combustion process are divided into four phases namely – ingnition delay , pre-mixed burning, diffusion/mixing conrolled combustion and late burning. The multiple injections plays key role in combustion processes which utimately control igintion delay, premixed and diffusion control phases. Lastly, it control the combustion chamber inside heat realease rate (HRR) , combustion pressure, bulk gas temperature. These are the enablers to control BSFC, Torque, emissions and combustion noise. The small quantity of fuel injection much before top dead centre (TDC) is called the early/pilot1 injection. This event happens around 35 to 60 °CA BTDC. On other hand, if a small quanity of fuel is injected just 5 to 25° before main injection event then it is called pilot 2 or pilot or pre injection. Simlary, any injection event after main injection is called the post or after injection which is intended for soot reduction. The double injections configuration may be of pilot-main (pM), early-Main (eM) or Main-after (Ma). Mainly three types of triple injection strategies are feasible namely pilot-main-after (pMa) , early- pilot- Main (epM) and eraly –main –after (eMa) .The quadruple injection stargety can be of two kinds namely early-pilot- main-after (epMa) and pilot -main -after-after (pMaa). A multiple injection strategy can be an effective way to decrease unburned emissions and combustion noise with improved fuel economy. Thus, multiple injection strategy has become a key research area of modern diesel engine and CRDI technology is the enabler.

There have been a number of studies in the domain of combustion optimization of modern diesel engine. It is with different multiple injection strategies [85-97], pilot [49-68] and post [69-79] injection parameter optimization (injection timing , Injection pressure [38-43], injection dwell, fuel quantity, rate shaped [44-48]), alternative fuels [98-103] and EGR - low temperature combustion (LTC) [80-84]; and predictive combustion model with parametric optimization/validation [104-132] with similar objectives. The injection parameter optimization is the sub set of multiple fuel injections. Presently, multiple injections in combination with alternative fuels and EGR-LTC are drawing attention to engine researchers/engineers fraternity. The selective outcomes of above-mentioned researches have been discussed in subsequent paragraphs.

2.1.1: – Effect of Injection Pressure

These researches [38-43] primarily focus on the effect of injection pressure on engine performance and emissions. With the increase of peak fuel injection pressure (FIP), there is significant reduction of PM at rated power [38]. This helps to take a trade-off among NOx –PM. An increase of fuel injection pressure (FIP) may cause an increase of both max power and combustion noise whereas reduction is observed in both BSFC and smoke [39]. Agarwal et al [40] have investigated the impact 3 different FIP (300, 500, 750 bar) and 4 different Start of injection (SOI) timing on particulate volume concentration. They revealed that advanced SOI at high fuel injection pressure, reduce the particulate number concentration as the advanced injection-timing offer extra time for mixing of fuel droplets with adjoining air prior to start of combustion. In another research, they reported that low FIP (among 500 & 1000 bar) with advanced SOI is effective in better BSFC, BTE and emissions (CO2 CO, HC and NOx) except Soot /PM [41].

Fayad [42] experimentally investigated the effects of different injection parameters (timing and pressure) on the combustion, NOx & Smoke emissions , BSFC and BTE at different engine operating conditions. He concluded that increase in the injection pressure and advanced injection timing improve the combustion performance and smoke level though BSFC and NOx level get adversely affected. Higher injection pressure found effective in improvement of IMEP, HC and Soot emission with a penalty of NOx emissions and BSFC level [43]. In addition, increase in Biodiesel content causes higher NOx level than Conventional at any particular injection pressure.

2.1.2:- Effect of Injection Rate shaping

The impact of injection rate shaping on combustion, performance and emissions are being evaluated by this research group [44- 48]. The injection rate shaping is more useful to control combustion noise and NOx emissions as NOx formation highly depends on a) quantity of fuel injected during ignition delay phase b) duration of ignition delay phase and c) the rate of mixture formation within the combustion chamber [7, 12]. Tanabe et al. [44] have recommended a map to define the optimum injection-rate shapes (by pressure-modulation) throughout the engine operating conditions (load & Speed) of a heavy Diesel engine. Injection rate shaping controls the NOx- BSFC trade off irrespective of EGR level. Thus, both EGR and injection-rate shaping can be independently use to control the engine combustion parameter.

Hountalas et al [45] have developed a multi zone Phenomenological model to investigate the effect of different injection rate shaping on BSFC, NO and PM emissions. It revealed that the boot injection rate is the finest at all operating conditions for NO-Soot tradeoff point of view whereas the constant injection rate is worst. Also found boot rate shape is the best at high engine speed and load but mixed up results observed at low engine speed. To obtain the lowest NO emissions boot shape can be used with a penalty of BSFC at high load whereas behaviors are opposite at part load. The ramp rate shape shows in between impact.

The boot injection rates showed the substantial reduction in NOx emissions, which is greater with the increase of boot length or reduce the boot pressure [46]. In contrary, by this process injection time increases which increases the BSFC and dry soot emissions especially at medium load condition. Benajeas et al [47] showed that injection rate shape has significant impact on premixed, diffusion combustion phase, and NOx emission with marginal effect on BSFC subject the strategy of SOI (start of injection) and Injection pressure. They worked with four different injection rate shaping (Squre1, Square 2, Boot and Ramp) along with variation of injection pressure (900 bar, 1100 bar, 1300bar, 1600bar) and SOI. Shuai et al [48] have revealed from a KIVA–CHEMKIN CFD model that an early injection timing (w.r.t TDC) provides lower soot, HC and CO emissions with higher NOx emissions than a late injection timing.

2.1.3: – Effect of Pilot injection and its parameters

Badami et al. [37] found in their work that increasing trend of the particulate emission level with increase of pilot injected fuel quantity at different operating conditions. In an investigation, Zhang L [49] found that pilot injection has key influence on finalization of EGR fraction and reduction of Combustion Noise (CN) at low to medium speed zone. Smoke value plays the major role in trade-off among EGR fraction and combustion noise at higher Load. Ishida et al. [50] studied the impact of pilot injection parameters on emission level of DI diesel engine. They found that the pilot injection reduces the ignition delay of the main injection, which leads to a reduction of peak combustion temperature due to lower burned fuel fraction during the premixed phase. This has huge impact on NOx Emissions. In their research, Durnholz et al. [51] and Minami et al. [52] demonstrated that particulate emissions not influenced with small quantity of pilot fuel injection but deteriorates with an increase in the pilot fuel quantity. Nehmer DA et al [53] have conducted an experimental investigation to understand the effect of rate shaped and split injections on NOx and Soot emissions on a single cylinder version heavy-duty diesel engine at 1600 RPM. They found that rate shaped injection does not affects in-cylinder pressure rise when optimized for lower BSFC. Further, Split injections were found very effective in reduction of NOx emissions without increasing the Soot subject to reduced quantity of first injection.

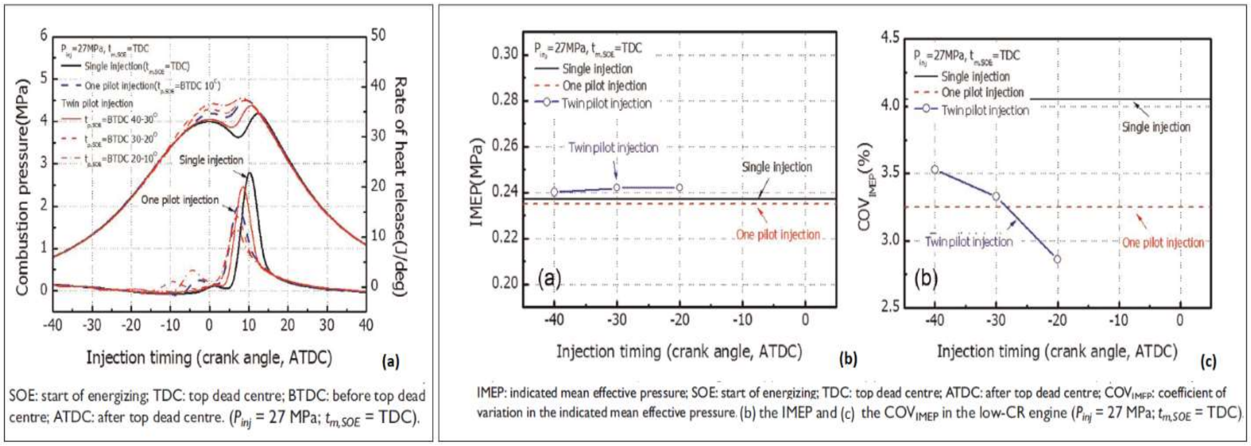
Carlucci et al. [54] investigated the epM strategy in comparison to the traditional pM and eM strategies with various injection parameters at different operating conditions (torque and speed). The study showed that a shorter early injection event coupled with a pilot injection is useful in reduction of both BSFC and emissions, specially the NOx and Particulate matter. The post injection timing and its mass has no such impact on centre of combustion and the peak HRR as it happened at late in the power stroke. It helps to increase the exhaust temperature [55]. The effect of multiple injection (single pilot and double-pilot injection) strategies on emissions were studied by Lee J et al [56] in a HD diesel engine with wide-ranging of injection parameters namely injection quantity ratio, injection timing and injection dwell. Double-pilot injection strategy found superior in reduction of NOx, Smoke and HC emissions by nearly 73%, 84% and 50% respectively, compared to the single-pilot injection due to better premixed mixture formation. Tanaka et al [57] examined the influence of pilot injection and its parameters (fuel quantity and timing) on combustion noise and emissions on an automotive CRDI diesel engine equipped with EGR. The research work concluded that simultaneous reduction of CN (combustion noise and emissions are feasible by reducing the influence of pilot burned gas by means of minimization of quantity and advancement the timing of pilot injection.

Tow et al [58] have reported significant reduction of particulate matter without sacrifice of BSFC by triple than double injections. Also, they found increase in BSFC at high load with dealyed injection timing. Yokta et al [59] showed a reducing trend in NOx emissions by moving from pM (pilot-main) to eM (early-main) to eMa (early-main-afrer) but this method incresaes the PM (Particulate matter) and BSFC. Very advanced early injection w.r.t TDC condition [60], provides a reduction in NOx without a significant rise in particulate emissions though increasing tendency found in BSFC due to very advanced ignition of the lean mixture. In a comparative study between epM and pM/eM, Carlucci et al. [61] found that a short early injection pulse coupled with a pilot injection is very effective in reduction of both fuel consumption and exhaust emissions, mainly the NOx and particulate matter. Among the injection parameter, early injection duration found influential on BSFC. Ghaffarpour et al [62] has investigated the effects of various factors [Ambient Temperature, Injection rate shape %, Injection dwell (ms), Compression ratio, dynamic injection timing (CA ATDC), induction swirl ratio, number of holes, nozzle flow rate] and pilot or split injection on combustion noise at idle, using KIVA model and L18 orthogonal array of Taguchi analysis. They found double pilot is more effective in noise reduction at low loads, speed and idle.

Fang et al [63] studied the impact of pilot injection and EGR on combustion and emissions of HCCI-DI Engine. They reported marginal increase in fuel consumption as pilot fuel quantity and EGR % increases.

Also, Optimal Fuel Quantity and EGR fraction are proposed to achieve lower level of emissions and fuel consumptions.

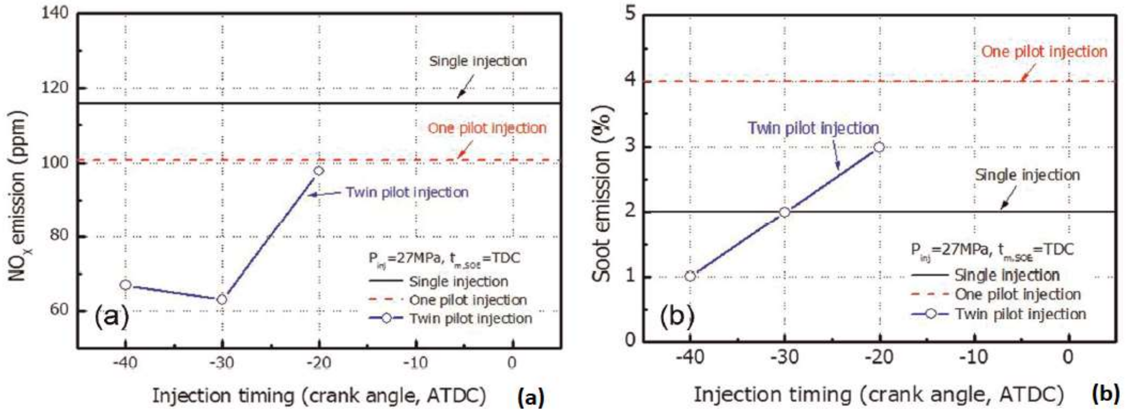
The pilot injection was found as effective to reduce combustion noise as well as emission subject to proper selection injected fuel quantity and its timing w.r.t main injection event. Nearly 3 dB of CN reduction is feasible by using an optimized pilot–main fuel injection strategy over a non-optimized one [65].



SOE: start of energizing; TDC: top dead centre; BTDC: before top dead centre; ATDC: after top dead centre. (P_{inj} = 27 MPa; $t_{m,SOE}$ = TDC).

IMEP: indicated mean effective pressure; SOE: start of energizing; TDC: top dead centre; ATDC: after top dead centre; COV_{IMEP}: coefficient of variation in the indicated mean effective pressure. (b) the IMEP and (c) the COV_{IMEP} in the low-CR engine (P_{inj} = 27 MPa; $t_{m,SOE}$ = TDC).

Figure 2.2:- Effects of the injection strategies in low CR Engine on (a) the combustion performance (b) the IMEP and (c) the COV_{IMEP} [Source 66]



NO_x: nitrogen oxide; SOE: start of energizing; TDC: top dead centre; ATDC: after top dead centre. (P_{inj} = 27 MPa; $t_{m,SOE}$ = TDC).

Figure 2.3:- Effects of the injection strategies in low CR Engine on (a) the NOx emissions (b) the Soot emissions [Source 66]

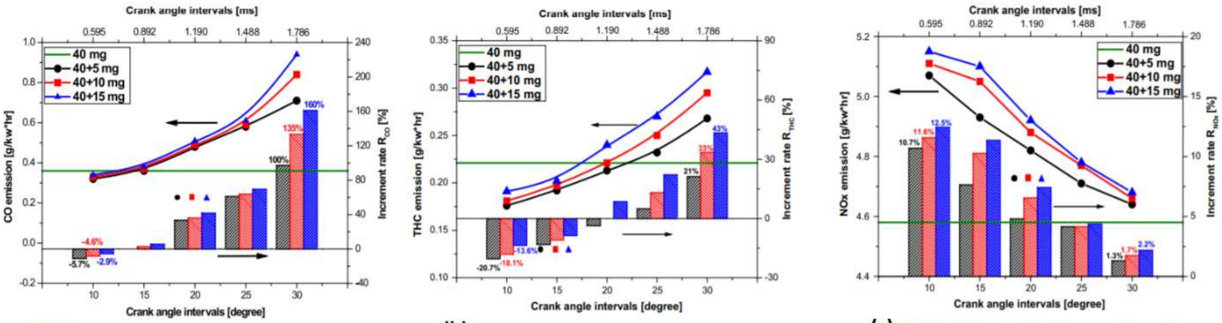
Suh [66] examines the effects of the double pilot injections on emissions and combustion performance on a modified (lowered) compression ratio HSDI engine. The investigation revealed lesser NOx level around 45.7%, whereas soot nearly unchanged with this multiple injection strategy having improved COV_{IMEP} . Similarly D'Ambrosio et al. [67] studied the impact of triple injections comprises of double pilot injection (Pilot-Pilot-Main- ppM) event over a double injection strategy (pM) on Euro5 Diesel engine. The ppM scheduling with high EGR (50%) found effective than baseline PM strategy in reduction in heat release rate, ignition delay, BSFC, combustion noise and both CO and HC emissions at low loads and engine speeds. Also, at medium loads and Speeds, NOx emissions reduced significantly with double pilot injections compared to pM.

In their work, Lee et al [68-69] have investigated the effect of both pilot and post injections on exhaust out emission at different EGR % (Moderate and heavy) on two different diesel engine and established with optimum combination to achieve the optimal emission level.

2.1.4: – Effect of Post injection and its parameters

In the Diesel engine featuring CRDI, post-injection or after injection happens after the main injection, even though the combustion process is still going on. Using post injection helps to re-ignite the soot particles and thus soot emissions reduce around 20-70%. In addition, Tsurushima et al. [70] stated that after-injection reduces THC, CO as well as Soot/PM emission level. This is mainly because of oxidation of unburnt fuel, which remains inside the combustion chamber post completion of main injection. Yun H et al [71] reported that Post injections is very beneficial to decrease soot emissions in LTC regimes by means of facilitating the late cycle mixing though determination of dwell time found important. In another work, they [72] have experimentally studied the influence of late-cycle mixing improvement on engine combustion and emissions in the low-temperature combustion (LTC) regime, using post-injection schemes. They have reported significant drop of soot without deterioration of NOx with post injection and relation with dwell time.

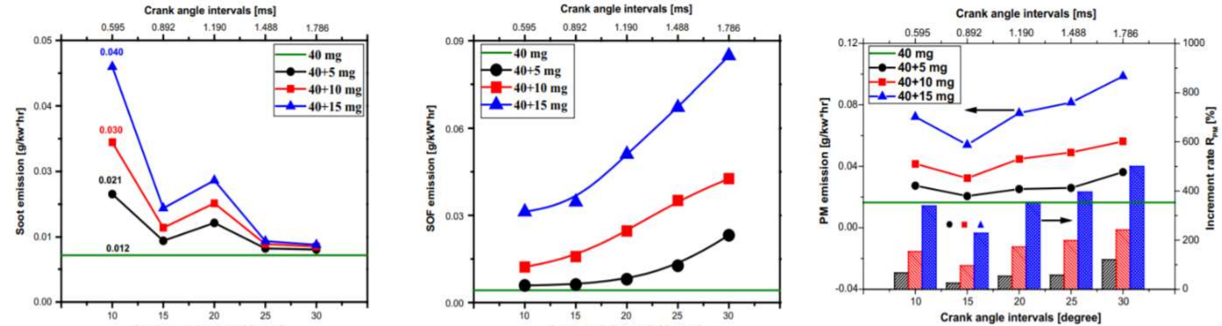
O'Connor et al [73-76] have worked on post injection strategy with different operating conditions to understand the effectiveness on soot reduction using optically accessible engine. Their first work [73] gives an overview on the efficacy of post-injections for soot reduction as a function of engine operational parameters including injection duration and dwell, exhaust-gas recirculation, load, boost, speed, swirl, and spray targeting. In another investigation [76], they have explored the role of load variation on effect of post injection for soot reduction at four different intake oxygen levels with fixed SOI of both main and post injection; compared with single injection.



(a) Effect of post injection on CO emission and corresponding increment rate.

(b) Effect of post injection on THC emission and corresponding increment rate.

(c) Effect of post injection on NOx emission and corresponding increment rate.



(d). Effect of post injection on soot emission

(e). Effect of post injection on SOF emission.

(f). Effect of post injection on PM emission and corresponding increment rate.

Figure 2.4:- Effect of post injection on (a) CO (b) THC (c) NOx (d) Soot (e) SOF and (f) PM emission [Source 77]

Liu et al [77] have reported an increasing trend of CO and THC emissions whereas NOx emission significantly reduces with delays post injection interval. On the other hand, closed post injection is beneficial for SOF and PM emission though Soot level increases. Poorghasemi et al [78] have investigated the effect of injection pressure with post injection for trade-off among soot and NO emissions. The multiple injection strategy with variable Pressure allows increasing the net soot level while NO formation well within the control. It reduces heat release rate to control NO formation and provides sufficient time for soot oxidation at high level. Hardalupas et al [79] has reported that a post-injection pattern close to the main combustion phase can be reduced the soot emissions and improve the engine performance like IMEP at same fuel consumption rates, though it could rise engine noise level.

2.1.5: – EGR LTC with multiple injections

Yin et al [80] have optimized the injection parameters (injection Pressure, Pilot fuel quantity, Pilot injection timing and SOI Timing) and EGR fraction (0-50%) on a typical four-cylinder diesel engine at 1600 RPM and IMEP of 1 bar and 3bar for trade-off emissions without negotiation of fuel economy. They reported simultaneous decrease in NOx and Soot by multi-parameter combined optimization (high EGR and late injection timing) though BSFC increase.

The influence of split injection strategies examined using a hybrid surrogate fuel CFD model and validation, to improve CN and HC and CO emissions under LTC conditions [81]. They have reported the importance of 1st and 2nd pulse in triple injection for controlling ignition delay and increase fuel quantity of 1st pulse help in reduction of HC and CO like NOx and Noise. According to Lie et al [82], incorrect injection timing leads to deterioration the performance of LTC. Whereas, optimize SOI main injection pulse of multi-stage injection strategy is effective in control of combustion phases which help to achieve better fuel economy and lower emissions. Asad et al reported [83] that variations in intake boost pressure, EGR rate and its temperature, engine speed, injection pressure and timing are found to have deep impacts on the operability limits, combustion stability and performances of diesel LTC. According to Krishnasamy et al [84], LTC strategies are evolving as one of most promising choice to meet further stringent engine (automotive) emission norms, along with both complexity and achieving fuel flexibility for a sustainable future.

2.1.6 –Effect of multiple injection strategies on emissions, performance and combustion noise

Effect of multiple injections on performance, combustion and emissions, are explored by a big research group [85-97] worldwide. Some of these studies done in combination with EGR.

In a comprehensive study, Chen [85] found that multiple injections featuring pilot and post injection pulse in combination with higher EGR (~30%) are very effective in trade-off between NOx and Smoke. In addition, small pilot fuel quantity found beneficial in terms of NOx reduction whereas significant reduction of particulate matters achievable using post injection vide improve oxidation rate due to increase in Bulk temperature inside the cylinder, subject to optimum timing of injection event. Pierpont et al. [86] have examined the combined effect of EGR and multiple injection strategies with two different injector nozzle spray angle on emissions and performance of a single cylinder DI diesel engine. NOx and PM reduce simultaneously with combined application of EGR and multiple injections with sacrifice of BSFC due to timing retard. Badami et al. [87] studied the effect of one Double (pM) and two Triple (pMa, epM) injections strategies on performance and emissions on typical CRDI diesel engine. The epM strategy found very influential in decrease of BSFC and combustion noise w.r.t the pM strategy with increase in emissions. In other hand, pMa strategy is effective largely to decrease the soot level with carefully selection of injection timing. In a numerical investigation using multi-dimensional computational code, Uludogan et al [88] revealed that use multiple injections is beneficial in DI diesel engine, to increase engine power density and to reduce the particulate and NOx emissions significantly.

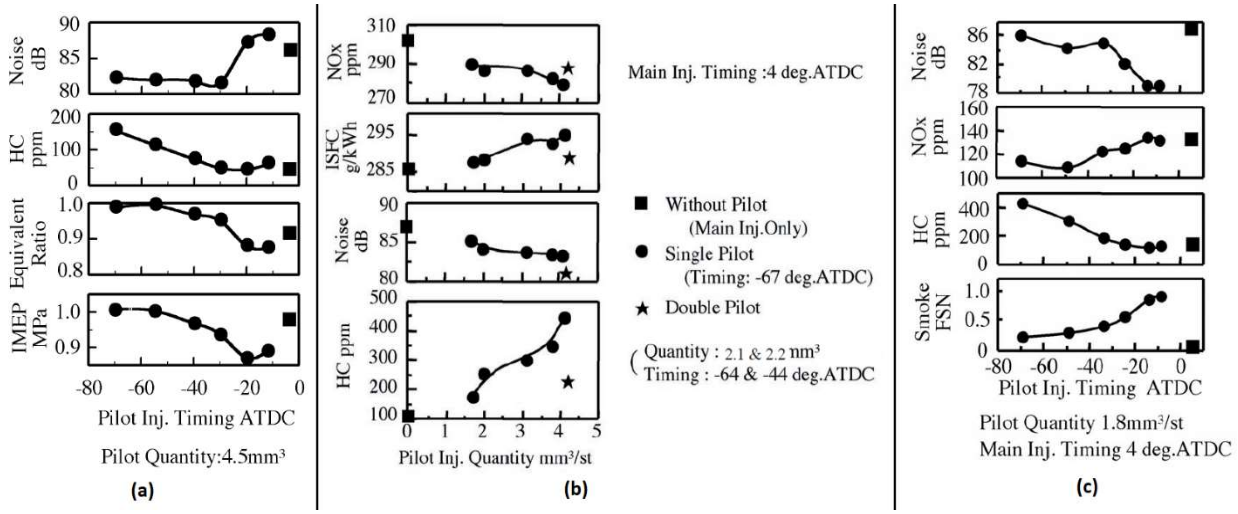
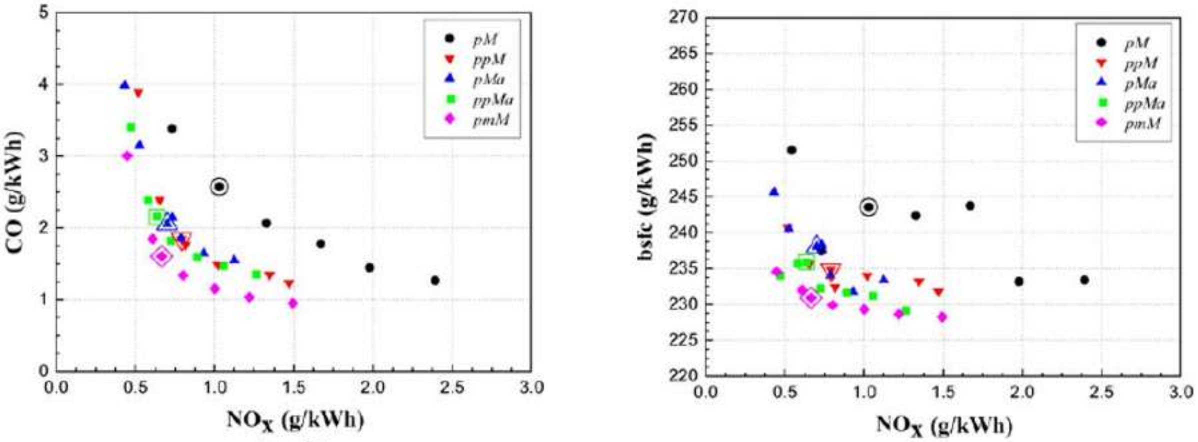


Figure 2.5:- Effect of pilot injection parameters on emissions and noise at (a) full load, (b) medium and (c) light load [89]

Hotta Y et al [89] have stuided the impact of multiple injections at high , medium and light load with different injection timing, dwell and fuel quantity on small HSDI engine . They reported that at lighter load, smaller quantity of pilot fuel with closer injection timing w.r.t main injection is effective. Different injection paramters are propsed for different loads [refer Fig. 2.5]. Mendez et al [90] have established through experimentation on a low Compression Ratio (CR) diesel engine that multiple injections strategies (Double , triple and quadruple) are beneficial in combination with high rate of EGR (46%) to enhance the emission level, combustion noise (CN) and trade-off of fuel efficiency; with acceptable amount of ignition delay.

Mohan et al [91] discussed about the influence of various fuel, injection parameters and injection strategies on engine performance, combustion noise and emissions in review article. The article suggested wisely selection of injection strategy to trade-off between emissions and performance. In another review article Rahman et al [92] has reported the importance of Fuel injection timing on the performance (Brake thermal efficiency {BTE}, BSFC) and emissions (HC, CO, NOx). The retarding injection time found favourable for NOx reduction due to low temperature and pressure inside the combustion chamber at a cost of low BTE and high BSFC due to incomplete combustion as well as high HC and CO.

D'Ambrosio et al. [93] concluded from a comprehensive evaluation of different multiple injection strategies that pilot–pilot-main-after (ppMa) strategy has the potentiality to decrease the combustion noise (CN) and NOx with increase in soot while BSFC remain unchanged compared to baseline pM strategy and both the triple injection strategies [pilot-main-after (pMa) and pilot–pilot-main (ppM)]. From their experimental research, Sindhu et al [94] have concluded that Split injections is superior in controlling the NOx emission level in comparison to increase of EGR percentage and retardation of injection timing without an excessive penalization of engine performance. Chong et al [95] have shown that 60-40 split main injection ratio is more beneficial to achieve lowest soot reduction on a single cylinder light duty diesel engine by developing a three-dimensional combustion model.



(a) CO

(b) bsfc

Figure 2.6:- Effect CO vs NOx (a) and bsfc vs NOx (b) for the pM, ppM, pMa, ppMa and pmM injection strategies, at 1500 ×5 [96].

In another work, D’Ambrosio et al [96] have concluded that significant CN can obtained with both double pilot and boot shaped main injection at lower loads. DoE based optimize triple and quadruple injection strategies enriched soot-NOx trade-offs in reference to pM strategy (calibration). To achieve the best trade-off of NOx and soot [97], compared to the single injection, for the three multiple injections, the lowest soot emissions found at post-injection proportion of 15% and post-injection timing range of 25, 30, and 35 CA ATDC, with NOx reductions of 5.88%, 21.2%, 40.3%, and soot reductions of 26.7%, 34.5%, , 112.8% respectively, for 1main+ 1post, 2main+ 1post, and 3main+ 1post injections.

2.2.7: –Effect of alternative fuels along with multiple injections and EGR

Influence of alternative fuel on performance, combustion and emissions, are explored by a researcher team [98-103] with variation of injection parameters or injection strategies. Also, combustion models are validated in few of researches.

Mohanraj et al [98] have shown that combined use of EGR and delayed injection timing on diesel engine, using distilled waste plastic oil blend (D1WPO30) reduced the emissions (NOx, THC and CO) from 8 to 16% in comparison to the standard operations. Use of B50 Bio-diesel in combination with retarded SOI timing with Triple injection scheme is effective way to simultaneously reduction of NOx and Smoke over baseline level diesel fuel [99]. Babu et al [100] have revealed experimentally that an increase in pilot injection timing caues a reduction in the in-cylinder pressure, whereas soot and NOx emissions decrease proporsionally . simarly increse in pilot injection fuel quantity caues increase of the in-cylinder pressure and NOx emission, whereas soot emission decreases. Simultaneous NOx and smoke emission reduction over baseline level of pure diesel fuel can be acheviable using B50 in combinantion with retarded SOI timing and deployment of triple injection scheme [101].

Chako et al [102] stuided the influence of B20 fuel in combination with multiple injections on performance and emissions characteristic by developing a phenomenological combustion and emission models. The multiple injections help to mitigate the NOx emissions with B20 fuel to the level of Diesel fuel. Pilot fuel quantity, Injection dwell between pilot and main and dwell among Main and post injection found as the key parameters to achieve desired NOx and soot emission level.
Qi et al [103] have investigated the effect of EGR fraction (10% and 20%) on the emission, performance, and combustion characteristics of CRDI diesel engine with double injection strategy (pM), using diesel fuel (D100) and ternary blends consisting of diesel, palm oil and ethanol by volume. The Ternary blends found effective to achive better BTE (Sligtly) , redcue large size particulate concentation and Soot/NOx trade off with suitable EGR % in comprision of pure diesel

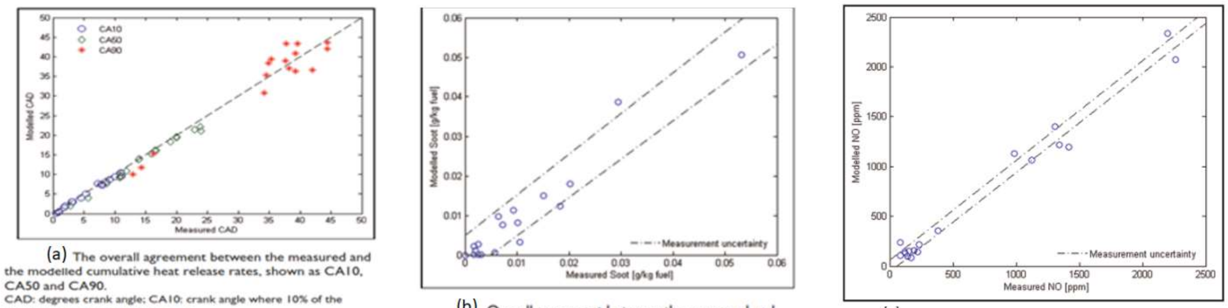
2.2.8 – Predictive combustion model for multiple injections and its parametric evaluation

A large group of reserch team [104-132] from across the world, are focusing on development of predictive combustion and emissions models (refer section 2.2.1.2 and Fig 2.9) for diesel engine over 4 decades. This is to help in development acitvites through parametric optimization at digital level and get desired out come with minimimization of physcial part develepment and time. Those are sarting from simple 0-D thermodynic models [104-111] for heat release rate, then 1-D Quasidimensioanl or phemenomenolgical [112-127] to complex 3D CFD models [128-132] for both in-cylinder and emission characteristics. All these selective reaserches are concisely discussed in this sub-section.

Modifed correlation based on simple relation between Nu and Re, to predict the gas side heat tranfer coefficent has been worked out by Finol et al [104]. It shows good predctivity of instantaneous coefficent acress the operating cycle of high Disesel engine.

Xue and Caton [105] have developed a six zone thermodynamic simulation for the DI diesel engine combustion process for predicting heterogeneous-type combustion systems, the formation of pre-ignition radicals, start of combustion (SOC), and eventual HRR (including oxidation of incomplete combustion products). It is predicted based on the conceptual model of Dec [136]. Six zones consists of the surrounding bulk gas, liquid-phase fuel, vapor-phase fuel, pre-ignition mixing, fuel-rich combustion products, as well as the diffusion combustion products. The model found capable to predict high EGR condition as well.

In another work [106], they have developed a 3 step phenomenological NOx and soot model for DI diesel engine. The soot model continents fuel pyrolysis, soot inception and soot oxidation. Whereas Nox model is based on Zelodovich –Thermal and N20 mechanism. The reported that advanced injection time and high injection pressure is not favourable for NOx emissions though this condition suitable soot reduction. Westlund et al [107] has developed a simplified one-dimensional model for combustion and emission formation in diesel engines to predict heat release rate, the emissions (soot and NO) during transient operation. The model is based on an earlier presented model which was evaluated for steady state conditions. This inexpensive and comprehensive model is developed founded on a correlation for the air entrainment rate, which is applicable to a discretized injection. In this model, the combustion rate and the emission formation rate are executed with simple models. It is validated for the targeted conditions and transient operation. The model was able to predict the heat release rate and the emissions of nitrogen oxide (NO) and soot with reasonable accuracy and also the requirement regarding the computational time was met. The main discrepancies of heat release rate are found in the last part, after the end of injection (refer Fig. 2.7).



(a) The overall agreement between the measured and the modelled cumulative heat release rates, shown as CA10, CA50 and CA90.
CAD: degrees crank angle; CA10: crank angle where 10% of the cumulative heat released is reached;

(b) Overall agreement between the measured and modelled soot emissions for the selected engine cycles.

(c) Overall agreement between the measured and modelled NO emissions for the selected engine cycles.

Figure 2.7:- The overall agreement between the measured and modelled (a) heat release rate, (b) soot emissions and (c) NO emissions for the selected engine cycles with measurement uncertainty [107]

Rao and Honnery [108,109] have worked two different thermodynamics models for prediction of NOx and Soot emissions. The first work is based on the extended Zeldovich model and Mellor model for NOx formation prediction. The other work [109] is related to integrated nine-step soot model into a phenomenological diesel engine. Finesso et al [111] have developed a real-time zero-dimensional diagnostic combustion model and assessed to evaluate in-cylinder temperatures, HRR (heat release rate) and NOx in DI diesel engine under steady state and transient conditions. The approach required very little computational time and hence, it is suitable for real-time applications. This three-zone thermodynamic model can applicable for post-processing analysis of earlier acquired Test data. Here, the combustion chamber is divided into a fuel zone, an unburned gas zone and a stoichiometric burned gas zone, where applied the energy and mass conservation equations. The key novelty of this model is that the equations can be resolved in closed form, which makes the approach suitable for real-time applications. Evaluating the temperature of burned gases, in-cylinder NOx concentration value calculated based on Zeldovich thermal mechanisms. The NOx level in the intake charge are also considered in this method. Therefore, it is suitable for engines equipped with traditional short-route EGR and long-route EGR systems and also for the engines equipped with SCR (Selective Catalytic Reduction). Karaky, H et al [111] has developed a new zero-dimensional, semi-physical, NOx prediction model based on a high frequency combustion model (Barba's approach) coupled with a thermodynamic calculation of the temperature (adiabatic flame temperature) in the burned gas products from a stoichiometric mixture. The model was validated over a wide range of operating conditions on typical Euro 5 diesel engine. The simulation results proved that it can predict the multiple effects of exhaust gas recirculation and different injection parameters for both single and multi-injection cases. The model offers the necessary trade-off among predictability (pure physical models) and simplicity (empirical models).

Dent and Mehta [112] and Hiroyasu et al. [113] established that the spray structure offered the evidence to have better heat release predictions. The injected fuel spary devided in to mulitiple small packages. The 2D axisymmetric spray calculations are tried considering the mixing of the injected fuel with the surrounding air entrained because of high shear velocity of the jet . Salem et al [114] have developed a multizone model to simulate the combustion process in a quiescent chamber diesel engine. The model divided the cylinder charge in to unburnt zone (surrounding air) and burnt zone (fuel spray with entrained air) whch is furrther subdivided into 16 concentric spray zone and each zone has its own temperature and composition. Among the considered paramaters, injection pressure and injector hole diamter found more infulencial in NOx emission and out put power. There is an improvement of engine power without any noticable detoration of NOx level with increase of injection pressure and injector hole diamater. Barba et al [115] has developed a single-zone phenomenological combustion model for high speed CRDI diesel engine consisting of pilot and main injection and focused on combustion noise oand NO-emission. Thus, the ignition delay , the premixed combustion and the mixing-controlled combustion phases are main parts of it. Developing a multi zone phenomenological model for predict soot and NOx emission of DI diesel engine, Gao et al [116] has concluded that an enrich oxygen of intake air is not viable to reduce soot emission as it increases NOx significantly. The model consists of a spray model, an evaporation model, a heat release model, and soot and NOx formation models. The volume of air for the process is time-dependent which is determined by the piston and cylinder geometry, while the total air mass remains unchanged. The basic concept of this model is the division of the injected spray into small packets (or multiple zones) in the radial and axial directions.

In their work , Jung et al [117] has developed a quasi-dimensional, multi-zone, direct injection diesel spray combustion model and implemented in a full cycle simulation of a turbocharged engine for the purpose of predicting engine performance and NO and soot emissions. The model accounts for transient fuel spray evolution, fuel-air mixing, ignition, combustion and NO and soot pollutant formation. In this model, the fuel spray divided into a number of zones, which are considered as open systems. In other hand, mass and energy equations are solved for each zone and a simplified momentum conservation equation is used to compute the amount of air entrained into each zone. The model found effective to predict the rate of heat release and engine performance with high reliability whereas enhancement required in predictive model for NO and soot emission.

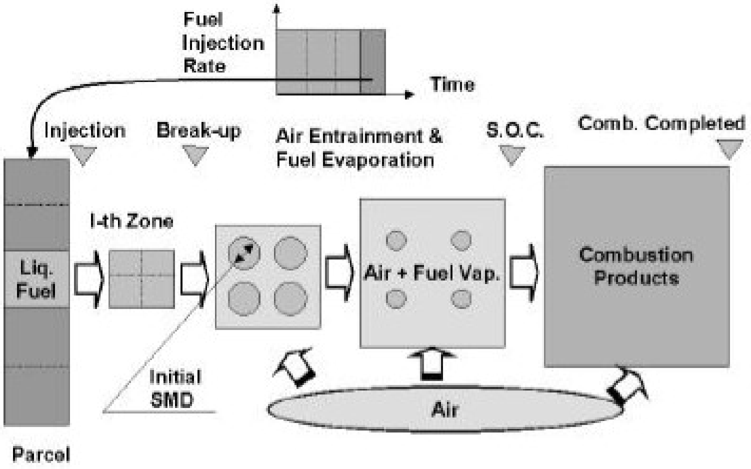
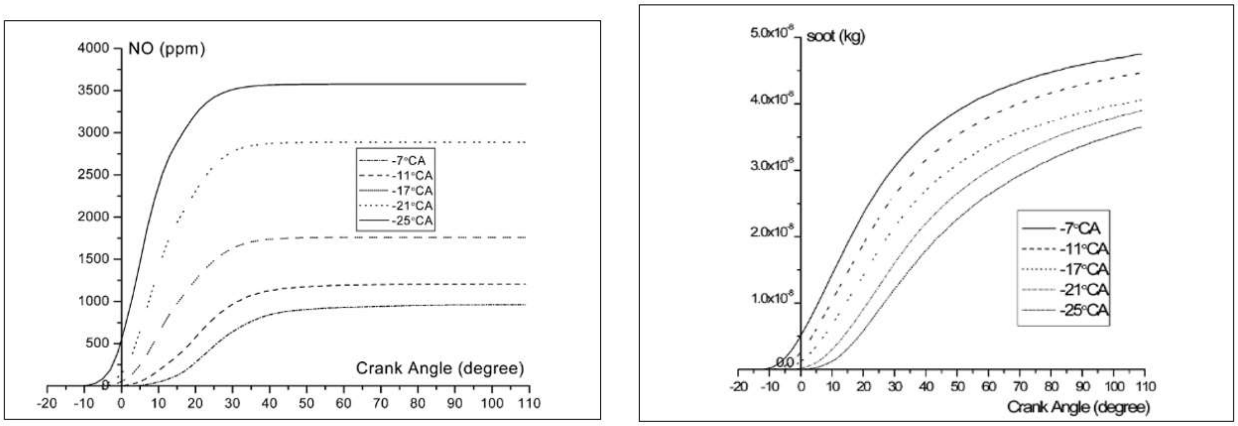


Figure 2.8:- Development of fuel parcels and zones within the parcels in multi-zone model [117]

From a comprehensive quasi-dimensional multi-zone Combustion model, Zhou [118] has concluded that major part NO generated between crank angles of 7° and 30° after top dead center where corresponding temperature in the cylinder is at its highest. On other, advancement of the injection timing, cause lesser soot generation. This is due to higher premixed burning leads to higher temperature with advanced injection timing resulting a high NO concentration but a low soot concentration.

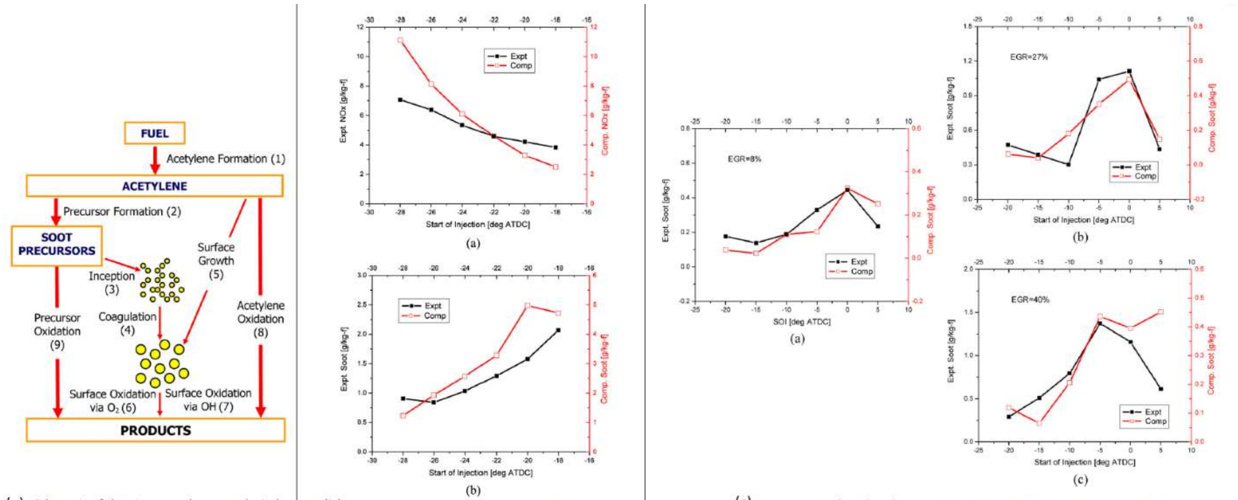


(a) Concentration of NO with different injection timings

(b)· Soot generation with different injection timings

Figure 2.9:- (a) Concentration of NO with different injection timings (b) soot generation with different injection timings [Source 118]

Cerri, T et al [119] has developed 1D multi-zone quasi-dimensional combustion model, tailored for multi-jet DI diesel engine and satisfactory agreement found between the predicted results and experimental data of soot and NO emissions at full load. The a two zone model of a direct injection (DI) Diesel engine by Rakopoulos et al [120] splits the cylinder contents into a non-burning zone of air and another homogeneous zone in which fuel is continuously supplied from the injector and burned with entrained air from the air zone. The model is then validated against the performance and emissions data results from an extended experimental investigation and found very effective in prediction the engine performance and exhaust emissions, specifically at varaition of load and injection timing. Tao F el al [121] have developed a nine-step phenomenological soot model and implemented into the KIVA-3V code for predicting soot formation and oxidation processes in diesel engines and validated the same on heavy and light duty diesel engine. The soot model found sound in prediction of soot specially at lower EGR.



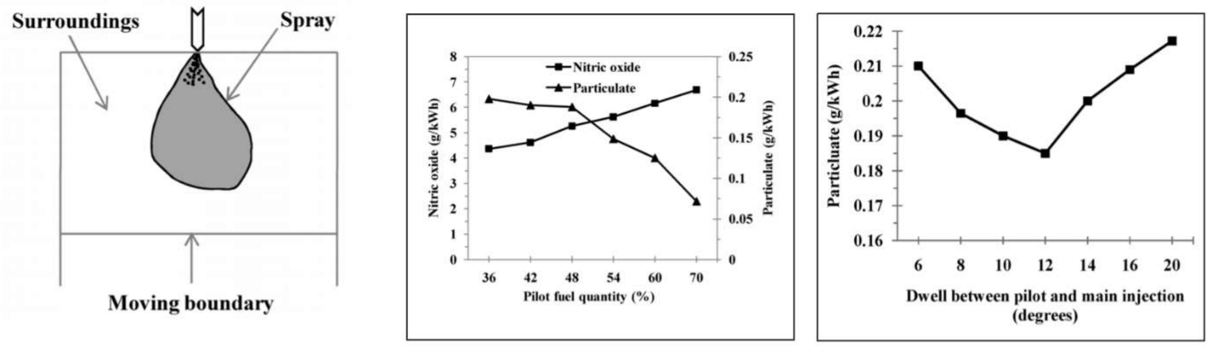
(a). Schematic of the nine-step phenomenological diesel soot model.

(b). Comparison of predicted engine-out and measured emissions for light-duty diesel engine: (a) NOx and (b) soot.

(c). Comparison of predicted engine-out soot and measured soot emissions for Caterpillar heavy-duty diesel engine: (a) 8% EGR; (b) 27% EGR; (c) 40% EGR.

Figure 2.10:- (a) schematic of nine-step phenomenological soot model (b) Comparison of predicted engine-out and measured emissions for light-duty diesel engine (c) Comparison of predicted engine-out soot and measured soot emissions for Caterpillar heavy-duty diesel engine [Source 121]

Rajkumar et al. [122] have developed a two-zone phenomenological model cosisting on fuel-air spray and surrounding for modern diesel engine to predict the emissions and combustion characteristics of single and Multiple injections (double and Triple). They conveyed the simultaneous decrease in smoke and NOx with rise of pilot fuel quantity and an optimize dwell between the main and pilot injection (Fig.2.11). In another work [123] with two zone models and paramteric investigation , they reported that optimum quanity of pilot fuel will reduce NOx emission where as optimize post fuel quanity and its dwell w.r.t main injection pluse will help in reduction of soot (Fig 2.12) . Further Rajkumar and Sudarshan [124] have developed a multizone phenomenological model (spary zone with different parcels) for predicting combustion and emission characteristics of CRDI engine having split and multiple injections. The model shows better predictive capablity with the conclustion that both pilot fuel quanity and its dwell are imporatant to achevie simultaneous reduction of NOx and soot emission [Fig.2.13].

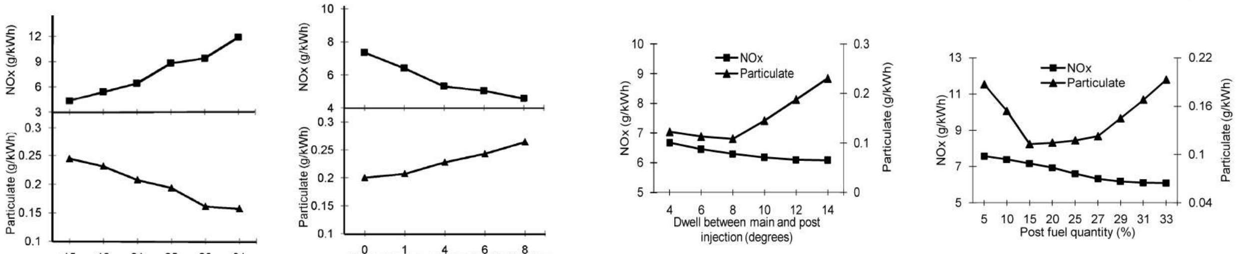


(a) Schematic of two-zone modeling.

(b) Effect of pilot fuel quantity on emissions.

(c). Effect of dwell between pilot and main injection on soot particulate emission.

Figure 2.11 :- (a) Schematic of two –zone modelling (b) Effect of pilot fuel quantity on emissions (NOx & PM) (c) Effect of dwell between Pilot and main injection on soot particulate emission [Source 122]



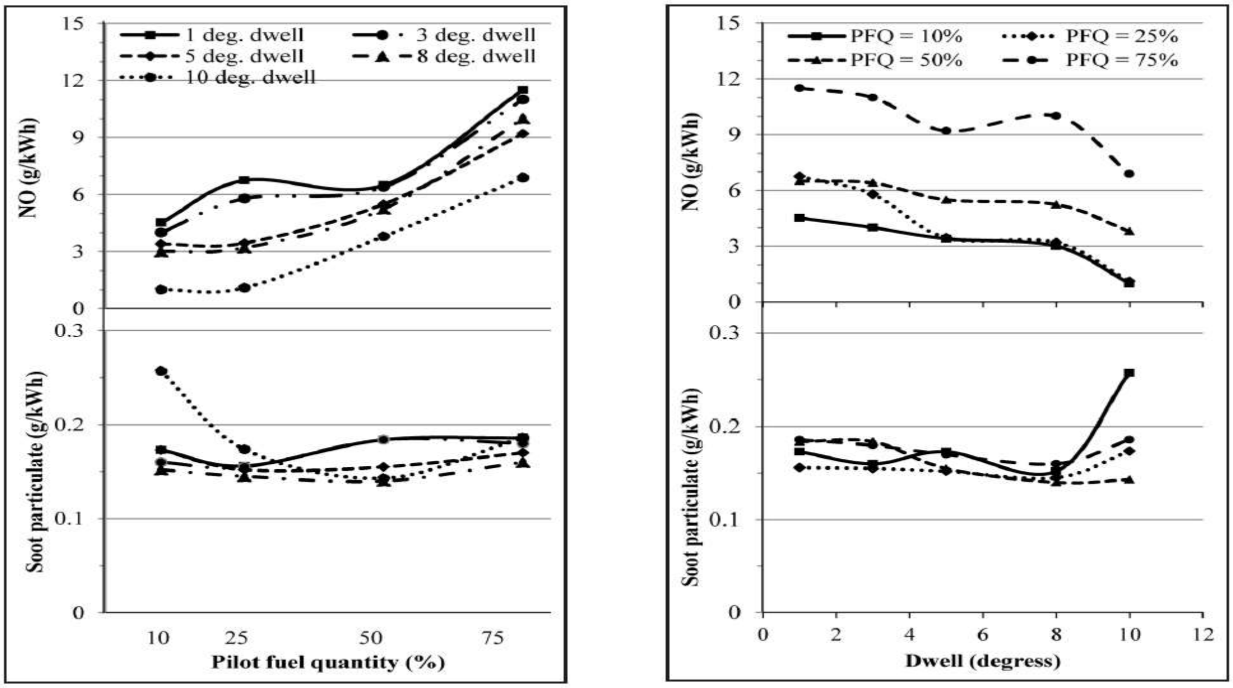
(a) Effect of pilot fuel quantity

(b) Effect of dwell between pilot and main injection

(c) Effect of dwell between main and post injection (post fuel quantity = 29%)

(d) Effect of post fuel quantity (dwell between main and post injection = 10 deg. CA)

Figure 2.12:- (a) Effect of pilot fuel quantity on emissions (b) Effect of dwell between Pilot and main injection (c) Effect of dwell between main and post injection (d) Effect of post fuel quantity [Source 123]



(a) Effect of the pilot fuel quantity on the NO emissions and the soot emissions.

(b) Effect of the dwell on the NO emissions and the soot emissions. PFQ: pilot fuel quantity.

Figure 2.13:- (a) Effect of pilot fuel quantity on the NO emissions and the soot emissions (b) Effect of the dwell on the NO emissions and soot emissions [124]

Finesso et al [125] has carried out an investigation on the spray penetration and soot formation processes in a research diesel engine using a quasi-dimensional multi-zone combustion model. The model integrates a predictive non stationary 1D spray model with a diagnostic multi-zone thermodynamic model. It is capable of predict the spray formation, combustion and soot formation processes in the combustion chamber. A new quasi-dimensional combustion model proposed by Zhang et al [126] with two-phase penetration and combustion phenomenon in diesel spray, which is capable for prediction of DI engine performance at different speeds, loads, and injection pressure and timing. Xu et al [127] have developed the multizone quasi dimensional model with modifed spray tip penetration submodel based on Hiroyasu concept [113] considering injection pressure and EGR. They modifed the ignition delay correlation to capture the effect of reduced oxygen concentration in engines with EGR. The model shows good agreement with meased data.

From an experimental and computitional study on diesel engine , Venkatesan et al [128] have reported that soot and NO can be simultaneously decrease with declining the air temperatures inside the combution chamber. De risi et al [129] has developed a modificed KIVA3V code for simulation DI engine and verified with experimental data over wide range of operating conditions comprising of single injection, pilot injections and EGR. Hasse et al [130] have concluded from the extednded flamlet model of multiple injection that main injection does not auto-ignite but ignition happned when strained premixed flame from the pilot injection propagate to the mixture field of the main injection.

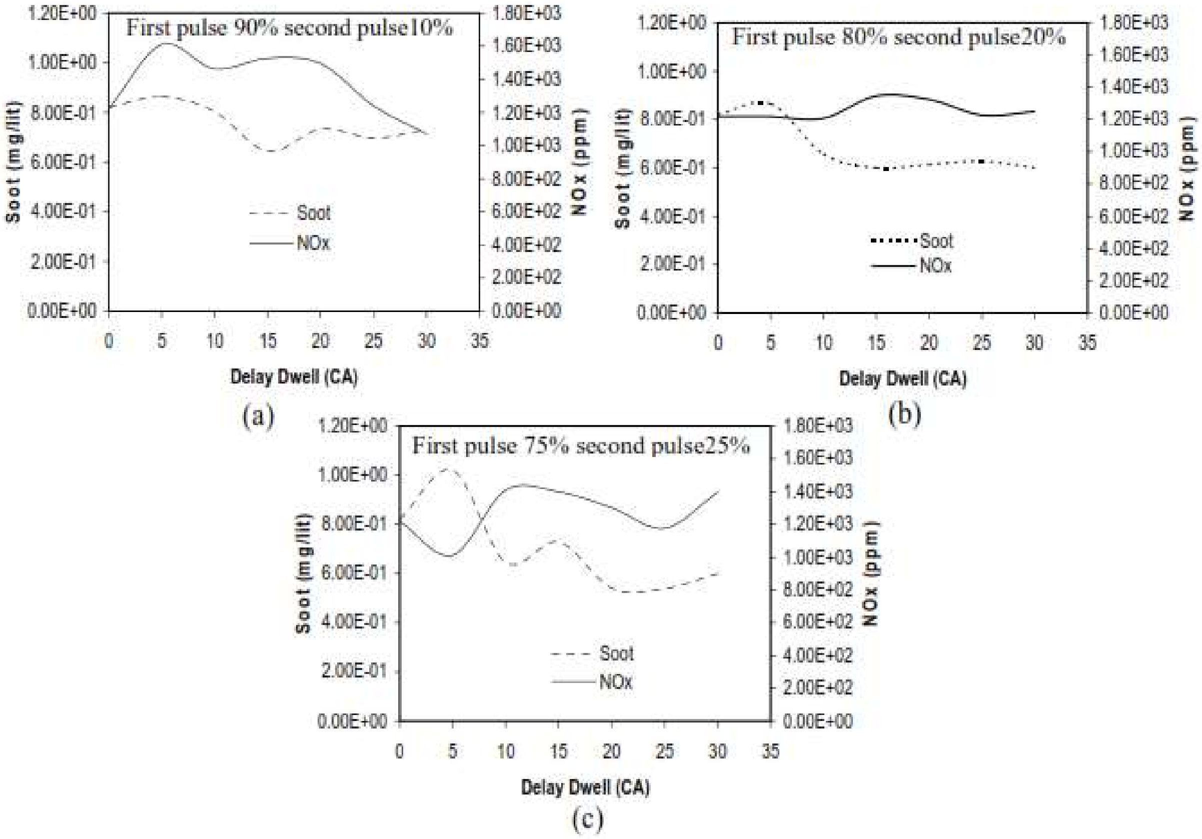


Figure 2.14:- Influence of injection pulse and delay dwell on soot and NOx emissions (a) First pule 90% second pulse10% (b) First pule 80% second pulse20% and (c) First pule 75% second pulse25% [Source 131]

Jafarmadar. S et al [131] have investigated the effect of three different split injections (including injection parameters – timing, dwell, and fuel quantity) on combustion and emissions level of a DI diesel engine under full-load using the multi-dimensional CFD code AVL-FIRE. They reported that second pulse of 25% of total fuel, reduces the soot and NOx emissions level effectively in DI diesel engine. Furthermore, the optimum delay dwell among the pulses is about 25˚CA (refer Fig 2.14).

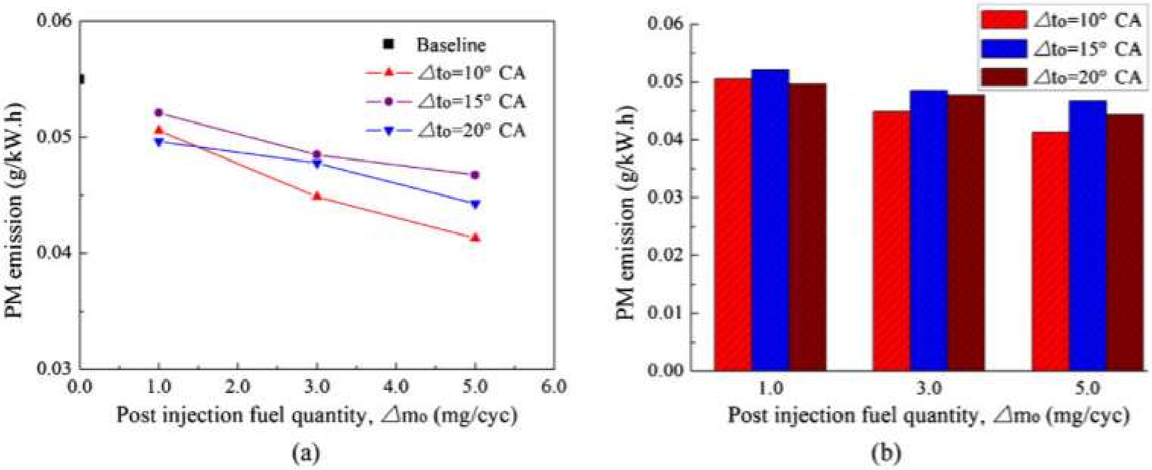


Figure 2.15:- Effect of the post-injection on soot emission: (a) variation in the post-injection fuel quantity; (b) variation in the main-injection–post-injection interval [132]

Shi et al [132] have developed Soot model for post injection and then integrated the same with CFD code to simulate the combustion process and pollution formation. They reported that a post injection enriched the soot oxidation process by increased level of turbulence. It has the strong potential to reduced soot and thus has the possibility to meet the strict emission regulation.

2.2:- The research Gap Analysis

The preceding section presents the selective key researches in the domain of Direct injection Compression engine with different injection strategies, Injection parameters, alternative fuels, EGR- LTC and predictive combustion models mainly to reduce emissions and improve performance. Many of them were in combination with EGR and multiple injection Strategies to achieve the same. It also revealed that adoption of multiple injections along with suitable EGR rate [i.e.- Low (<30%) or Medium (>30%- <45%) or High (>45% - <60%) or Heavy(>60%)] on the basis engine size/configuration appears to be an encouraging technique to take care of Thermal efficiency, Performance (BSFC or fuel economy) and emissions to meet the regulatory norms. Adoptation of EGR specially high or heavy percentage allows to achive low teamperature combustion (LTC) condition. However, all these researches give limited insights on quadruple injections strategy consisting of double pilots (early and pilot or ep) and one-post injection pulse in combination with high EGR-LTC on diesel engine. This is one of key research gap as per the literature review. The other research gaps are as follows-

a) Lack of comprehensive study on the impact of quadruple injection strategy(epMa) at wide operating conditions (Engine speeds and Loads) on multicylinder CRDI diesel engine with EGR.

b) Comprehensive results covering both rig level (like BSFC, Torque, Combustion noise) and vehicle level meaurement (like Fuel economy/CFSC , Pass by Noise (PBN)) are missing. Real time evalution (i.e- on actual vehicle) is not found.

c) Available researches have not covered the comparison of quadruple injection strategy (epMa) with single and double and triple injection at same operating and injection parameter (like SOI Main, total injected fuel quantity/cycle) condition.

d) Available studies have not shown the comparative eavalution of the quadruple injection strategy (epMa) and latest triple injections at same operating and injection parameter

e) Sufficent evidences are missing for Quadruple injections (epMa) in combination with EGR with variation of injection parameters (injection timing (for early, pilot and Main) , injection timing dwell)

f) Predictive combustion and emission models are not available for Quadrauple injections with twin pilots/pre-injections (ep) in association with EGR

2.3:- The Research objectives

The available literatures indicated that the multiple injection strategy and High –EGR LTC are two promising techniques. These are complementary to each other to eliminate drawbacks of each other and to achieve the goal of simultaneous reduction of NOx and Soot/PM with improvement in BSFC performance and reduced CN of CRDI diesel engine. These are summarized in pictorial form in Figure 2.16. EGR technology works on the principle of reduction of the flame temperature and O2 concentration in inside the combustion chamber. Thus, NOx reduces as the EGR rate increases, along with decrease in soot oxidation due to the lowered local burnt gas temperature. Hence, the LTC concept has become very attractive for both NOx and soot emissions but it produces high combustion noise and CO and HC emissions with lower fuel economy. For simultaneous reduction of emissions and combustion noise without any penalty on BSFC value by adopting suitable high EGR fraction LTC with multiple injections become an attractive method. Among the multiple injections, the quadruple injection strategy (epMa) is most recent for diesel engine

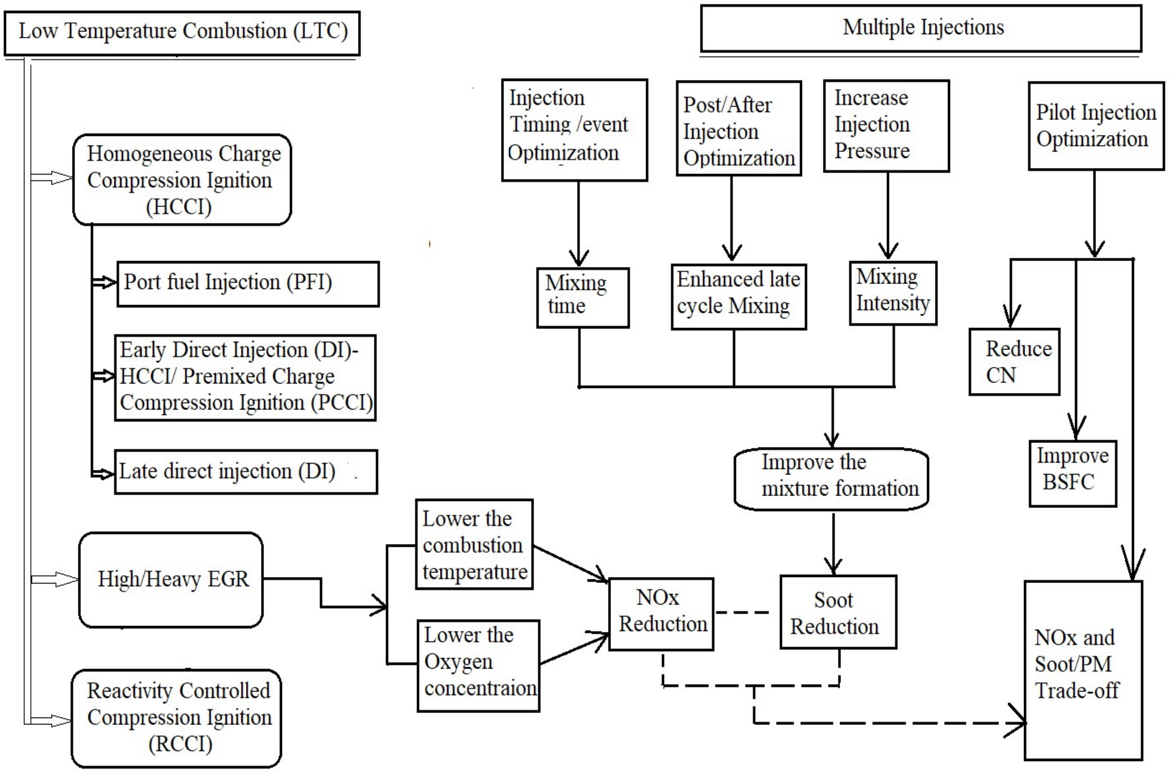


Figure 2.16:- Diesel engine Low temaperature combustion (LTC) and Multiple Injections link

In view of the research gap analysis, the present reserach predominantly focused on the complete assessment of the newest quadruple injection (epMa) strategy over base line triple injection strategy (pMa) on an automotive 6 cylinder inline CRDI diesel engine with high EGR (Fixed -45%) at different operating loads and speeds. EGR fraction is conastant for all the investigations done in present thesis.

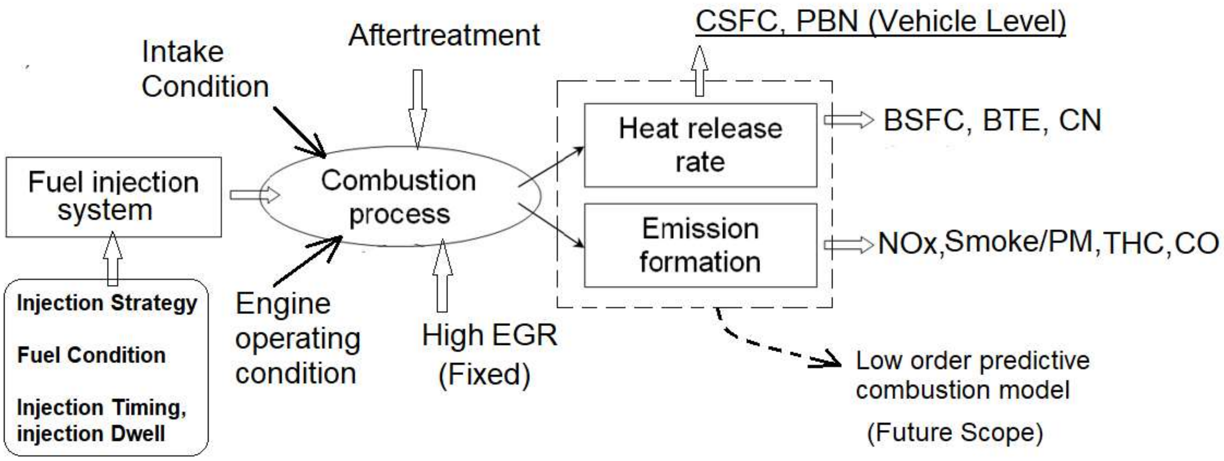


Figure 2.17: - Graphical Representation of the objectives of current study

The investigation organized as follows

1. Assessment of multiple injections (Double, Triple, Quadruple) over single injection (Main) at full load with fixed Main injection timing (SOI Main).
2. Comparison and optimization of quadruple injection strategy (epMa) over baseline Triple injections (pilot-main-after; pMa) with variable main injection timing (SOI Main)
3. Comparative Analysis of quadruple injection strategy (epMa) over baseline Triple injections (pilot-main-after; pMa) and double injection (Pilot-Main; pM) with fixed e main injection timing (SOI Main)
4. Assessment of the quadruple injection strategy (epMa) over three different Triple injections (early-main-after [eMa], early- pilot- main [epM] and pilot-main-after [pMa]) with fixed main injection timing
5. Effect of the quadruple injection strategy with different pilot (both early & pilot) and post injection timing (dwell).

Fuel efficiency, Torque and Brake thermal efficiency (BTE) are considered under performance evaluation. Brake specific fuel consumption (BSFC) measured in all the studies. In addition, Vehicle level fuel economy has been evaluated as a requirement of HDFE norms in study no.4. Pass by noise (PBN) at vehicle are captured along with Rig level noise (Nearby Noise; NBN) performance in few of the investigations (study no. 4 and 5). One of the unique focus of the researches (study no. 4 and 5) is to evaluate the outcome in real time or vehicle application. Available scientific literatures are followed to provide correlation in terms of in cylinder characteristics (combustion pressure, heat release rate and temperature).This research is part of the effort to achieve further improvement of emissions and fuel economy by adopting quadruple injections with fixed EGR as in production version engine. Objectives of present research has been represented in Fig. 2.17.

Chapter -3

Experimental Setup, Test Engine, Test Vehicle details and Uncertainty Analysis

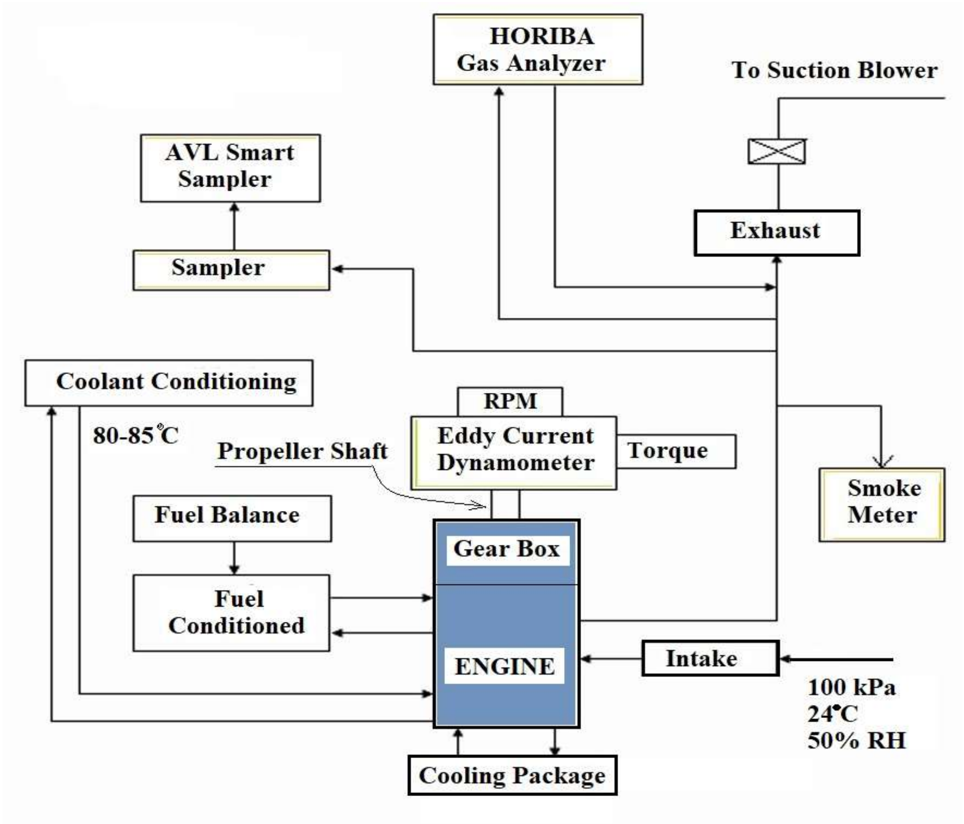
3.1 Experimental Setup, Instrument & Test Engine Details

The experimental analysis are conducted on a six-cylinder inline common rail direct injection (CRDI) production diesel engine (refer Table-3.1). The engine consists of an in-cylinder NOx reduction device namely EGR (short route cooled type) and Bosch make CRDI system (Bosch –EDC 17). It has a definite FMTC (fuel-mass torque cycle) where broad outline of fuel demand for any particulate torque and speed are mapped. Calibration, diagnostics and validation activities are monitored using INCA software. Fuel Mass (FM) and engine speed are interrelated with fuel injection Pressure (FIP). Therefore, FIP varies based on the fuel mass and engine speed (RPM). The fuel injection pressure (FIP) range is in between 120- 170 MPa. The permissible smoke limit for the base line/ production engine has been outlined for full as well as part load application. EGR percentage is kept same at 45% as existing typical production engine to achieve LTC regime and to compare with the base/production version engine having triple injections. Hence, EGR variation is not part of any of studies. As per the requirement calibration changes done to adopt different multiple injections considering the research demand.

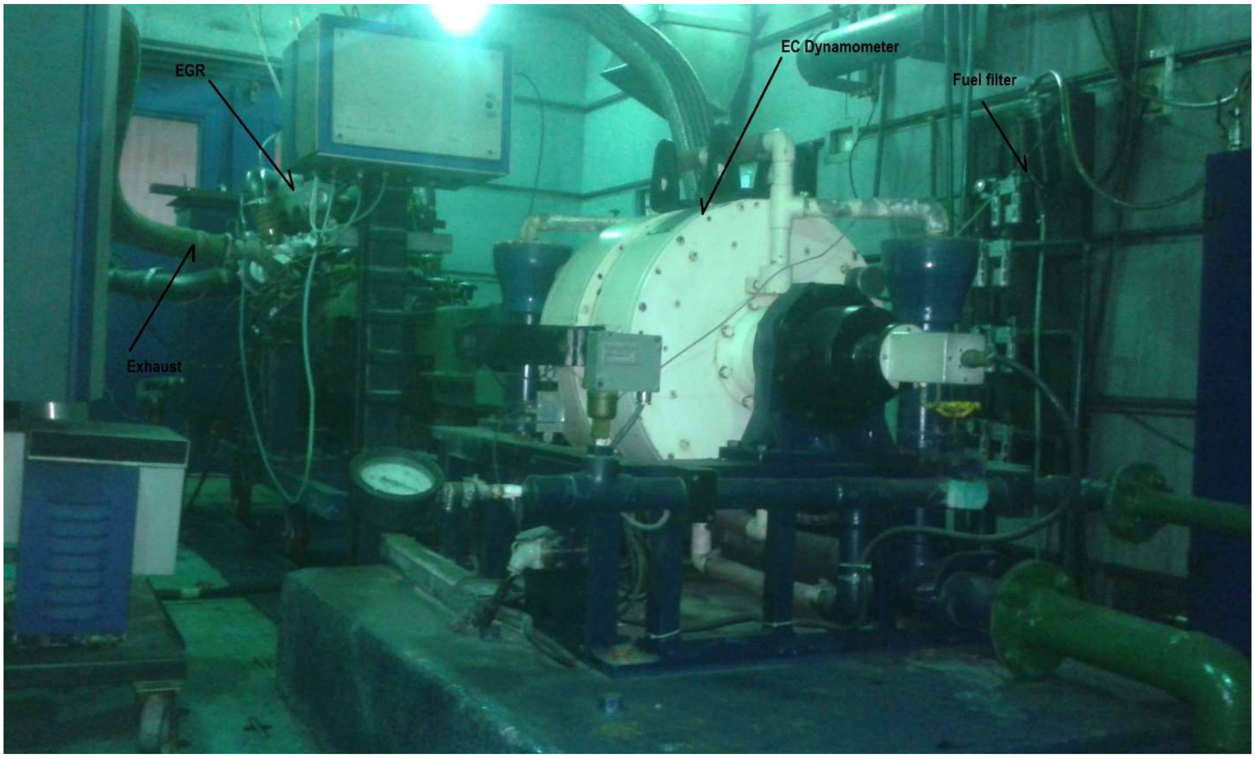
Table 3.1: Specifications of Test Engine

Parameters	**Value**
Engine Type	BS-IV 6 cylinder inline, Turbocharged
Total displacement volume	5.67L
Max Power	130 PS @ 2400 rpm
Max Torque	485 Nm@ 1500 rpm
Max Speed and Min Speed (Idle)	2750 rpm and 700 rpm
Compression Ratio	17.5:1
Injection System	CRDI, Bosch –EDC 17
Injection Pressure	120-170MPa
Injection Timing	As per Calibration (Production Engine is with pMa)
EGR Type	Short Route Cooled EGR
No of holes at Injector and Tip Angle	8 Nos and 148 Deg
Combustion chamber Type	Shallow bowl / Semi quiescent
Boost Pressure @ Max Power	214 kPa

The external cooling system is TCIC (Turbo charged inter cooled) type which is attached at front side of the engine (refer Fig.3.1). After-treatment arrangement was carried over from production/base engine during the trials. In this engine test bed, the clutch, Transmission/Gearbox, external cooling system, intake system and engine mounts adapted from production vehicle models were the typical engine in use.



(a) Test Rig- Schematic layout



(b) Test Rig - LH back View

(c) Test Rig -RH Front View (d) Test Rig - RH Back View

Figure 3.1:- (a) Schematic layout of data acquisition system
(b), (c), (d) - Snaps of engine test rig

In engine test bed, the engine is propelled by the M/S Dynomerk make Eddy current dynamometer (Model- EC 440TR). Typical 6-speed transmission is fitted with the engine, which is compatible with SAE-4 type housing. The drive shaft is connected in between the dynamometer and the transmission/gearbox. Appropriately conditioned and metered fuel and air were used during testing as shown in the data acquisition system (Fig.3) for performance and emissions. M/S AVL installed both fuel-flow-measurement-system and smoke measurement system where as M/S Yantra Shilpa setup the Fuel conditioning system (model- S42248). The Airflow measurement system is from ABB, Germany. Similarly, Gas analyser system has been installed by M/S Horiba, Japan (model- MEXA 7100DEGR).

Combustion Noise (CN) - The engine-radiated/nearby noise was measured according to the location shown in Fig. 3.2, using M/S Brüel & Kjær make Sound Level Meter (Model-2250-S). Also, Vehicle level pass by noise (PBN) measurement was done to verify the effectiveness of multiple injection strategies in noise reduction based on IS:3028 [142] using aforementioned sound level meter.

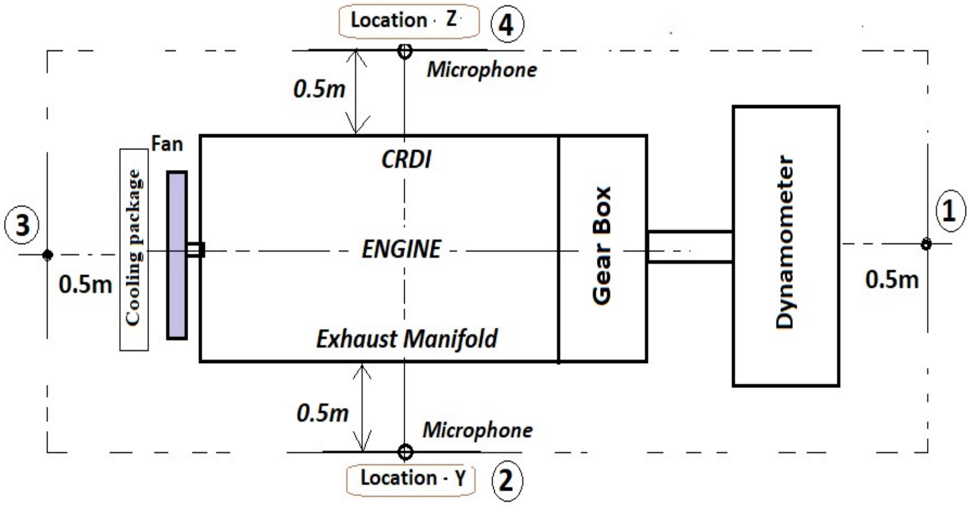


Figure 3.2:- Schematic layout of nearby noise (NBN) test [141]

Table 3.2: Specifications of Test Bed and Instruments

Test Bed Breakup		**Specification**
1. Dynamometer	*Type*	Eddy Current
	Make	Dynomerk, Pune
	Model	EC 440TR, S.No.:- 0707018
	Max speed	6000 rpm
	Max torque	2200 Nm @ 1000 to 4000 rpm
	Max power	600 KW @ 4000 to 6000 rpm
	Load cell capacity	500 kg
2. Dynamometer Controller & Data Acquisition	*Workstation*	AVL, Graz
	Instrument panel	AVL, Graz
3. Fuel flow measurement system	*Type*	733S
	Make	AVL, Graz
	Range	0-150 kg/hr
4. Air flow measurement System	*Type*	Sensy flow 700P
	Make	ABB, Germany
	Range	0-2400 kg/hr
5. Fuel conditioning system	*Make*	Yantra Shilpa
	Model	S42191
	Range	16.10.2006
6. Smoke measurement System	*Make*	AVL, Graz
	Model	415S
	Accuracy	0.5 PB (Paper Blackening)
7. Gas analyser system	*Model*	MEXA -7100DEGR
	Make	HORIBA, Japan
	Accuracy	± 2% Full Range

3.2 Test Vehicle and Vehicle level Noise Test Details

3.2.1 Test Vehicle Details: -

The test vehicle used only for Pass by Noise (PBN) test and Constant speed fuel economy (CSFC) trial as per research demand. The vehicle is typical 16T Truck with 6 –Speeds Gear box (same used in engine test bed), 10 x20 Size Tyres (both Bias & Radial play rating) and Rear Axle Ratio – 5.85 & 5.28. The cabin is non-sleeper fixed type. Also, same BS-IV engine used in this vehicle with triple injection strategy. The vehicle exhaust system is with a silencer and after treatment system (ATS). The ATS is combination of Diesel oxidation catalyst (DOC), particulate Oxidation Catalyst (POC), Differential pressure sensor and temperature sensor.

3.2.2 Vehicle level Pass by noise (PBN)**:-** PBN measurement done in many of investigations to authenticate the efficacy of multiple injection strategies to improve noise reduction in assistance of IS 3028 standard [142]. The vehicle level noise at moving state is called as pass by noise (PBN).The schematic of PBN test on test track shown below (Fig 3.3). The vehicle PBN is the combination of vehicle noise and exterior noise [134]. Tyre-road frictional and Wind noise are the contributors of exterior noise. Similarly, Engine, Intake, Exhaust, Transmission/drive line and cabin insulation are the key giver of vehicle noise. Among these, engine noise is louder which contains combustion/radiated noise (CN), piston slap noise and fan belt noise primarily. Also, Exhaust system has significant contribution in PBN performance. Hence, exhaust system carried over from production version model where the engine in use for apple-to-apple comparison. Gear number selection [142], rear axle ratio and tires specification are important for performing PBN test. During the trials, Gear number was chosen as n/2 and (n/2 +1). Here, n is indicating no of gears or speeds (e.g.- 6 speeds, 9 speeds gear box /transmission)

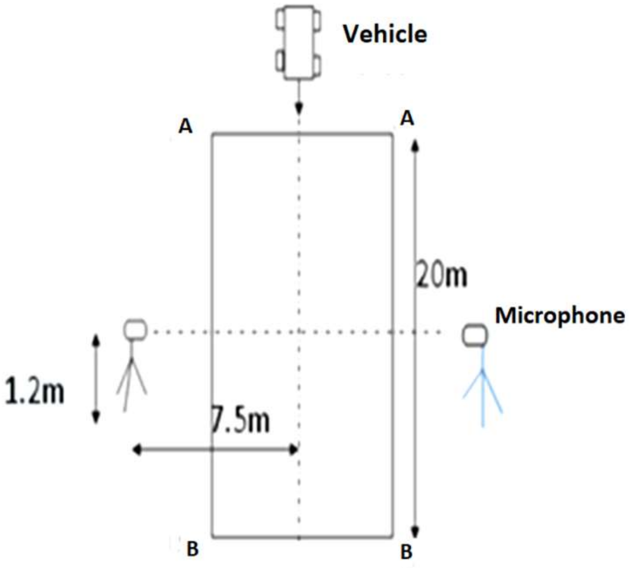


Figure 3.3:- Schematic layout of Pass by Noise test (PBN) of vehicle [142]

3.3 Uncertainty Analysis

The uncertainty of measurement is calculated as per the NABL-141 guidelines [143]. The Guide to the Expression of Uncertainty in Measurement (GUM) approach recognizes the need for providing high level of confidence associated with an uncertainty and uses the term-expanded uncertainty. The GUM is rigorous and equally applicable to test results and calibration. In this work, the uncertainty of measurement for each calibration is estimated at 95% confidence level. The expanded uncertainty U is a confidence interval and it is expressed as

$$\mathrm{u} = \mathrm{k.Uc} \qquad (3.1)$$

Where, k is coverage factor and

Uc is combined standard uncertainty

Here, coverage factor k is driven from effective degree of freedom v_{eff} of the standard uncertainty u(y) associated with the output estimate y from the Welch-Satterthwaite formula and student "t" distribution table [28]

$$\mathrm{Uc} = \sqrt{(\mathrm{Type\ A})^2 + (\mathrm{Type\ B})^2} \tag{3.2}$$

$$\mathrm{Type\ A} = \mathrm{S}(\mathrm{q_k})/\sqrt{\mathrm{n}} \tag{3.3}$$

Where, $S(\mathrm{q_k})$ is standard deviation. In Type A is number of measurement "n" are made under the conditions of the test and the measurements are assumed to be normally distributed. This is evaluated based on statistical method. The standard deviation of the measured results can be calculated from the measured values as

$$S^2(q_k) = \frac{1}{n-1}\sum_{k=1}^{k}(q_k - \bar{q})^2 \tag{3.4}$$

Where, $\bar{q}$ = Mean, n = No. of readings, $\mathrm{q_k}$= Actual Reading, s^2=Variance

The mean is calculated using below equation

$$\bar{q} = \frac{1}{n}\sum_{k=1}^{n} q_k \tag{3.5}$$

Where, n = No. of readings, $\mathrm{q_k}$= Actual Reading. As per the guideline n should be minimum 5 nos.

The Type B of equation no.2 is evaluated by other means. It is based on following inputs namely – Manufacture's Specification, Data provided in calibration certificate and Environment Condition respectively. The equipment used in this study including the measurement range and accuracy of the instruments are part of the inputs. Based on the NABL guideline, only normal and uniform distribution are followed for distribution of measurements in the engine testing laboratory.

This is can be expressed as $\mathrm{u} = {}^{\mathrm{U}}/_{\mathrm{k}\,*}$ (3.6)

Here, k* is cover factor. For a confidence level of about 95%, the value of k* is 2 and for a confidence level of 99%, the value of k* is 2.58.

The other case of uniform distribution, at 95 % Confidence,

$$\mathrm{u} = \mathrm{U}/\sqrt{3} \tag{3.7}$$

The GUM is bottom up kind of approach. It is required to estimate the "U" in equation 1 by calculating all other equations for Type A and Type B.

The engine test laboratory is NABL accredited where Uc is key parameter. The expanded uncertainty of the engine test laboratory is ± 3.011% at 95% confidence level. The NABL accreditation help to reduce the time line for ARAI certification due to acceptable expanded uncertainty. As per this, minimum 5 sets of data needed to capture during experiments.

Chapter -4

Assessment of the impact of multiple injection Strategies over single injection

4.1 Objective of this Work

This chapter deals with study of the impact of 5 different multiple injection strategies [2-Double {(Pilot – Main [pM]); (Main-after [Ma])}, 2-Triple {(Pilot-Main-after [pMa]), (Early-Pilot-Main [epM])} and Quadruple (Early –pilot –main –after [epMa])] in comparison with single injection on combustion noise (CN), brake specific fuel consumption (BSFC), Torque, brake thermal efficiency (BTE) and Smoke emissions. The experimental evaluation was done on a typical 6 cylinder inline CRDI (Common rail Direct Injection) diesel engine in low temperature combustion regime with high EGR of 45%, and fixed main injection Crank angle (CA) using conventional diesel (BS-IV) fuel at full load and 8 Speeds (low to high). Available scientific literatures are followed for detailed analysis on the influence of afore mentioned injection strategies in terms of engine in-cylinder characteristics (combustion pressure, temperature and heat release rate).

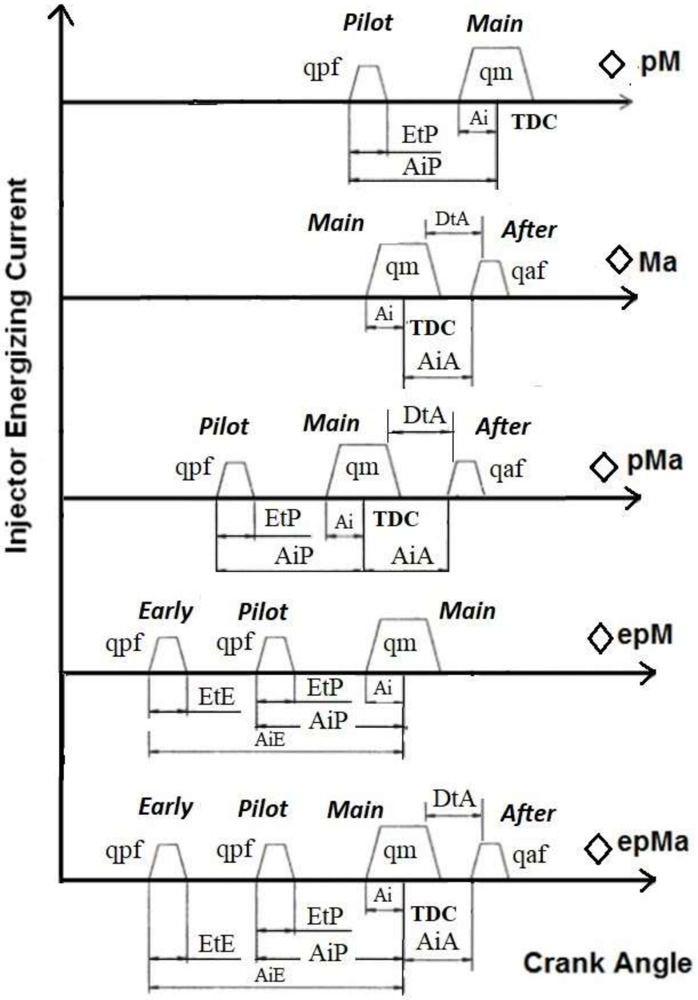


Figure 4.1: Multiple Injection Strategies – pM (Pilot-Main), Ma (Main-After/post); pMa (pilot-main-after); epM (early-pilot-main); and epMa (early – pilot –main –after/post)

4.2 Experimental Methodology

The engine is with cooled EGR and external cooling system. Details of experimental engine mentioned in Figs. 3.1 and tabulated in Table 1. The typical engine has a certain FMTC (i.e.-fuel mass torque cycle) where basic outline of fuel demand for any particulate torque and speed are mapped. Calibration, diagnostics and validation activities are monitor using INCA software. Allowable smoke limits for the production engine have been outlined for part loads as well as full load application. The base engine is with qpf - 1.5 mg/hub, qaf - 2 mg/hub and DtA - 1350 ms. Fixing the main injection timing and EGR %, key focus has been given on comparative study and understanding the effect of different multiple injection strategies on combustion noise, smoke emission and performance (BSFC and torque). After-treatment arrangement is similar to production engine during the experiments. Also, clutch, gearbox (transmission), external cooling/ intake system, engine mounts adopted in this test bed from regular models. Engine out radiated or Combustion Noise was measured based on the IS: 10399 [141] guideline and Location scheme as per Fig 3.2. The IS: 10399 [141] standard is about noise measurement methodology at stationary vehicle. There is no other special measurement arrangement available to measure noise level inside the combustion chamber. Design of Experiments (DoE) technique is used in this experimental research work for systematic approach of testing. The experimental tests have been conducted as per the DoE matrix shown in Table -4.2 for performance and emissions. The inputs for DoE matrix are represented in Table -4.1. The data captured under steady state condition and average of 20 cycles for each set of data. Emission tests were done based on ELR (European load response) smoke trial.

Table 4.1: DoE matrix inputs –Factors, Level and Value

Factors	Level	Value
Variable Factors		
Double injection1	A	pM
Double injection2	B	Ma
Triple Injection1	C	epM
Triple Injection2	D	pMa
Quadruple Injection	E	epMa
Single Injection	F	M
Speed (rpm)	S1, S2, S3,S4 S5,S6 ,S7, S8	1100,1300,1500,1700, 1900,2100, 2300,2500
AiP	2	21° & 19° CA BTDC
AiE	2	41° & 39°CA BTDC
Fixed Factors		
	EGR	45%
	Load %	Full (100%)
	Ai	1°CA BTDC
	DtA	1100ms

Table 4.2: DoE matrix for Performance and Smoke Tests

Injection strategy & Speed combination		Speed (RPM)							
		S1	S2	S3	S4	S5	S6	S7	S8
pM	A	AS1	AS2	AS3	AS4	AS5	AS6	AS7	AS8
Ma	B	BS1	BS2	BS3	BS4	BS5	BS6	BS7	BS8
epM	C	CS1	CS2	CS3	CS4	CS5	CS6	CS7	CS8
pMa	D	DS1	DS2	DS3	DS4	DS5	DS6	DS7	DS8
epMa	E	ES1	ES2	ES3	ES4	ES5	ES6	ES7	ES8
M	F	FS1	FS2	FS3	FS4	FS5	FS6	FS7	FS8

Table 4.3: Nearby Noise Trial Plan

Noise Trial Strategy		Location	Speed (RPM)		
			S1	S2	S3
pM	A	Y	AYS1	AYS2	AYS3
		Z	AZS1	AZS2	AZS3
Ma	B	Y	BYS1	BYS2	BYS3
		Z	BZS1	BZS2	BZS3
epM	C	Y	CYS1	CYS2	CYS3
		Z	CZS1	CZS2	CZS3
pMa	D	Y	DYS1	DYS2	DYS3
		Z	DZS1	DZS2	DZS3
epMa	E	Y	EYS1	EYS2	EYS3
		Z	EZS1	EZS2	EZS3
M	F	Y	FYS1	FYS2	FYS3
		Z	FZS1	FZS2	FZS3

Two sets of trial done with each injection timing combinations (AiP- 21°CA BTDC + AiE- 41°CA BTDC) and (AiP- 19°CA BTDC + AiE- 39°CA BTDC).

4.3 Results and Discussion

All experimental outcomes are expressed in tabulated and graphical form in this section for better understanding.

4.3.1. Combustion Noise (CN) Performance

The noise data are captured for lower speeds (S1, S2 and S3). During noise trials, microphone was placed 0.5m away from engine surface/envelop and Positioned as per scheme shown in Figure 3.2. After stabilizing the exhaust out gas temperature, testing data were acquired. Also, Ambient noise level of Laboratory are captured before start of engine.

Table 4.4: Nearby Noise Test data

Injection Strategy /Speed/ Location		**AiP-** 21°CA BTDC **AiE**- 41°CA BTDC			**AiP-** 19°CA BTDC **AiE**- 39°CA BTDC		
		1100	1300	1500	1100	1300	1500
pM	**Y**	94.2	94.9	95.3	94.3	95	95.3
	Z	93.9	94.6	95.1	93.9	94.6	95.1
	Avg	***94.05***	***94.75***	***95.2***	***94.1***	***94.8***	***95.2***
Ma	**Y**	94.6	95.2	95.6	94.6	95.2	95.6
	Z	94.3	94.7	95.2	94.3	94.7	95.2
	Avg	***94.4***	***94.95***	***95.4***	***94.4***	***94.95***	***95.4***
pMa	**Y**	94.0	94.7	95.2	94.1	94.8	95.3
	Z	93.7	94.5	94.9	93.7	94.6	94.8
	Avg	***93.85***	***94.6***	***95.05***	***93.9***	***94.7***	***95.05***
epM	**Y**	93.4	94.0	94.5	93.5	94.1	94.6
	Z	93.0	93.8	94.3	93.1	93.8	94.3
	Avg	***93.2***	***93.9***	***94.4***	***93.3***	***93.95***	***94.45***
epMa	**Y**	93.2	93.8	94.3	93.3	93.8	94.4
	Z	92.9	93.5	93.9	92.9	93.6	93.9
	Avg	***93.05***	***93.65***	***94.1***	***93.1***	***93.7***	***94.15***
M	**Y**	95.1	95.7	96.2	95.1	95.7	96.2
	Z	94.9	95.5	95.9	94.9	95.5	95.9
	Avg	**95.0**	**95.6**	**96.05**	**95.0**	**95.6**	**96.05**

All tests data are presented in Table 4.4. It observed that epMa is the best in noise reduction compared to remaining multiple injection strategies. Single injection M is worst in combustion noise in comparison to the epMa and other multiple injections. It is found inferior by around 1.95 dBA with delayed pilot injection timing combination (i.e- AiP- 21°CA BTDC + AiE- 41°CA BTDC) w.r.t main injection. The epMa can reduce the combustion noise within 0.2 to 1.1 dBA w.r.t other multiple injections. Ma injection scheduling is poor among the multiple injections. Pilot injection helps to control the rate of heat release and pressure rise inside the combustion chamber after ignition delay period. Thus, double pilots has significant impact on combustion noise reduction. As a result both epM and epMa injection strategies demonstrated good noise reduction. Pilot-Main (pM) injection scheduling also shows good noise reduction performance in comparison to other double and single injection.

4.3.2. Soot Concentration /Smoke emissions

In this work, mainly smoke emission results are captured as per ELR standard [139,140]. Further, soot concentration values are calculated using empirical equation. Those test results are represented in bar chart and line diagram format.

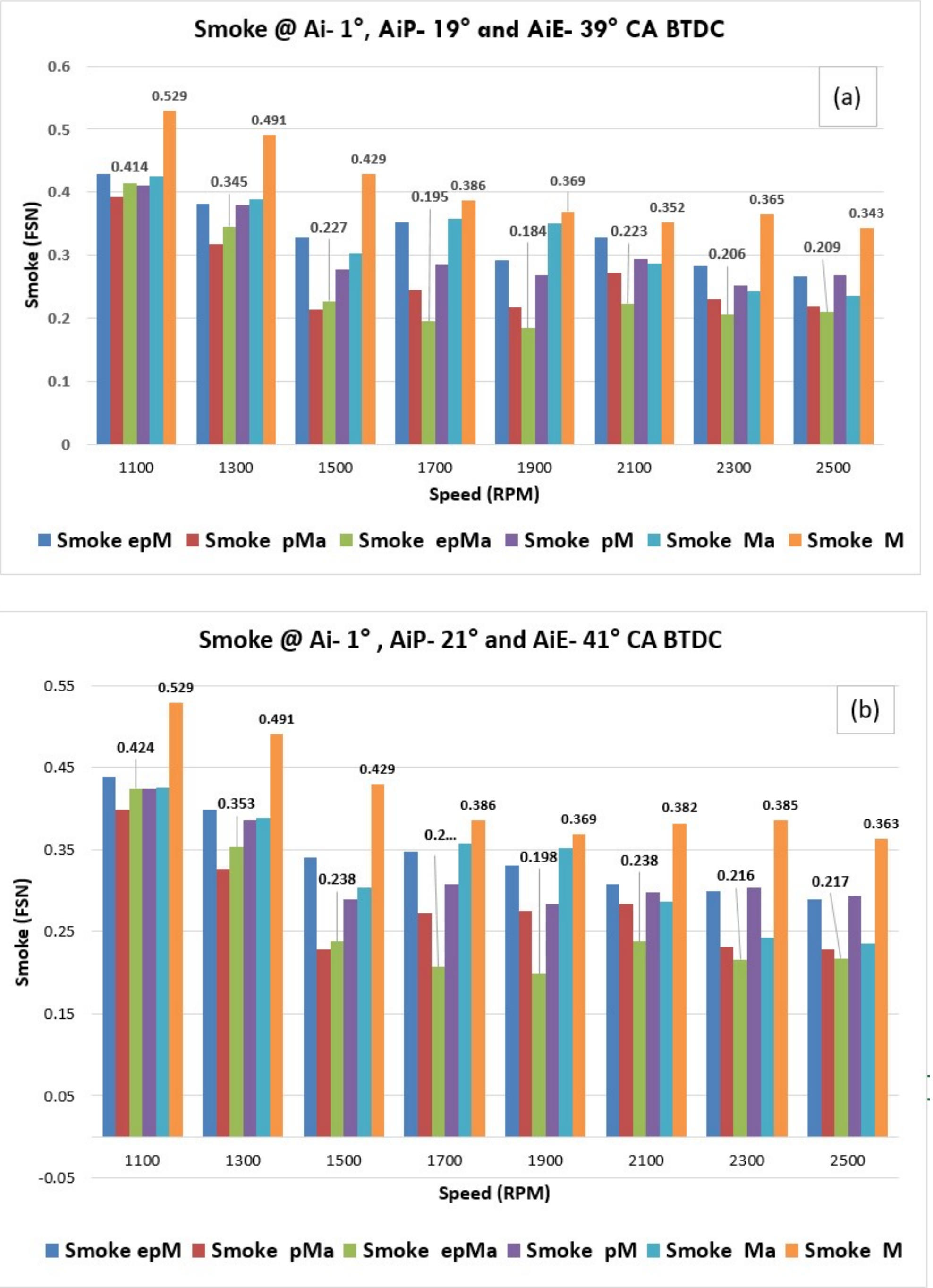


Figure 4.2: Comparative Smoke Bar chart – a) AiP-19° & AiE- 39° CA BTDC; b) AiP-21° & AiE- 41° CA BTDC

Using the following equation, soot concentration (St) values (in mg/m^3) are calculated for the injection strategies [135].

$$St = \frac{1}{0.405} \times 4.95 \times FSN \times e^{(0.38 \times FSN)} \qquad (4.1)$$

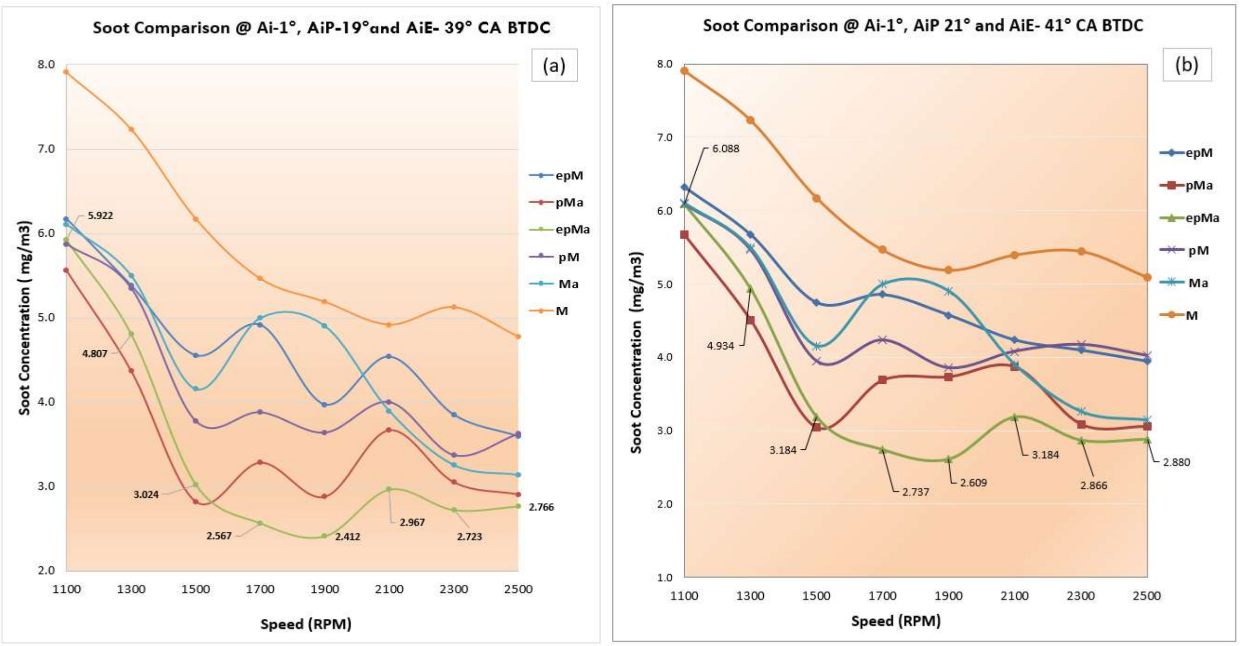


Fig 4.3: Comparative Soot concentration – a) AiP-19° & AiE- 39° CA BTDC b) AiP-21° & AiE- 41° CA BTDC

The smoke (Fig.4.2a and 4.2b) and soot plots (Fig.4.3a and 4.3b) are indicating multiple injections are better in particulate matter (PM) emissions compared to single injection. Further, these results also indicating that multiple injections featuring with post or after injection pulse are beneficial in smoke reduction. Also, more pilot fuel quantity (by more pilot pulses) worsens the smoke /soot emission level. The pMa produces lowest smoke compared to other multiple injections. The epMa exhibited second best average smoke level where highest smoke level is found at low to medium speed ranges among the multiple injections. Double injections are displayed more smoke/soot emissions than other multiple injection scheduling. Here, the epM is intermediate performer in smoke emissions. The results also show the influence of pilot- injection- timing combination w.r.t to main injection timing. It has no impact on Ma and M injection strategies. The smoke and soot concentration graphs are representing that the close pilot-injection timing combination (i.e- AiP-19° & AiE- 39° CA BTDC) is favorable for the epMa, epM , pMa and Ma injection strategies. The fix Main injection timing Ai is not favorable for multiple injections (Ma, pM, epM, pMa, epMa) which causes abnormal peaks in soot /smoke curves specially at higher speed zone.

4.3.3 BSFC and Torque Performance

Following the DoE matrix (Table- 4.2), Torque data are captured and BSFC, BTE are calculated for all 6-injection strategies and demonstrated those in comparative graphical form in this section.

4.3.3.1. BSFC Performance

Torque (Tr in Nm) and Fuel Flow rate (FFR in kg/hr) are directly measured during experimentation. BSFC (g/kWh) value calculation done using below equation. S is engine speed in RPM.

$$BSFC = (FFR \times 1000 \times 9549.57)/(Tr \times S) \quad (4.2)$$

Where, Power (P) in kW= 2π N (Speed in RPM) Tr (Torque in Nm) x 1000/60 (4.3)

According, 9549.57 = (60 x 1000)/ 2π (4.4)

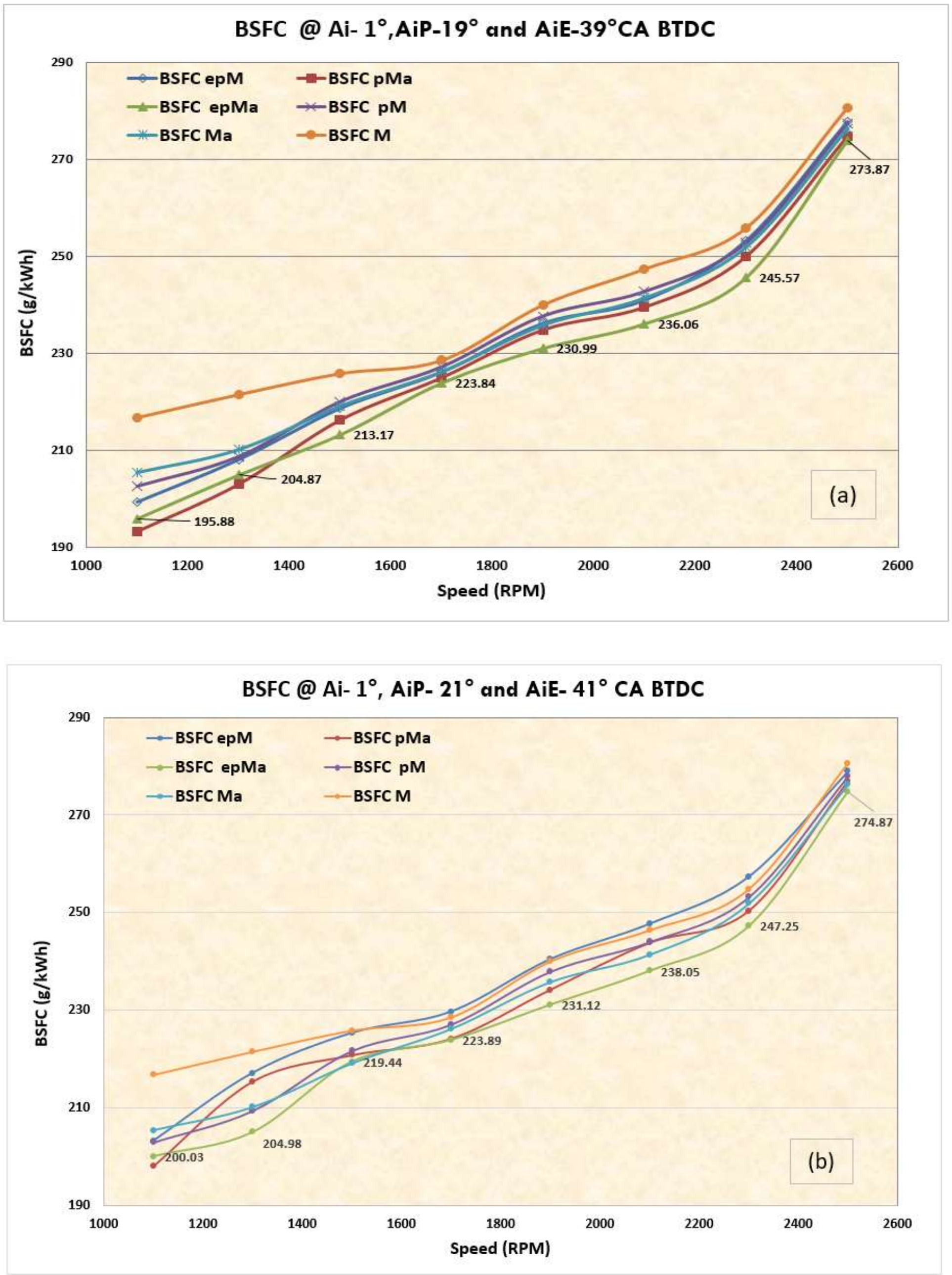


Figure 4.4: Comparative BSFC Graphs - a) AiP-19° & AiE- 39° CA BTDC ; b) AiP-21° & AiE- 41° CA BTDC

From the BSFC Graphs (Fig.4.4a and 4.4b), it observed that the epMa provides best BSFC performance from medium to high-speed range for all load conditions with quite smoother curve. In other hand, it exhibited relatively poor BSFC at low speed-range w.r.t the pMa injection strategy. Among these double injection strategy (pM) shows poor BSFC performance at multiple speeds among the multiple injection strategies. Single injection strategy is worst in BSFC compared to multiple injections. This is only because of better combustion characteristics with multiple injection specially in presence of pilot and post injection pulse. The close couple pilot injection timing (i.e- AiP-19° & AiE- 39° CA BTDC) combination helps to provide better results in BSFC for the epMa, epM, pMa and pM.

4.3.3.2. Torque Performance

Torque comparison data of all 6 injection strategies are shown in combined graphical format for each load case sub- Sequentially. DoE table mentioned in previous section has been followed for doing the experiments.

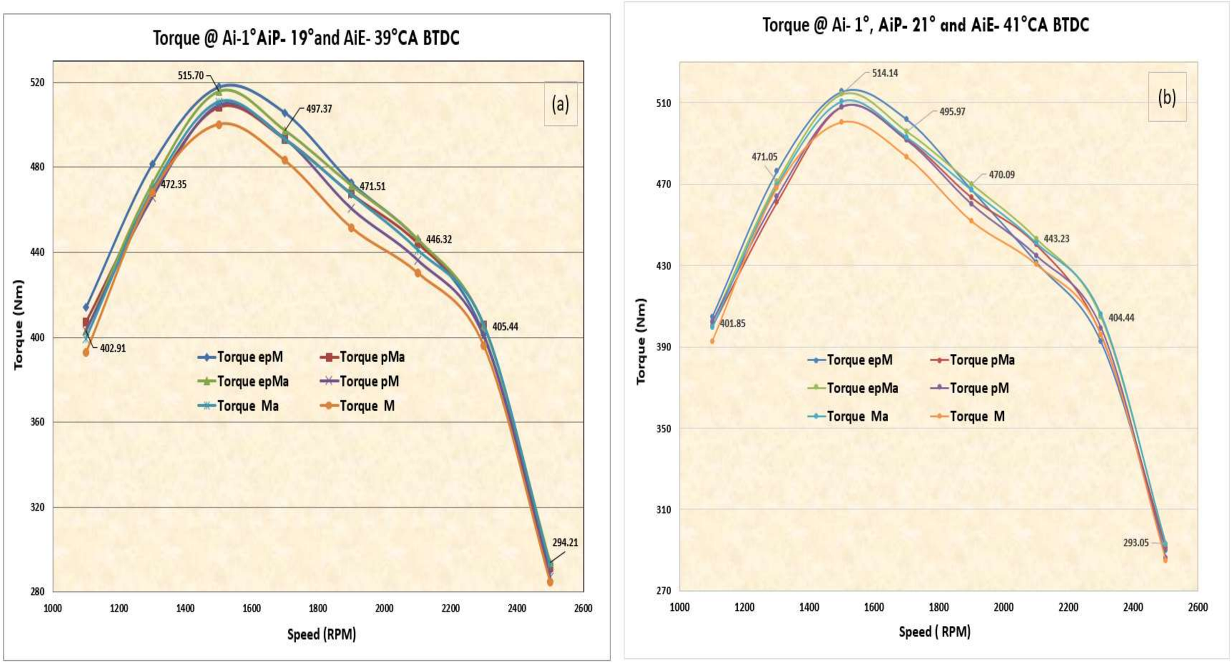


Figure 4.5: Comparative Torque curves– a) AiP-19° & AiE- 39° CA BTDC; b) AiP-21° & AiE- 41° CA BTDC

Fig.4.5 shows that mix type of Torque performance curves at different speed bands; low to medium (1000- 1700 RPM) and Medium to high (1800- 2500 RPM). Following are the key responsible for this namely Heat release rate (HRR) & mean gas temperature due to influence of injection strategy on combustion characteristics. Double pilots help in better combustion control in premixed, ignition delay, diffusion/ rapid combustion phases, which ultimately influence in achieving higher torque values in low to medium speed ranges. Thus, the epM showed best torque performance specially al low to medium speed zone. In other hand, the epMa exhibited optimum torque curve among the injection strategies. The pMa injection strategy is the third best among the injection schemes. Among the double injection strategies, the Ma shows the better Torque performance at high-speed zone. Single injection strategy is worst in Torque compared to other injections. The close couple pilot injection timing (i.e- AiP-19° & AiE-39° CA BTDC) combination w.r.t main injection found helpful to get better outcomes in Torque for the epMa, epM, pMa and pM injection strategies.

4.3.3.3. BSFC / Torque Combined Performance

This section is combining the information from last two sections to provide a summarize information of performance (Torque and BSFC) in a single figure. This graphs (Fig.9a and 9b) is basically providing the information that none of thease multiple injection strategies are perfect to deliver good or optimistic BSFC and Torque performance simultaneously in the same operating zone (i.e.- Speed range). Single injection is poor in both torque and BSFC throughout the operating speeds.

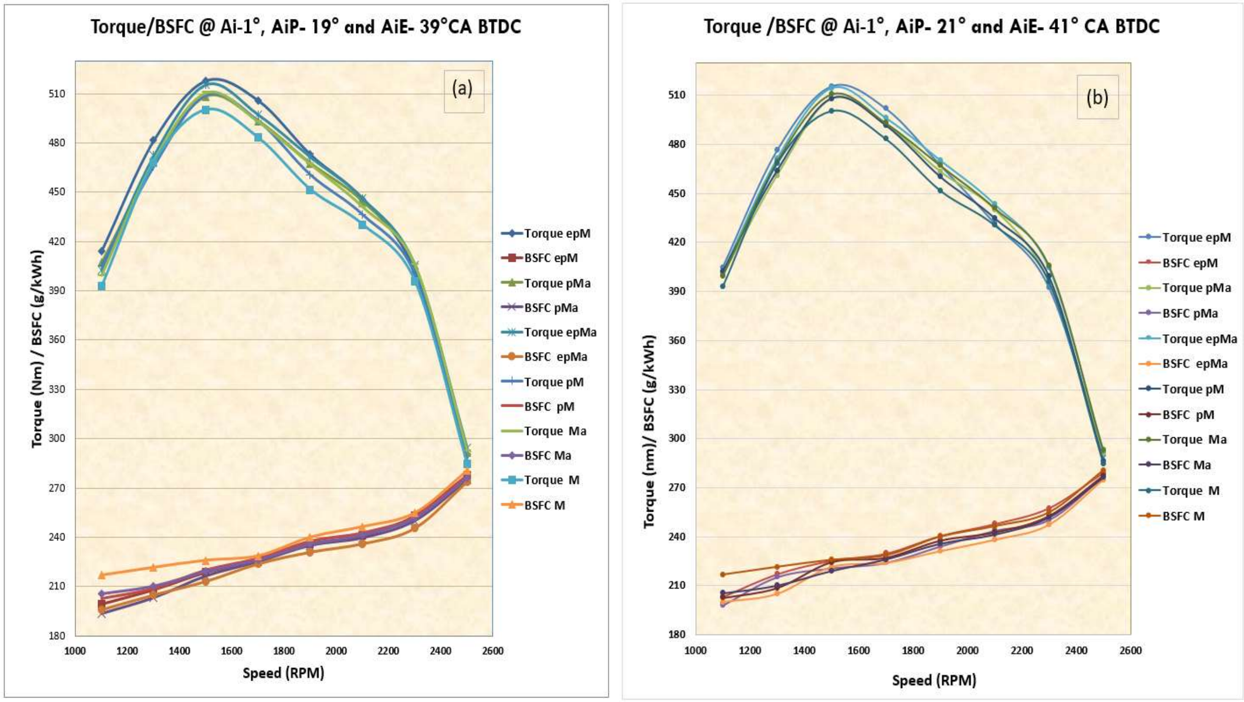


Figure 4.6: Comparative Torque/BSFC data a) AiP-19° & AiE- 39° CA BTDC ; b) AiP-21° & AiE- 41° CA BTDC

4.3.4. Brake Thermal Efficiency (BTE) performance

It is calculated based on measured Torque (T_r), Speed (S) and FFR. Calorific Value (CV) of BS-IV Diesel fuel considered from Standardization Report as 42.8MJ/kg (this is LHV). FFR is fuel flow rate in kg/hr. Using Torque and Speed data, Brake Power (BP) is calculated.

$$BTE = \frac{BP \times 3600}{FFR \times CV} \tag{4.5}$$

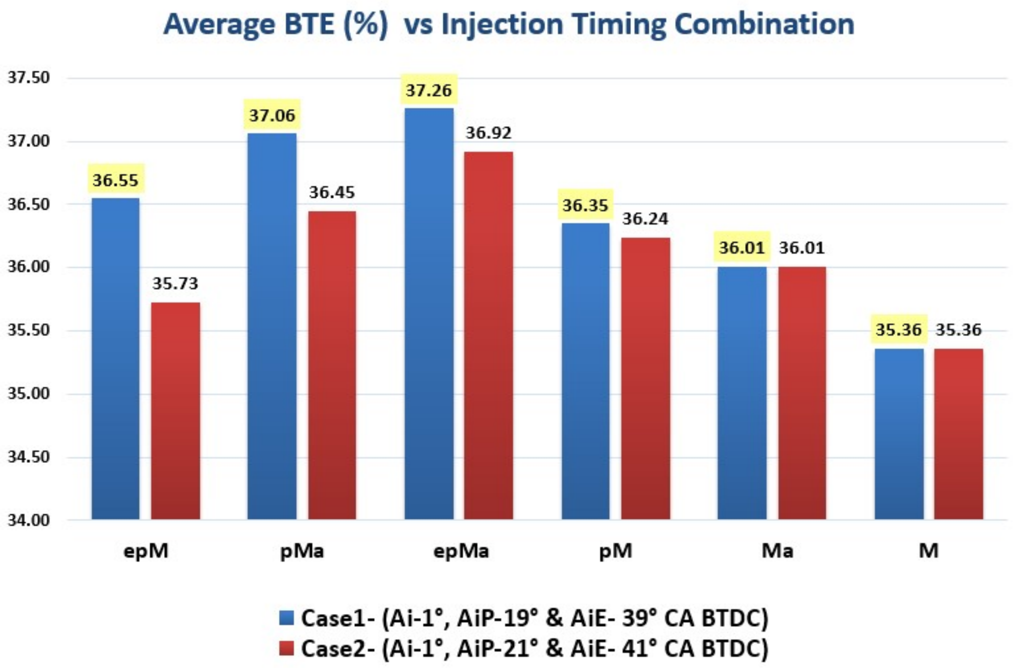


Figure 4.7: Comparative BTE data a) AiP-19° & AiE- 39° CA BTDC ; b) AiP-21° & AiE- 41° CA BTDC

Fig. 4.7 shows the average BTE of each injection strategies for both the injection-timing combination. There is no impact of early/pilot injection timing on Ma and M injection strategy. The results indicates the closed pilot with respect to the main injection is more effective. Thus , better BSFC and Torque performance achieved with AiP-19° & AiE- 39° CA BTDC as a results, average BTE is found better for epMa, pMa, epM and pM injection strategies. The epMa shows the best BTE performance among the injection strategies and pMa is 2nd best in this category. The pM is the best among double and single injection strategies.

4.4 Conclusion

The effects of 5 different multiple injection strategies [pM, Ma, pMa, epM and epMa] in comparison to the single injection on combustion noise, BSFC, Torque, BTE and Smoke/Shoot emissions have been examined on a typical LTC CRDI heavy engine at full load condition with fix EGR and Main Injection applying DoE approach. Following conclusion can be drawn from this study.

- Multiple injections featuring with pilot injection pulse is effective in combustion noise reduction at lower speeds. Double pilot injections are more impactful to reduce the combustion noise as it control the rate of heat release and pressure rise inside the combustion chamber.
- At low speeds, the epMa can reduce the combustion noise between 0.2 to 1.3 dBA, compared to other multiple injections. Similarly, the epM injection strategy displayed the second best

performance in CN reduction. The delayed pilot injection timing (i.e AiP-21° & AiE- 41° CA BTDC) is favourable for CN reduction.

- Multiple injections are better than single injection in particulate matter (Soot , Smoke) reduction
- The epMa exhibited second best average smoke level whereas pMa is best in smoke emissions among the injection strategies.
- The Ma injection scheduling worst among the multiple injections in Smoke emission/soot concentration level.
- Double pilot with post/after injection scheduling (epMa) Quadruple injection strategy is better to provide optimum BSFC and torque performance even at un-optimized fixed main injection timing, pilot and post injection timing compared with single injection, Double (pM, Ma) and triple (pMa, epM) injection strategies.
- The epMa strategy is rational and showed best BSFC results from medium to high operating speeds for both injection-timing combinations. Single injection is worst in BSFC performance. The pMa displayed best BSFC performance only in low speeds.
- Mix type of Torque performance observed depending on the speed bands; low to medium (1000- 1700 RPM) and Medium to high (1800- 2500 RPM). Mix type of Torque performance observed depending on the speed bands; low to medium (1000- 1700 RPM) and Medium to high (1800- 2500 RPM). The epM displayed best torque performance specially al low to medium speed zone. In other hand, epMa shown optimum torque curve among the injection strategies. The pMa injection strategy is the third best among the injection strategies
- The epMa shows the best BTE whereas M is the worst one among the injection strategies. Average BTE is found better with closed pilot injection combination w.r.t main injection. This combination gives the better BSFC and Torque performance for the epMa, epM, pMa and pM.
- Due to complexity of experimentation, other exhaust out emissions (NOx, THC, CO) are not covered in this Study. But, it can judge from literature survey that pilot injection may help in reduction in NOx due to reduction of mean gas temperature inside the cylinder. Double pilot with a post injection (epMa) and pilot-main –post (pMa) may be the best two injection scheduling to reduce NOx and PM (Smoke/soot) simultaneously.

It is quite difficult to handle six numbers of injection strategies at different speeds and optimization of injection parameters (timing, quantity, dwell etc.). Other emissions like NOx, THC, CO also not studied in this work due to the complexity of experimentation. As Further Scope of Work, it may be helpful to study only with quadruple injection strategy for optimization of injection parameters; and to get optimum emissions (Smoke/PM, NOx, THC, CO) and performance (BTE, Torque and BSFC) with reduced combustion noise.

Chapter -5

Effect of Quadruple Injections over Triple injections with variable Main Injection timing

5.1 Objective of this Work

An emissions, combustion noise and performance study was conducted to explore the effects of two different multiple injections strategies on emissions, combustion noise and performances without altering EGR %. The experiments were done on a six cylinder inline CRDI diesel production engine. The aim of this study is to improve performances (brake specific fuel consumption [BSFC], torque) and combustion noise (reduction) using multiple injection strategies without violating emission regulations. The other objective of this study is to examine the influence of different operating parameters (Speed and Load) and main injection timing combined, on same multiple injection strategies (Pilot- main – after {PMA}and Early - pilot- main –after {EPMA}) by means of analyzing emissions/soot, combustion noise and performances data. The total carried-out analysis was done using a typical top-down flow chart of methodology and experimental matrices have been formulated based on DOE (design of experiments) approach. .

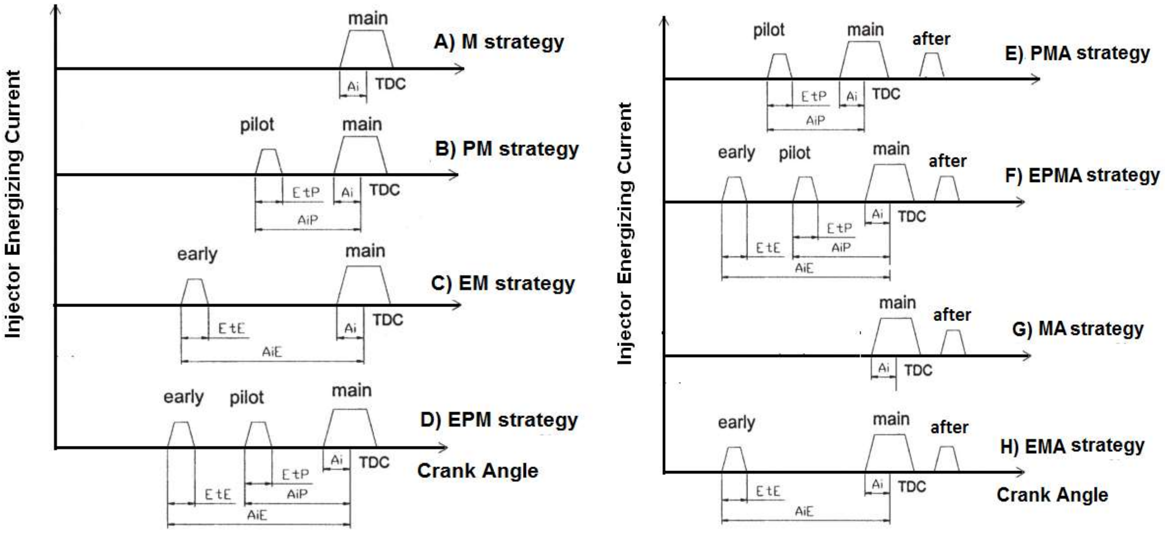


Figure 5.1: Injection strategies (M- Single or Main injection; PM- pilot–main; EM- early–main; MA- main-after; EPM- early–pilot–main; PMA-pilot–main-after; EPMA early–Pilot-main-after; and EMA early -main-after

5.2 Experimental Methodology

The engine is with cooled EGR and external cooling system. Details of experimental engine mentioned in Figs. 3.1 and tabulated in Table 1. The typical engine has a certain FMTC (i.e.-fuel mass torque cycle) where basic outline of fuel demand for any particulate torque and speed are mapped. Calibration, diagnostics and validation activities are monitor using INCA software. Allowable smoke limits for the production engine have been outlined for part loads as well as full load application. The base engine is with qpf - 1.5 mg/hub, qaf - 2 mg/hub and DtA - 1350 ms. Fixing the EGR % same, key focus has been given on comparative study and understanding the effect of two different multiple injection strategies on performance (BSFC & Torque), combustion noise, emission (Smoke, NOx, PM, THC, CO) and performance (BSFC and Torque). After-treatment arrangement is similar to production engine during the experiments. Also, clutch, gearbox (transmission), external cooling/ intake system, engine mounts adopted in this test bed from regular models. Engine out radiated or Combustion Noise was measured based on the IS: 10399 [147] guideline and Location scheme as per Fig 3.2. The IS: 10399 [147] standard is about noise measurement methodology at stationary vehicle. There is no other special measurement arrangement available to measure noise level inside the combustion chamber.

To study the influence of two different multi injection strategy on performances, emissions and combustion noise, a flow chart diagram have been prepared to do the work methodologically. This chart comprises of maximum 9 steps based on expected outcome (Fig 5.2).

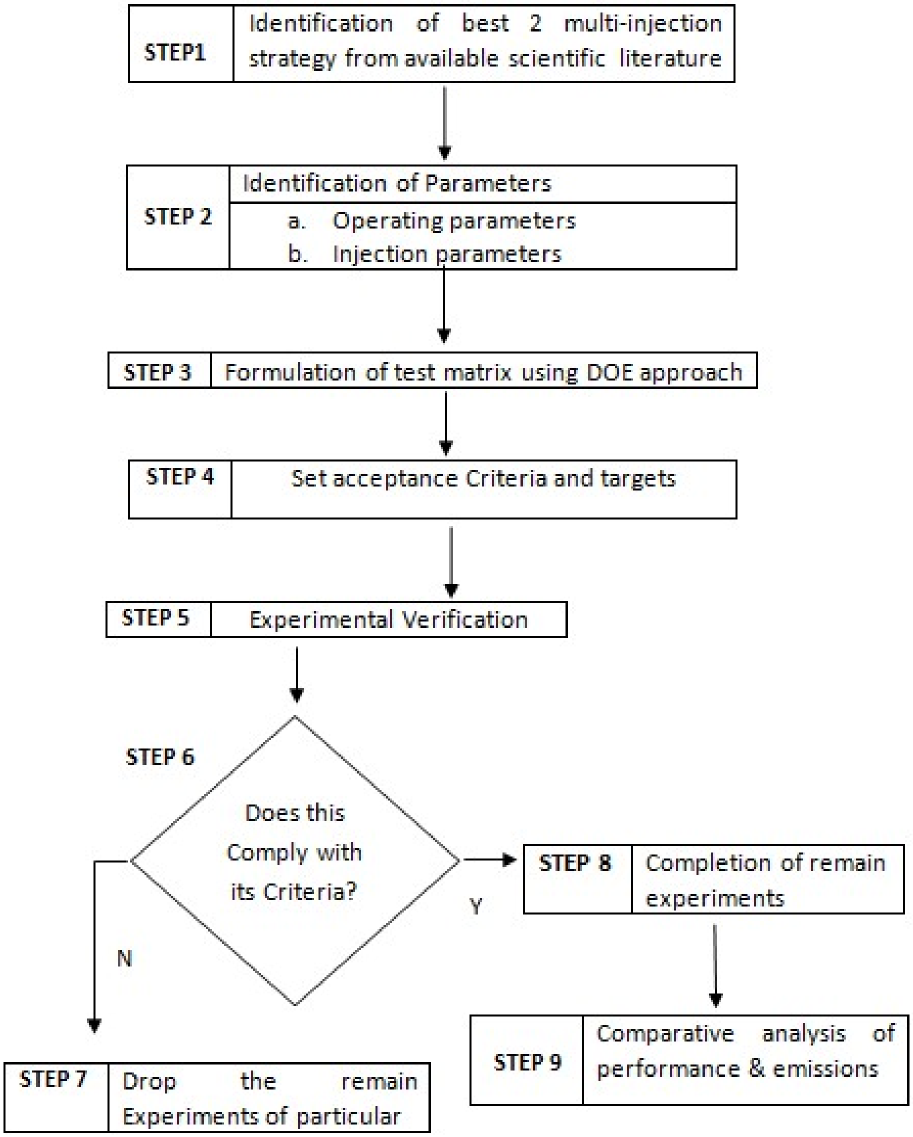


Figure 5.2:- Flow chart diagram of methodology

STEP 1:-

Best two multiple injection strategy has been identified from available literature in first step of flow chart diagram. Out of 8 different injection strategies as shown in Figure 5.1, EPMA and PMA are elected and used in present work. The typical production engine which is used for this experimental work has PMA injection strategy.

STEP 2:-

In this stage, Operating and injection parameters were acknowledged. Like many research, Speed and Load are belong to the operating parameters for this workout. There are many injection parameters which affect engine combustion, emissions and performances but main injection timing (SOI- CA BTDC) is considered here only.

STEP 3:-

This is the step where experimental matrix is formulated using DoE approach. This work consists of four factors of different levels. Total 256 numbers of experiments were planned as per DoE tables (Table 5.6). For each experiment, 20 numbers of cycles were sampled and averaged during data capturing.

STEP 4:-

In this step, acceptance criteria and targets have been finalized. Emissions level is set as criteria as one of the aims of this carried-out analysis is to improve performances (BSFC, Torque) and combustion noise using multiple injection strategies without violating emission regulations. In other hand, Performance and combustion noise are designated as targets.

STEP 5:-

This step is for Experimental work as per DoE table.ESC and ETC standards are followed.

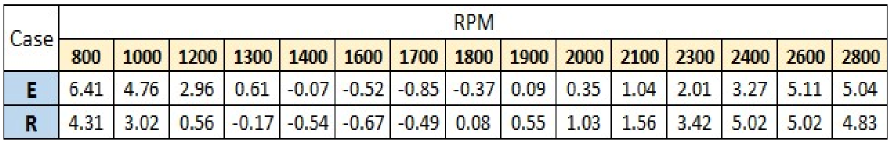
STEP 6:-

This step is basically evaluation of experimental results with respect to set criteria

STEP 7, STEP 8 and STEP 9:-

From the results section, it can be concluded whether process flow chart will end at Step 7 or step 9. If any experimental combination violates the set criteria of emissions level then it will follow path or Step 7 and remaining performance/combustion noise measurement tests will stop. Performances and Noise measurement were performed for those combination and flow path 8; which satisfied set criteria (i.e. - emissions). Discussion section is basically content step -9 of flow chart diagram of methodology.

Table 5.1- Average main injection Timing (SOI- CA BTDC) Vs RPM



Case	RPM														
	800	**1000**	**1200**	**1300**	**1400**	**1600**	**1700**	**1800**	**1900**	**2000**	**2100**	**2300**	**2400**	**2600**	**2800**
E	6.41	4.76	2.96	0.61	-0.07	-0.52	-0.85	-0.37	0.09	0.35	1.04	2.01	3.27	5.11	5.04
R	4.31	3.02	0.56	-0.17	-0.54	-0.67	-0.49	0.08	0.55	1.03	1.56	3.42	5.02	5.02	4.83

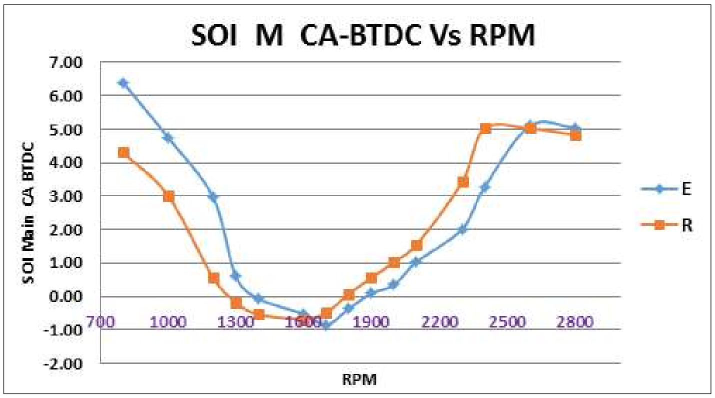


Figure 5.3:- Graph of Avg main injection Timing (SOI- CA BTDC) Vs RPM

Table -5.2: - Main injection timing-E (SOI –CA BTDC) Vs RPM

Fuel Qty mg/hub	RPM														
	800	1000	1200	1300	1400	1600	1700	1800	1900	2000	2100	2300	2400	2600	2800
0	5.45	4.77	4.20	3.85	3.71	3.63	3.49	3.47	3.52	3.60	3.78	4.06	4.99	5.52	6.28
5	5.43	4.64	3.93	3.49	3.32	3.21	3.03	2.97	2.97	3.03	3.21	3.52	4.57	5.16	5.76
10	5.47	4.50	3.65	3.05	2.88	2.72	2.50	2.40	2.35	2.37	2.50	2.83	4.11	4.86	5.23
15	5.52	4.35	3.27	2.50	2.24	2.07	1.78	1.67	1.63	1.63	1.74	2.07	3.71	4.72	4.75
20	5.73	4.33	2.92	1.76	1.34	1.05	0.73	0.68	0.70	0.79	0.94	1.38	3.45	4.70	4.37
25	6.26	4.55	2.57	0.88	0.20	-0.26	-0.59	-0.51	-0.31	-0.04	0.31	0.94	3.32	4.66	4.15
30	6.77	4.77	2.24	-0.02	-0.90	-1.54	-1.82	-1.52	-1.41	-0.97	-0.13	1.34	3.01	4.66	4.04
35	6.99	4.75	1.87	-0.79	-1.82	-2.50	-2.64	-2.15	-1.85	-1.25	-0.35	1.34	3.01	4.66	4.02
40	7.01	4.61	3.54	-1.34	-2.46	-3.21	-3.12	-2.42	-1.89	-1.23	-0.40	1.47	2.22	4.59	4.09
45	7.03	4.53	3.36	-1.60	-2.79	-3.56	-3.38	-2.55	-1.60	-0.83	-0.29	1.71	2.22	4.46	4.33
50	7.03	5.56	3.41	-0.51	-1.32	-1.87	-2.81	-2.59	-1.58	-0.99	0.00	1.71	2.22	4.70	4.70
55	7.01	5.63	3.63	-0.11	-1.16	-1.89	-2.90	-2.37	-0.48	-0.48	0.73	1.41	2.42	6.26	6.04
60	6.99	4.68	1.87	-0.66	-1.43	-2.09	-3.10	-1.45	-0.40	-0.40	1.32	2.33	3.52	6.26	6.35
65	7.01	5.01	1.01	-2.02	-2.72	-3.10	-3.10	-0.75	-0.40	-0.40	1.16	2.00	3.01	6.26	6.46

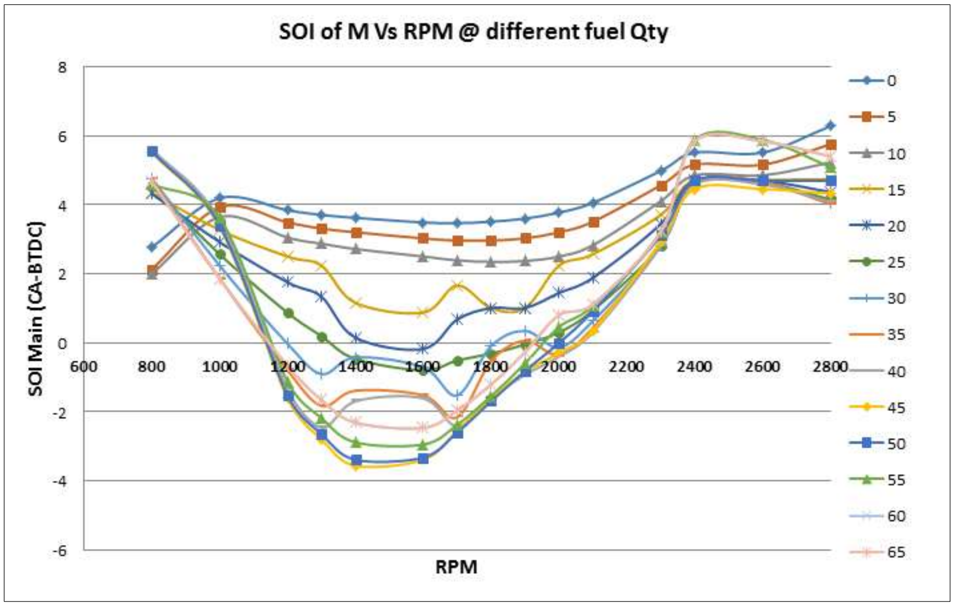


Figure 5.4:- Graph of main injection timing –E (SOI –CA BTDC) Vs RPM

Table -5.3: - Main injection timing (SOI –CA BTDC) Vs RPM

Fuel Qty	RPM													
mg/hub	800	1000	1200	1300	1400	1600	1700	1800	1900	2000	2100	2300	2400	2600	2800
0	2.77	4.20	3.85	3.71	3.63	3.49	3.47	3.52	3.60	3.78	4.06	4.99	5.52	5.52	6.28
5	2.13	3.93	3.49	3.32	3.21	3.03	2.97	2.97	3.03	3.21	3.52	4.57	5.16	5.16	5.76
10	2.00	3.65	3.05	2.88	2.72	2.50	2.40	2.35	2.37	2.50	2.83	4.11	4.86	4.86	5.23
15	4.35	3.27	2.50	2.24	1.16	0.88	1.67	1.01	1.01	2.24	2.57	3.71	4.72	4.72	4.75
20	4.33	2.92	1.76	1.34	0.15	-0.18	0.68	1.01	1.01	1.45	1.89	3.45	4.70	4.70	4.37
25	4.55	2.57	0.88	0.20	-0.46	-0.79	-0.51	-0.31	-0.04	0.31	0.94	2.81	4.66	4.66	4.15
30	4.77	2.24	-0.02	-0.90	-0.42	-0.70	-1.52	-0.09	0.35	-0.13	0.64	2.81	4.66	4.66	4.04
35	4.75	1.87	-0.79	-1.82	-1.38	-1.52	-2.15	-0.53	0.07	-0.35	0.44	2.81	4.66	4.66	4.02
40	5.63	3.54	-1.34	-2.46	-1.69	-1.60	-2.42	-1.58	-0.92	-0.40	0.31	2.81	4.59	4.59	4.09
45	5.54	3.36	-1.60	-2.79	-3.56	-3.38	-2.55	-1.60	-0.83	-0.29	0.35	2.94	4.46	4.46	4.33
50	5.56	3.41	-1.52	-2.64	-3.38	-3.32	-2.59	-1.69	-0.81	0.00	0.92	3.12	4.70	4.70	4.70
55	4.61	3.63	-1.12	-2.18	-2.88	-2.94	-2.37	-1.54	-0.59	0.46	1.08	3.21	5.89	5.89	5.10
60	4.68	1.87	-0.66	-1.65	-2.31	-2.46	-1.96	-1.21	-0.26	0.81	1.12	3.23	5.84	5.84	5.41
65	4.68	1.87	-0.66	-1.65	-2.31	-2.46	-1.96	-1.21	-0.26	0.81	1.12	3.23	5.84	5.84	5.41

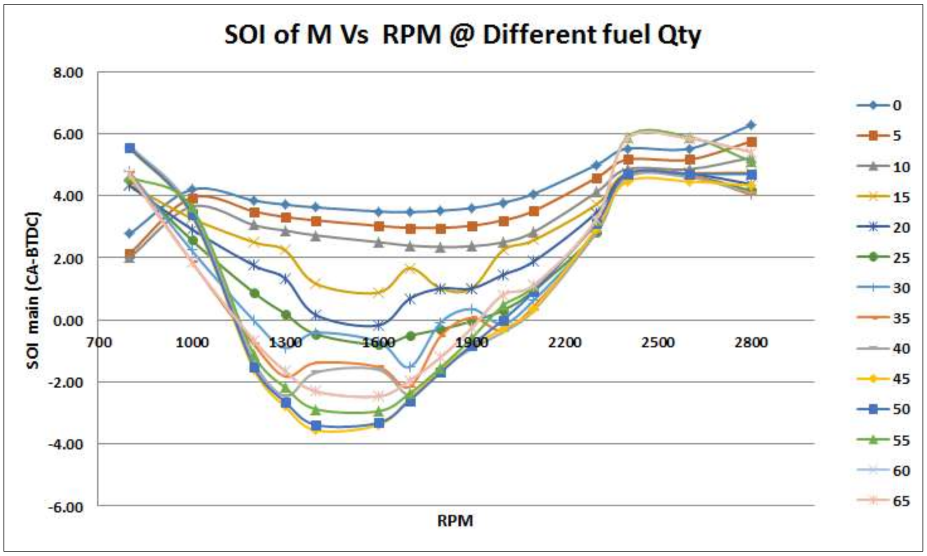


Figure 5.5:- Graph of main injection timing –R (SOI –CA BTDC) Vs RPM

As pointed out earlier (in Step-2), main injection timing (CA-BTDC) namely E and R are used in this carried-out analysis (refer Fig-5.3, Table-5.1). Details of both these injection strategies are represented in tabulated and graphical format in Appendix-A. Here, "E" is the existing main injection timing of base engine. Injection timing was advanced by few crank angles at low to mid RPM of engine in injection timing-R with respect to base one (refer Figure 5.3) . On the other hand, it is just opposite in nature at later part of engine speed range. Initially, benchmarking was done for existing main injection timing of base production engine which was used for experiments. Aforesaid main injection timing R was established based on literature review and study of FMTC matrix of engine by advancing and regarding the main injection timing w.r.t CA from base one. Start of Pilot injection w.r.t (SOI)main injection varies within 19.9° to 39.9° crank angle depending on engine rpmand fuel quantity as per FMTC (1.5 mg/hub) for this engine. Post or after injection is introduced w.r.t main within 1000 to 1350 ms and fuel quantity is as per FMTC data base (2 mg/hub). Early injection timing has been kept same as it is w.r.t Pilot injection. The early injection has been introduced near the torque region speed zone at all load condition in EPMA injection strategy.

Emissions measurements were done as per ESC and ETC standards [139,140]. After evaluation of these results, further decision was taken whether Noise and performance measurement were needed. At the same, combustion noise cannot be measured in test cell along with performance. Hence, engine radiated noise tests were done separately. Mainly DoE approach is used in this carried-out analysis to formulate experimental matrix. The numbers of factors are

1. Injection Strategy – Level2 (i.e.- PMA & EPMA)
2. Main Injection timing - Level 2 (i.e.- E & R)
3. Load – Level- 8 (100%, 90%, 75%, 60%, 50%, 40%, 25% & 10%)
4. RPM- Level-6 (1200, 1400, 1500, 1600,1800,2000,2200 and 2400)

Table-5.4:- DoE Table for Injection Strategy and main injection timing

			Main Injection timing (CA-BTDC)	
			E	R
Injection Strategy	PMA	A	AE	AR
	EPMA	B	BE	BR

Load % and Speed range has been selected considering application of this engine. Here, Load % is indicating the percentage of maximum torque for that particular RPM.

Table-5.5:- DoE table for Injection Strategy -main injection timing combination and load

		Load							
		100%	90%	75%	60%	50%	40%	25%	10%
		1	2	3	4	5	6	7	8
Injection Strategy - timing combination	AE	AE1	AE2	AE3	AE4	AE5	AE6	AE7	AE8
	AR	AR1	AR2	AR3	AR4	AR5	AR6	AR7	AR8
	BE	BE1	BE2	BE3	BE4	BE5	BE6	BE7	BE8
	BR	BR1	BR2	BR3	BR4	BR5	BR6	BR7	BR8

Table-5.6:- DoE table for Injection Strategy and Load combination and RPM

		RPM							
		1200	1400	1500	1600	1800	2000	2200	2400
		S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**
Injection Strategy and Load Combination	**AE1**	AE1S1	AE1S2	AE1S3	AE1S4	AE1S5	AE1S6	AE1S7	AE1S8
	TO								
	AE8	AE8S1	AE8S2	AE8S3	AE8S4	AE8S5	AE8S6	AE8S7	AE8S8
	AR1	AR1S1	AR1S2	AR1S3	AR1S4	AR1S5	AR1S6	AR1S7	AR1S8
	TO								
	AR8	AR8S1	AR8S2	AR8S3	AR8S4	AR8S5	AR8S6	AR8S7	AR8S8
	BE1	BE1S1	BE1S2	BE1S3	BE1S4	BE1S5	BE1S6	BE1S7	BE1S8
	TO								
	BE8	BE8S1	BE8S2	BE8S3	BE8S4	BE8S5	BE8S6	BE8S7	BE8S8
	BR1	BR1S1	BR1S2	BR1S3	BR1S4	BR1S5	BR1S6	BR1S7	BR1S8
	TO								
	BR8	BR8S1	BR8S2	BR8S3	BR8S4	BR8S5	BR8S6	BR8S7	BR8S8

5.3 Results and Discussions

In this section, all relevant Experimental results are shown in tabulated and graphical format better for better understanding. Interferences are drawn at the end.

A. *Results*

This analysis consists of three major experiments namely emissions tests, Noise tests and performance tests respectively. All these are represented below successively. Initially emissions measurement was done as per the plan shown in flow chart diagram (Figure 5.2).

1. Emission Tests

NOx, CO and THC emissions have been measured by sampling of exhaust gases and analyzing using Analyzer. Smoke emissions have been characterized in terms of FSN of exhaust and it was measured using AVL Smoke Meter as shown in schematic (Figure 3.2). The test conditions followed for emissions measurement are as per ESC and ETC standards [139, 140]. Comparative data among the injection strategies have been represented in tabulated format below for analysis.

1.1. *PM, NOx, CO , THC measurement data*

Table 5.7- ESC Test results

	PMA-E	PMA-R	EPMA-E	EPMA -R	Limits
PM	0.015	0.014	0.018	0.013	0.020
NOx	3.13	3.12	**3.513**	2.97	3.500
THC	0.059	0.04	**0.47**	0.01	0.460
CO	0.065	0.07	0.14	0.01	1.500

Table 5.8–ETC Test Results

	PMA-E	PMA-R	EPMA-E	EPMA-R	Limits
PM	0.016	0.022	0.019	0.0123	0.030
NOx	3.133	3.013	**3.527**	3.134	3.500
THC	0.072	0.062	**0.51**	0.047	0.550
CO	0.087	0.071	0.16	0.011	4.000

Above results (Table 5.7 & 5.8) showed that EPMA injection strategy failed marginally in emission tests with existing main injection timing "E". Hence, remain performance trials and combustion noise measurement has not been performed as per the conditions mentioned in flow chart diagram (Figure 5.2).

1.2. *Smoke measurement data*

Smoke values were measured using AVL smoke meter as this provides tentative estimation of soot concentration. Test data are organized for different load cases (100% to 50%) comparative values of smoke level for both the multiple injection strategies (EPMA-R and PM-R) are represented vide graphs (refer Figs-5.6, 5.7, 5.8 and 5.9) for better understanding.

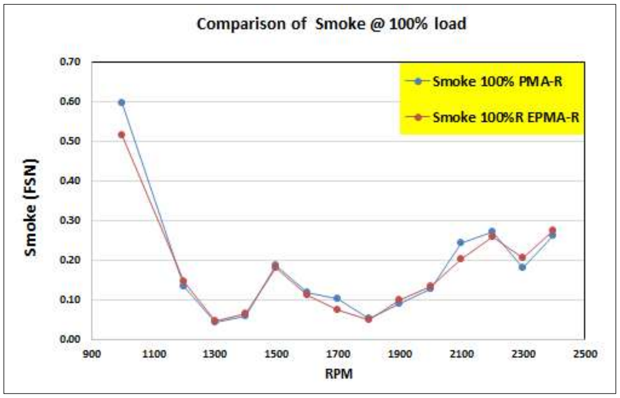


Figure-5.6:-Smoke vs RPM at 100% load

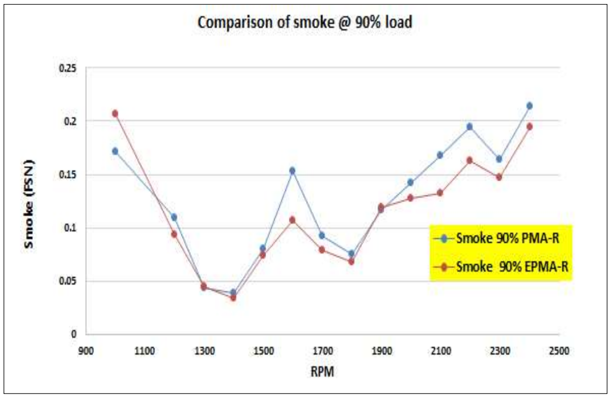


Figure-5.7:- Smoke vs RPM at 90% load

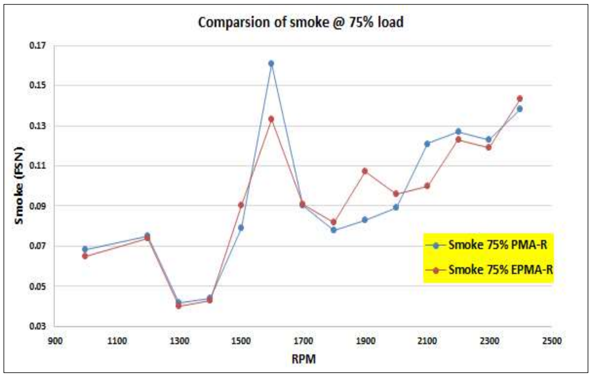


Figure- 5.8:-Smoke vs RPM at 75% load

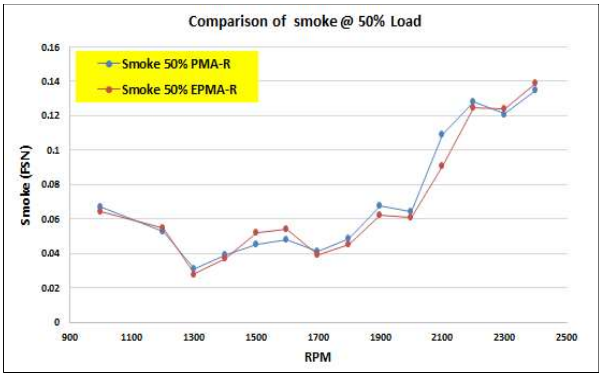


Figure-5.9:- Smoke vs RPM at 50% load

2. *Performance Tests*

Performances tests were performed as per DoE table (Table-5.6). Comparative test data among the injection strategies are characterized below vide graphs.

2.1. BSFC performances

2.1.1. BSFC Performances at combined effect (Load & Speed)

Measured BSFC data for both injection strategies are shown below in comparative graphical format successively.

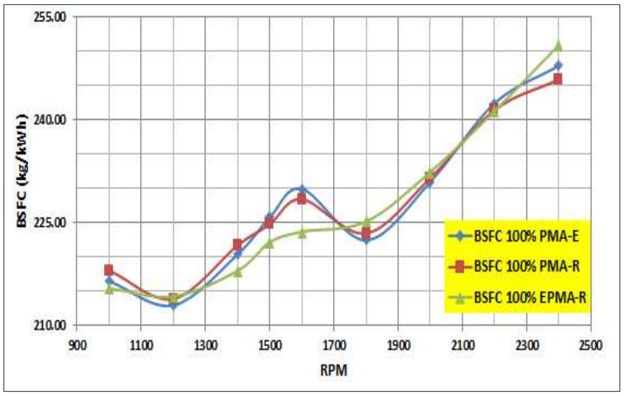


Figure 5.10:-BSFC vs RPM at 100% load

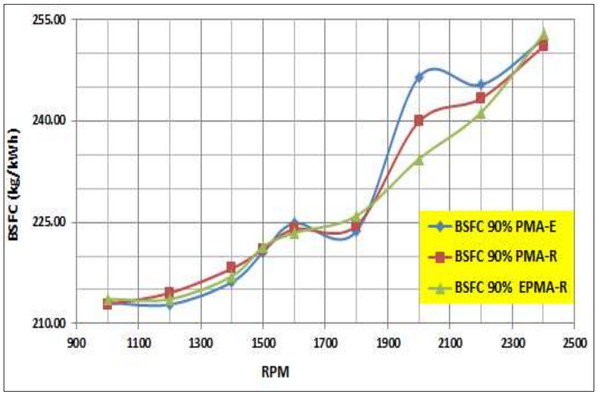


Figure 5.11:- BSFC vs RPM at 90% load

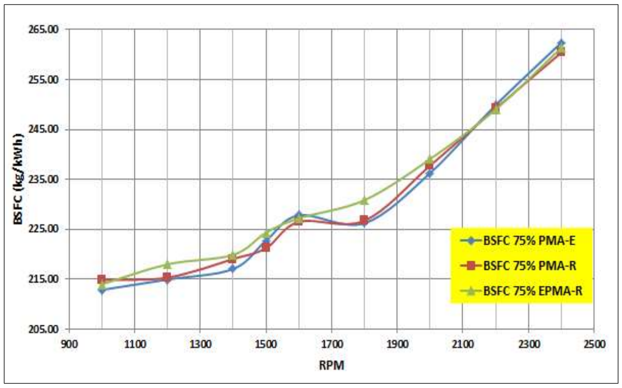


Figure 5.12:- BSFC vs RPM at 75% load

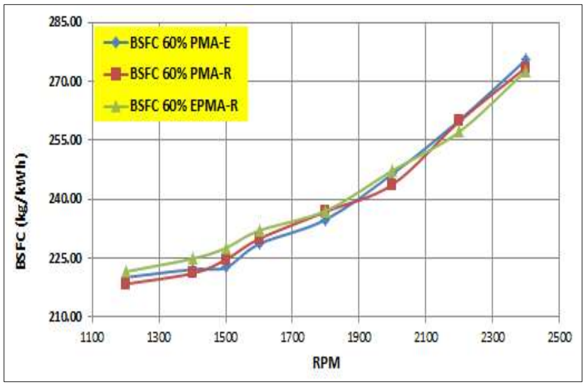


Figure 5.13:- BSFC vs RPM at 60% load

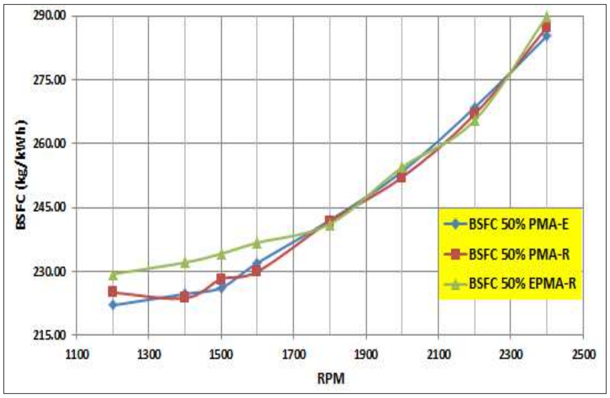


Figure 5.14: -BSFC vs RPM at 50% load

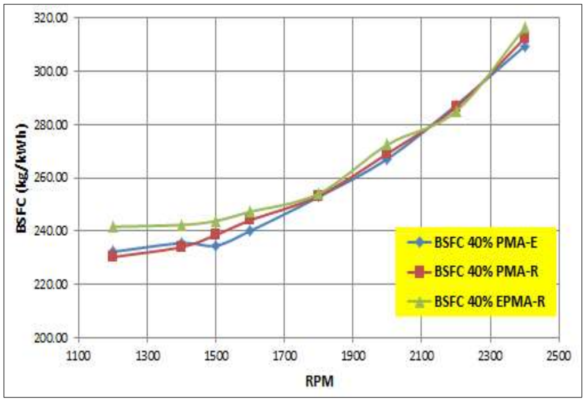


Figure 5.15: - BSFC vs RPM at 40% load

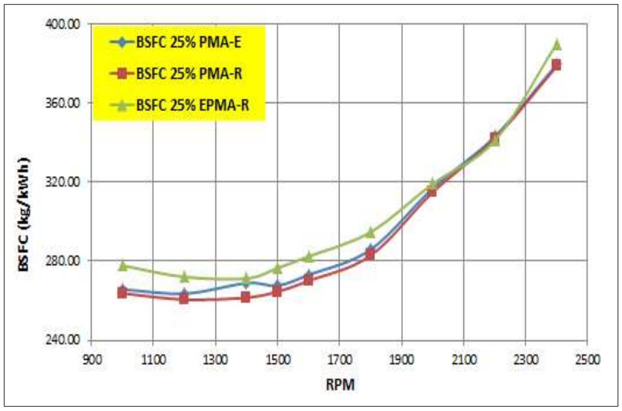


Figure 5.16: - BSFC vs RPM at 25% load

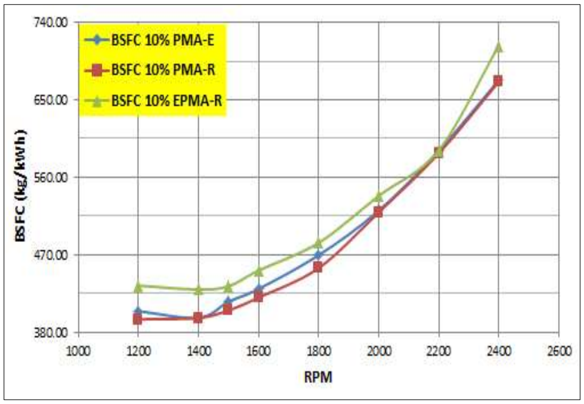


Figure 5.17: - BSFC vs RPM at 10% load

2.1.2. BSFC Performances at Individual Effect

Average BSFC comparison graphs are shown here with reference to operating parameters Load and Speed when either of one of them has not been considered with injection strategies.

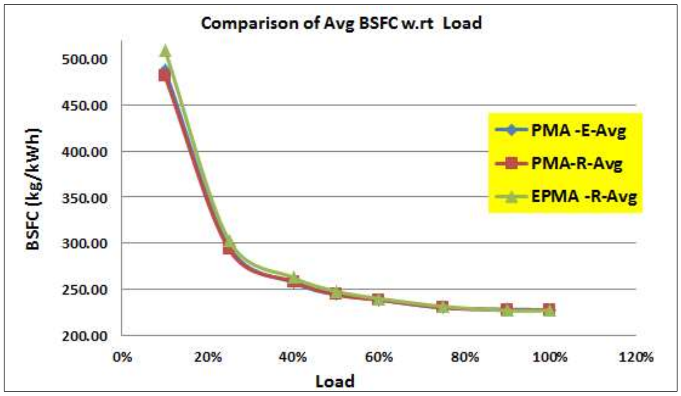


Figure-5.18:–Average BSFC vs Load

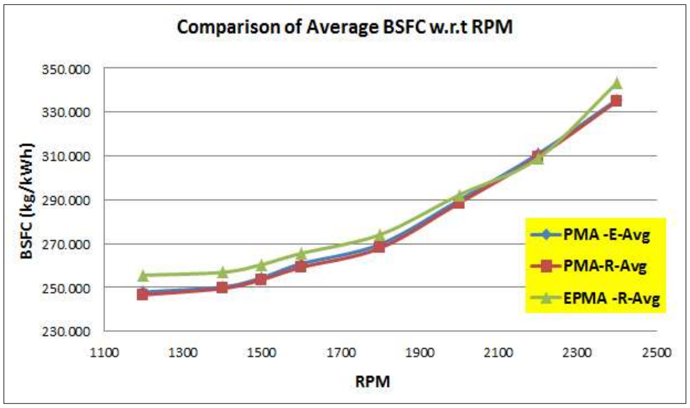


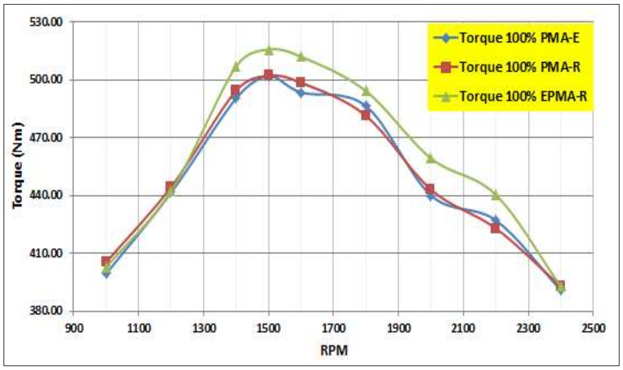
Figure- 5.19:–Average BSFC vs RPM

2.2. Torque Performances

Torque comparison data of both PMA and EPMA injection strategies with reference to existing injection strategy are shown sequentially.

2.2.1. Torque Performances at different combined effects (Load & Speed)

Torque data were measured as per DoE table and those are represented in graphical format below.



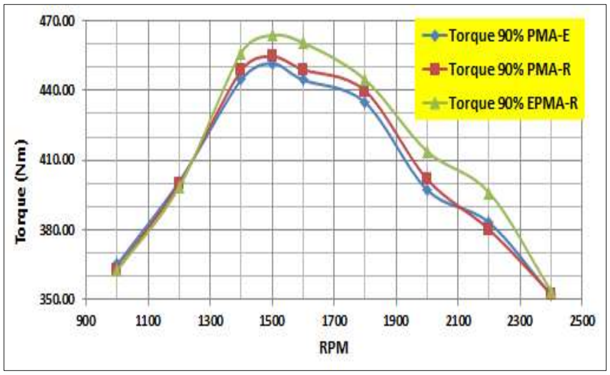


Figure-5.20:- Torque Vs RPM at 100% load

Figure-5.21:- Torque Vs RPM at 90% load

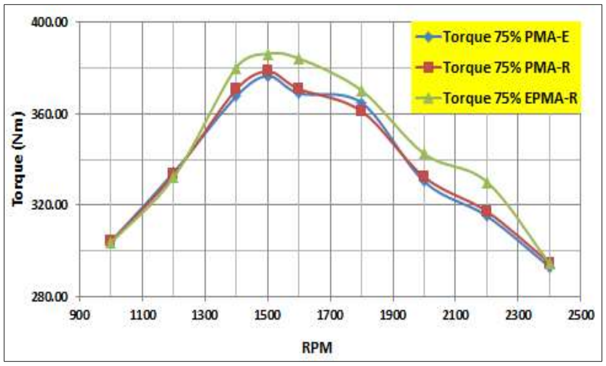


Figure-5.22:- Torque Vs RPM at 75% load

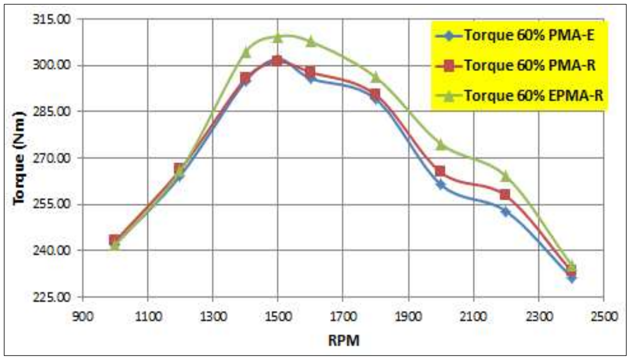


Figure-5.23:- Torque Vs RPM at 60% load

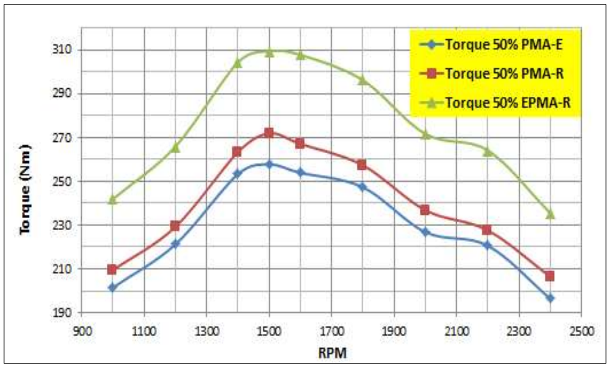


Figure-5.24:- Torque Vs RPM at 50% load

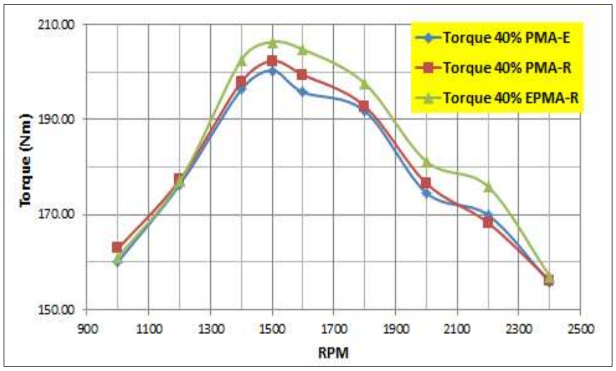


Figure-5.25:- Torque Vs RPM at 40% load

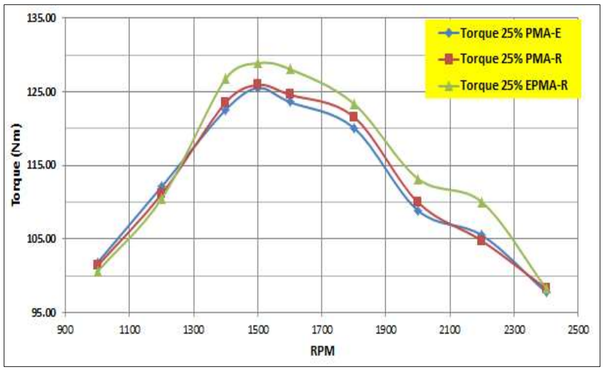


Figure-5.26:- Torque Vs RPM at 25% load

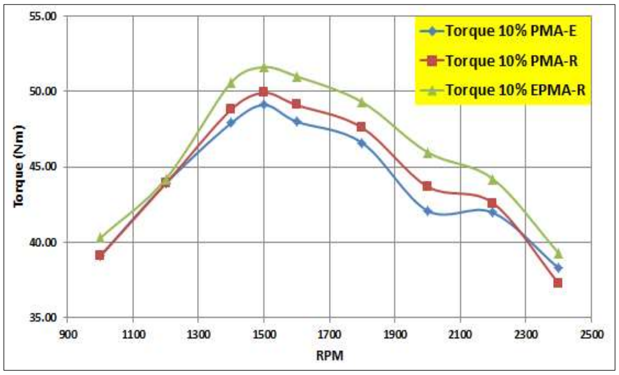


Figure-5.27:.- Torque Vs RPM at 10% load

2.2.2. Torque Performances at Individual effect

Average Torque comparison graphs are characterized underneath with reference to Load and Speed when either of one of them not considered with injection strategies.

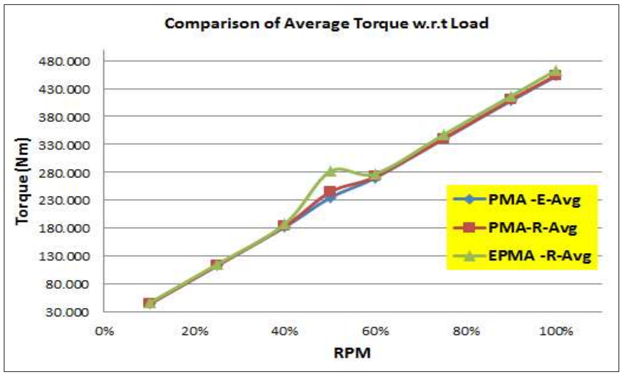


Figure-5.28:-Average Torque Vs Load

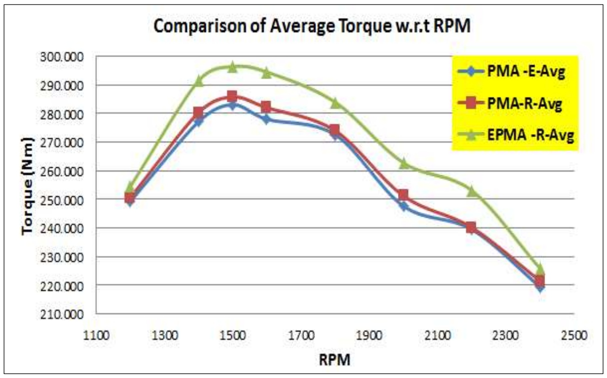


Figure-5.29:-Average Torque Vs RPM

2.3. Power output performances

Engine brake Power output can be calculated for each of injection strategies using below equation and Torque and RPM data.

Power (kW) = Torque (Nm) x Engine Speed (RPM)/ 9549.57 …. (5.1)

3. Noise Tests

Engine radiated noise level was measured following IS: 10399 [141] standard. There are no other specific setup available to measure the combustion noise. During noise tests, microphone was placed in those positions shown in Figure -3.2 and it was 0.5m away from engine surface/envelop. Tests data were captured only after stabilization of exhaust gas temperature at large extend. Also, Laboratory inside ambient noise level data was measured prior to start of engine. All tests date are represented below.

Table 5.9: – Ambient Noise level data of testing laboratory

Location	**1**	2	3	Avg.
Noise Level (dBA)	63	61.9	62.6	62.5

Table 5.10: – Engine radiated Noise Test data

	Location	**100% Throttle**				**50% Throttle**			**30% Throttle**
		2250	**1800**	**1500**	**1200**	**1800**	**1500**	**1200**	**1200**
PMA-E	**1**	98.4	95.5	90.9	91.1	95.4	93.2	91.8	88.4
	2	96	93	90.1	89.3	92.7	90.5	88.9	86.8
	3	98.1	94.7	92.1	92.2	95.5	92.9	91.4	88.2
PMA-R	**1**	98.3	95.4	90.8	91.2	95	92.9	91.4	88
	2	95.9	92.9	90	89.1	92.4	90.1	88.6	86.4
	3	98	94.5	92	92.2	95.1	92.3	91.2	88.5
EPMA-R	**1**	98.2	95.3	90.7	90.9	95.3	91.1	91.2	85.6
	2	95.7	92.7	89.9	89.2	92.4	89.8	88.3	83.3
	3	97.9	94.5	91.9	92.1	95	91.8	91.3	85.3

B. Discussions

From test data which are represented in tabulated and graphical format, the following points can be inferred:

a. EPMA injection strategy is failed in emission tests with existing base main injection timing –E. Hence, remaining performances and Noise tests have not been done with main injection timing –E as per DoE table (refer Table- 5.6- BE1- BE8). This is as per the flow chart diagram of methodology (Fig-5.2)

b. In terms of emissions level, significant improvement witnessed in PM, THC and CO level with EPMA injection strategy in comparison to PMA with main injection timing –R. whereas emission level of NOx is marginal inferior for same as per ETC in comparison to PMA (refer Table- 5.7 and 5.8).

c. EPMA injection strategy has revealed marginal improvement on smoke level (reduction) in almost entire engine speed range at higher load conditions among the injection strategies (refer Fig- 5.6 to 5.9). This indicates the reduction of soot concentration with EPMA injection strategy.

d. Base PMA injection strategy with main injection timing –E (AE1- AE8 in Table-5.6) has exhibited hump nature BSFC curve near peak torque zone at 100% load and 75% load (Fig-5.10 and Fig-5.12). Same kind of feature was observed near 1800-2200 rpm when it's operated under 90% load (Fig-5.11). PMA injection strategy with new main injection timing –R has exhibited some extend of improvement over base one (PMA-E). EPMA-R injection strategy has shown significant improvement on fuel consumption or BSFC at higher loads especially at peak and 90% load (refer Fig-5.10, 5.11 and Fig-5.12).

e. For decreasing load cases, BSFC values increase marginally with EPMA-R injection strategy with respect to other (base PMA-E and PMA-R)in the zone of lower RPM to peak torque RPM (refer Fig-5.13, 5.14, 5.15, 5.16 and 5.17) .

f. The average BSFC curves for both EPMA and PMA injection strategy have exhibited the tendency of higher fuel consumption at decreasing loads (ref Fig-5.18) and this is up to same level similar to BSFC curves at combination effects (refer Fig- 5.13 to 5.17). In other hand, average BSFC curves are smoother and parallel whereas these are not similar at combination cases with higher to mid-range loads (refer Fig-5.10, 5.11, & 5.12). Average BSFC curves w.r.t RPM are quite similar to BSFC curves of 60% load case in combination effects (refer- Fig-5.19, 5.13)

g. EPMA-R injection strategy combination has shown quite smoother torque curve and increasing trend of value of torque after 1200 rpm in comparison to other one (PMA-E and PMA-R) at each load cases(Fig- 5.20, 5.21, 5.22, 5.23, 5.24 and 5.25). It is known that smooth Torque pattern provides better drivability and EPMA-R injection strategy has able to satisfy large extend. PMA injection strategy with new main injection timing –R has exhibited marginal improvement in both torque value and smoothness over base one (PMA-E).

h. Average Torque curve for base PMA-E case is straight and increases as load % increasing whereas, it is not similar for EPMA-R injection strategy. Average Torque value increases suddenly from near 40% to 75% loads and creates dome curve shape. (Refer Fig-5.28).Average Torque curves w.r.t RPM is quite similar with Torque curves at 50% load case in combination effects (ref- Fig-5.29, 5.23).This is indicating that pilot (specially twin pilot –EP) injection with advancement of injection timing increases the in-cylinder pressure and heat release rate which causes improvement of torque without penalty of smoke level.

i. EPMA-R Injection Strategy has influenced engine radiated noise level significantly. Table 5.10 is conveying the impression of same. Noise reduction was observed at entire RPM range but major impact perceived at low RPM at low throttle %. On an average 3dBA of noise reduction has been detected at Low rpm in comparison to existing PMA-E. Also, PMA-R injection strategy combination has displayed marginal improvement of noise reduction of around 0.2-0.5 dBA w.r.t existing one (PMA-E).

5.4 Conclusions

From this analysis, it can be concluded that EPMA injection strategy is better with respect to PMA in terms of performances (Torque, BSFC), smoke, emissions and Combustion noise level without violating emissions norms and at same EGR %. Emissions level of THC, CO and PM are improved with this injection strategy except NOx at ETC standard. PMA injection strategy with few degree advancement of main injection timing, is marginally superior in performances specially Torque and combustion noise.

This Carried-out analysis has given an idea, how BSFC and torque nature and combustion noise level while different parameters, such as load, speed and main injection timing are tweaked simultaneously. This work deals with 3 parameters namely Speed, Load and main injection timing (dynamic). Among these, Load and main injection timing are more sensitive on performance and emissions of engine (refer preceding section). This has been proved from outcome of experimental results as per DoE-Table.

It is well known from literate that a short early injection coupled with a pilot injection is effective in reducing both fuel consumption and exhaust emission levels, particularly the NOx and particulate emission. This study has corroborated this statement. The BSFC is strongly affected by the early injection duration, whereas the other injection parameters are less influencing.

Also, previous literatures suggest, EPM strategy is very effective in reduction of combustion noise and fuel consumption in comparison to double injection (PM) strategy but emissions level increases. In other hand, PMA strategy influences largely to reduce the soot but timing is needed to be selected carefully. In the present study, EPMA injection strategy has revealed the above statement.

Prior scientific researchers have shown that Injection rate shape, compression ratio, and dynamic injection timing, have dominant effects on combustion noise at idle. At idle and at low speeds and loads, the pilot or split injection and the double pilot or split injection reduce the noise level significantly. Present work deals with the single pilot, Double pilot injection strategy and dynamic injection timing. For Twin Pilot EPMA injection strategy, near 3 dBA of noise reduction observed with respect to base one (PMA-E) at low Speeds. Marginal (near 0.3-0.5dBA) level of noise reduction exhibited with advance injection timing (main injection-R) among the single pilot injection strategies (i.e. - base PMA-E and PMA-R).

BSFC Curve of EPMA injection strategy is much better and smoother but BSFC values are comparatively higher at mid to low speed range in comparison to other injection strategy (Base PMA-E and PMA-R). Hence, it can be work further to investigate and improve BSFC performance of EPMA strategy at aforesaid speed range.

From this research work, it can be further concluded that engine torque which is limited by exhaust smoke number, can be improved by pilot injection with advancement of injection timing inline to reduction of combustion noise. Specially, double pilot injection strategy (EPMA-R) having advanced injection timing shows significant improvement (~5 to 14% at different load %) of torque over existing (PMA-E). Torque curves, noise test data and emission measurement data (including smoke curves) of this work is representing the same. This phenomenon can be explained by using in-cylinder heat release rate and pressure data analysis. But, this is one of innovativeness of present work that facts are clarified based on survey of available literatures and without doing sophisticated measurement of in-cylinder pressure and heat release data. Actually, pilot (especially double pilot –EP) injection with advanced injection timing enhances the in-cylinder pressure and heat release rate which causes increase of engine torque without crossing smoke number. Double pilot injection increases the total heat release. This leads to decrease of ignition delay of the main injection fuel due to the increased temperature at the start of the main injection. Thus, combustion noise reduces significantly in double pilot injection strategy (EPMA) in comparison to existing.

Present analysis has been conducted with single injection parameter namely dynamic main injection timing (SOI CA-BTDC) along with two operating parameters. Few other important injection parameters like dwell timing, pilot fuel quantity can be included and worked out further. Details sensitivity analysis is to be done among these parameters. Further, this work done without altering EGR% and hence, this is one of further broad scope of work to include.

Chapter -6

Comparative Analysis of Combustion Noise, Performance and Emission of LTC Diesel engine with multiple Injections

6.1 Objective of this Work

Fuel injection strategy has become the heart of modern diesel engine due to its better control on combustion process, which ensures improvement in performance (BSFC, Torque) and combustion noise (CN) with simultaneous reduction of emissions. In this chapter, impact of Quadruple(epMa), Triple (pMa) and Double (pM) injection strategies have been studied on a typical 6 cylinder Low Temperature Combustion (LTC) CRDI diesel engine. Experiments were conducted at 5 different speeds (Low to high) and 3 engine load conditions (20%, 60% and 100% of maximum torque respectively) with higher EGR fraction of 45% and fixed main injection timing (Crank angle) using conventional diesel (BS-IV) fuel**.**

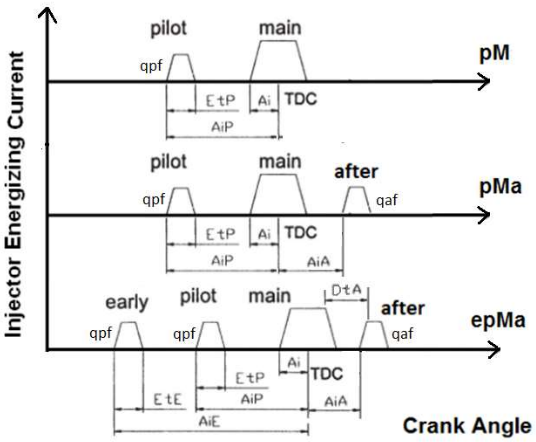


Figure 6.1:- Injection Strategies – (i) pM (Pilot-Main) (ii) pMa (pilot-main-after); and (iii) epMa (early –pilot –main –after/post)

In Fig 6.1, following are the representation : qpf -quantity of fuel at pilot or early pilot injection, qaf-quantity of fuel at after or post injection, DtA- After injection Dwell, Ai- main injection advance w.r.t TDC; AiE- early injection advance w.r.t TDC, AiP- pilot injection advance w.r.t TDC, AiA **-**After injection w.r.t TDC, TDC- Top dead centre.

6.2 Experimental Methodology

The typical engine is with a defined FMTC (fuel-mass-torque cycle) where broad outline of fuel demand for any particulate torque and speed mapped by Bosch (EDC-17). Calibration, diagnostics and validation activities are monitor using INCA software. Allowable Smoke limits for the production engine has been outlined for part loads as well as full load application. The base BS-IV engine is with Triple injections and have AiP 19.9 CA BTDC, SOImain 6 to -3 CA BTDC and AiA -12 CA BTDC with qpf – 1.5 mg/hub , qaf – 2 mg/hub , DtA is 1350 ms. Keeping EGR % unchanged, key focus has been given on comparative study and understanding the effect of different multiple injection strategies on performance (BSFC and torque) and exhaust emissions trade off and combustion noise. To adopt all three injection strategies (i.e. - epMa, pMa, pM) delta optimization done on base level calibration to reduce variable factors in experimentation and complexity. After treatment arrangement, remain same as in production engine during the experiments. Also, Clutch, Gearbox (transmission), external Cooling/ Intake system, engine mounts adopted in this test bed from production models where the typical engine in use.

Table 6.1:- DoE matrix inputs –factors, Level and Value

Factors	Level	Value
Double injection	X	pM
Triple injection	Y	pMa
Quadruple Injection	Z	epMa
Load (%)	L1, L2, L3	20, 60, 100
Speed (rpm)	N1, N2, N3, N4, N5	1200,1500,1800, 2100, 2400
Fixed Factors	EGR	45%
	Ai	1°CA BTDC
	AiP	19°CA BTDC
	AiE	39°CA BTDC
	AiA	-12°CA BTDC
	DtA	1100ms

DoE method is used in this experimental research work for systematic approach of testing. The experimental tests are conducted as per the DoE matrix shown in Table -6.2 for performance and emissions. The data captured under steady state condition and average of 20 cycles for each set of data. Emission tests were done based on 13-modes ESC (steady state cycle) with an ELR (dynamic load response) smoke test and more realistic operating condition ETC standard to check whether it's meeting the regulatory norms or not. Engine radiated (combustion Noise) noise level was measured taking reference of IS: 10399 [141] standard.

Table 6.2:- DoE matrix for Performance & emissions Tests

Injection strategy, Load and Speed combination		**Speed (rpm)**					
		N1	***N2***	***N3***	***N4***	***N5***	
pM	*XL1*	XL1N1	XL1N2	XL1N3	XL1N4	XL1N5	
	XL2	XL2N1	XL2N2	XL2N3	XL2N4	XL2N5	
	XL3	XL3N1	XL3N2	XL3N3	XL3N4	XL3N5	
pMa	*YL1*	YL1S1	YL1N2	YL1N3	YL1N4	YL1N5	
	YL2	YL2S1	YL2N2	YL2N3	YL2N4	YL2N5	
	YL3	YL3S1	YL3N2	YL3N3	YL3N4	YL3N5	
epMa	*ZL1*	ZL1N1	ZL1N2	ZL1N3	ZL1N4	ZL1N5	
	ZL2	ZL2N1	ZL2N2	ZL2N3	ZL2N4	ZL2N5	
	ZL3	ZL3N1	ZL3N2	ZL3N3	ZL3N4	ZL3N5	

6.3. Results and Discussion

Here, all experimentally found test results are presented in tabular and graphical form for better understanding. Interferences are drawn afterwards.

6.3.1 Combustion Noise (CN) Performance

CN level date are measured based on IS: 10399 [141] standard which is about noise measurement methodology at stationary vehicle. There is no other explicit experimental setups available for measurement of noise inside the combustion chamber. The noise data are captured for lower speeds (N1&N2). During noise trials, microphone was placed 0.5m away from engine surface/envelop and Positioned as per scheme shown in Figure 3.2 Testing data were acquired only after stabilization the exhaust out gas temperature at larger extend. Prior to start of typical experimental engine, ambient noise (dBA) level values are captured of inside of Laboratory.

Table 6.3:- Nearby Noise (CN) test results

Injection Strategy Speed/Location		**Load 20%**			**Load 60%**			**Load 100%**		
			1200	*1500*		*1200*	*1500*		*1200*	*1500*
pM	2		89.8	91.2		93.1	93.5		95.3	96.3
	4		89.3	90.8		92.8	93.2		94.9	96.0
pMa	2		89.9	91.3		93.3	93.6		95.5	96.5
	4		89.5	90.9		93.0	93.3		95.1	96.1
epMa	2		87.5	89.4		90.9	91.4		93.1	94.2
	4		87.1	88.8		90.6	91.1		92.8	93.9

All tests date are represented in Table no. 6.3 and from this results, it observed around 2-3 dBA noise reduction with epMa found at low load condition.

6.3.2 BSFC Performance–

6.3.2.1 Effect of Engine speed on BSFC at Fixed Loads

Figs. 6.2 - 6.4 show the effect of engine speed on BSFC at fixed loads as indicate in the figure captions

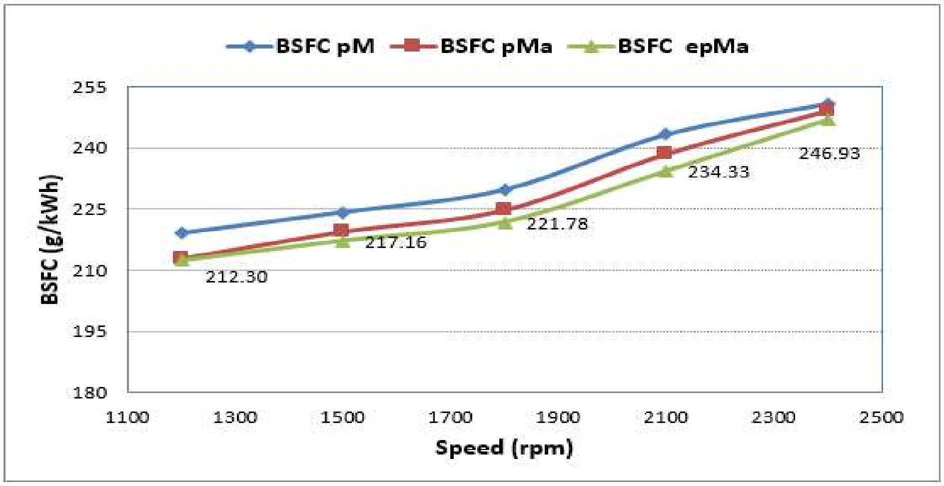


Figure 6.2: BSFC Graph at 100% Load

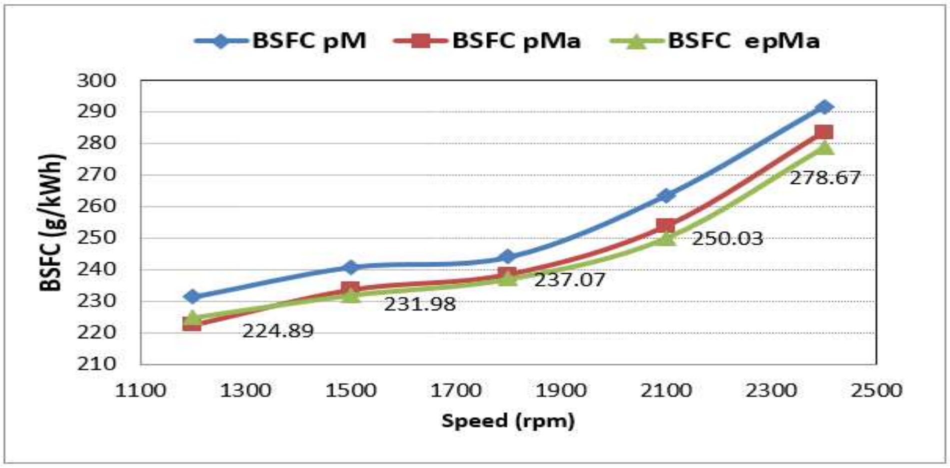


Figure 6.3: BSFC Graph at 60% Load

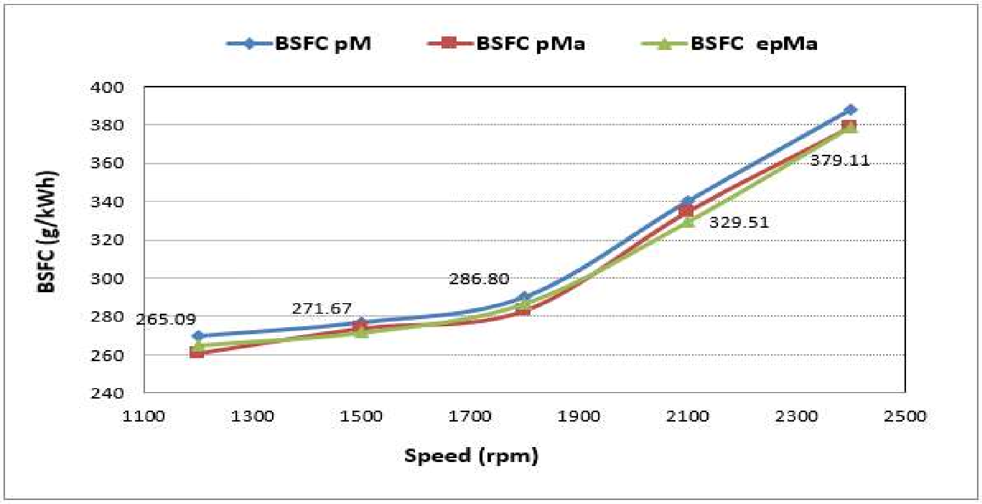


Figure 6.4: BSFC Graph at 20% Load

6.3.2.2 Average BSFC at different speeds

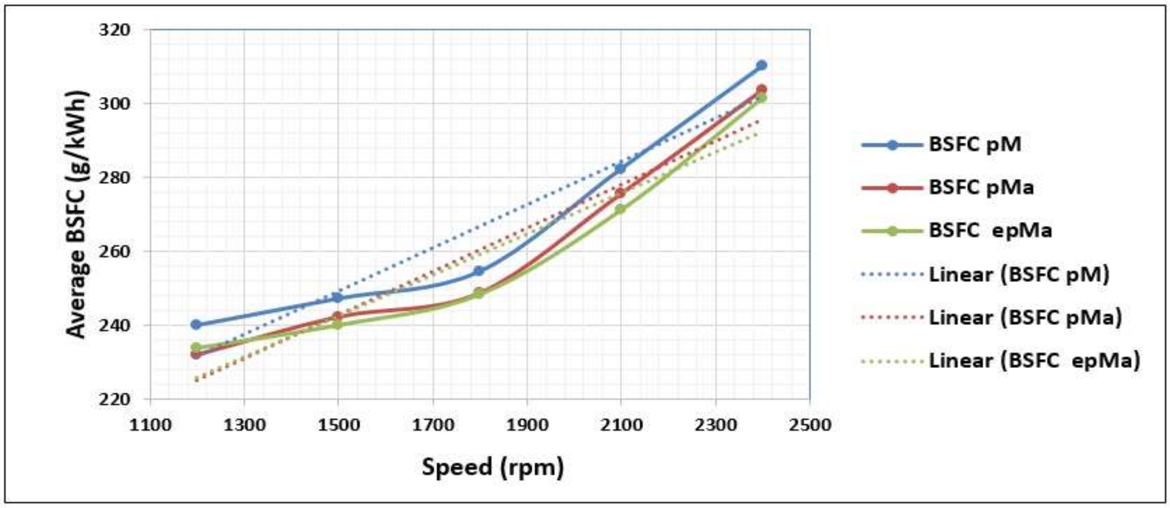


Figure 6.5: Average BSFC Trend at different Speeds

From the BSFC Graphs (ref Fig 6.2- 6.5), it has been observed that epMa provides better BSFC performance from medium to high speed range for all load conditions with a smoot variation. On the other hand, it exhibits relatively poor BSFC at low speed range w.r.t pMa injection strategy. Among these double injection strategy (pM) shows worst BSFC performance.

6.3.3 Smoke (FSN) emission - Fixed Load at different speeds

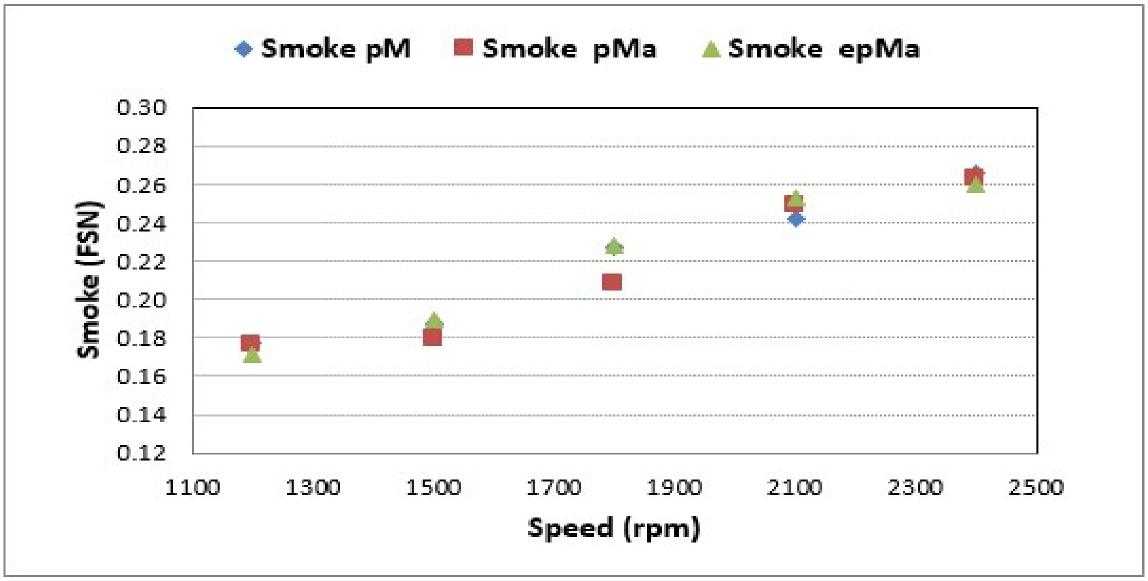


Figure 6.6: Smoke plot at 100% Load

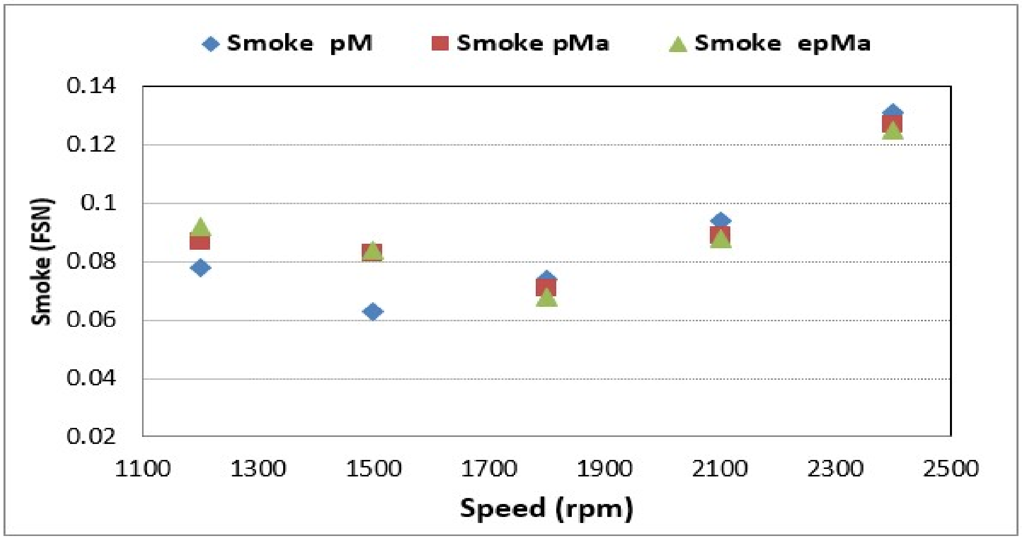


Figure 6.7: Smoke plot at 60% Load

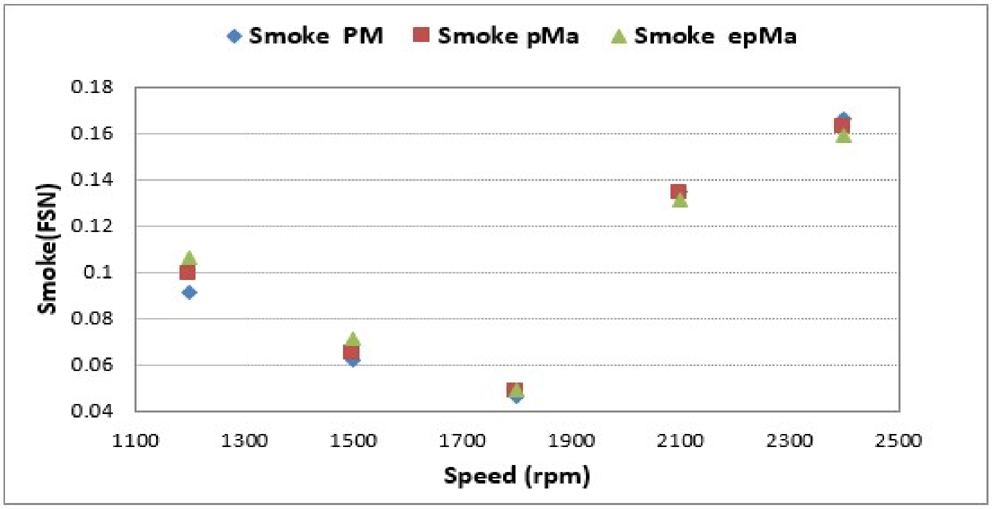


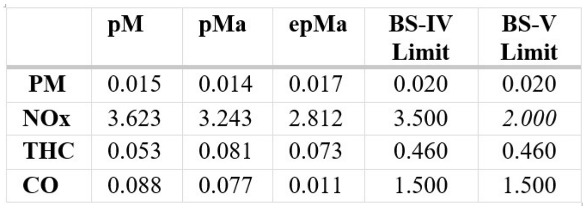
Figure 6.8: Smoke plot at 20% Load

The tests were conducted in reference of to ELR. The smoke plots (Refer Fig 6.6, 6.7 & 6.8) indicating that epMa produce (marginally) highest smoke level especially at low to medium speed ranges where as pMa gives intermediate results.

6.3.4 Emission test as per ESC and ETC standard

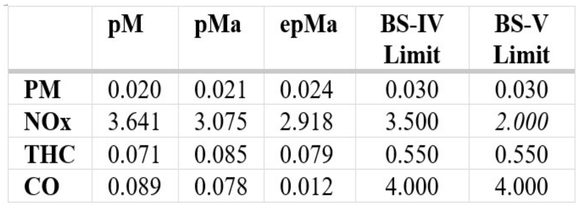
Emission test results as per ESC (European Stationary Cycle) and ETC (European Transient Cycle) standards [140] are represented in tabulated format below. These Test standards are applicable for up to BS-V emission legalization and Part of ARAI- MoRTH /CMVR/TAP-115/116 guide line [139].

Table 6.4:- ESC Test Results



	pM	pMa	epMa	BS-IV Limit	BS-V Limit
PM	0.015	0.014	0.017	0.020	0.020
NOx	3.623	3.243	2.812	3.500	*2.000*
THC	0.053	0.081	0.073	0.460	0.460
CO	0.088	0.077	0.011	1.500	1.500

Table 6.5:- ETC Test Results



	pM	pMa	epMa	BS-IV Limit	BS-V Limit
PM	0.020	0.021	0.024	0.030	0.030
NOx	3.641	3.075	2.918	3.500	*2.000*
THC	0.071	0.085	0.079	0.550	0.550
CO	0.089	0.078	0.012	4.000	4.000

Both pMa & epMa injection strategies meet the emission test norms among the injection scheduling but epMA results are optimum due to controlled heat release rate inside the combustion chamber. In case of pM, heat release rate and mean gas temperature are highest amongst the injections, which justifies the emission results (Refer Table 6.4 and 6.5).

6.4. Conclusion

From this experimental study, it can be concluded that double pilot with a post/after injection scheduling (epMa) Quadruple injection strategy is better in providing optimum BSFC performance and emission level even at fixed main injection timing w.r.t Double (pM) and triple (pMa) injection strategies. Also, this epMa strategy is finest and capable of reducing Combustion noise around 2-3 dBA at low loads and speeds over other two injection strategies. NOx emission level is also lowest as a consequence of marginal higher smoke level at low speeds and loads with Quadruple injections. In totality, it is indicating that quadruple injection scheduling has better control on combustion process by reducing the ignition delay, controlling the rate in cylinder pressure rise and heat release rate and combustion gas temperature during rapid or diffusion combustion phase. These are the key factors which controls NOx, Particulate Matter (or Soot), THC, CO, Combustion Noise and BSFC.

Chapter -7

Assessment of Quadruple Injection Strategy over three different Triple Injections

7.1 Objective of this Work

The present study aims to investigate the effectiveness of quadruple (early-pilot-main-after [epMa]) injection strategy over three different triple [early-main-after (eMa), early-pilot-main (epM) and pilot-main-after (pMa)] injection scheduling in terms of emissions, performance [brake specific fuel consumption (BSFC), torque, brake thermal efficiency (BTE) and fuel economy] and noise. The experimentation was carried out on a heavy-duty BS-IV diesel engine with 45% EGR fraction and fixed main injection (Crank-angle) scheduling at eight different RPMs and three loads of engine (20%, 60% and 100%) using design of experiments(DoE).

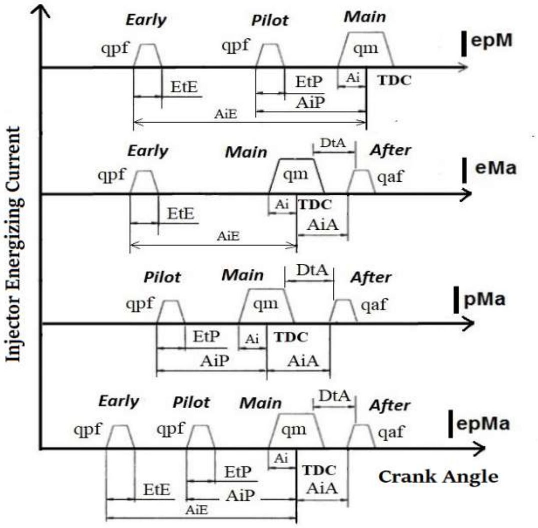


Figure 7.1:- Schematic representation of quadruple and three triple injection strategies

In Fig.7.1, the following are represented: epM, eMa and pMa-triple injections; epMa-Quadruple injections; TDC-Top dead centre; CA-Crank angle; Ai-Main injection advanced w.r.t TDC; AiE-Early injection advanced w.r.t TDC; AiP-Pilot injection advanced w.r.t TDC; AiA-After injection w.r.t TDC; DtA-after/post-injection Dwell; p-Pilot or Pilot injection 2; e-Pilot injection 1 or early injection; qm-quantity of fuel at main injection; qpf/qaf-Quantity of fuel at pilot/early and after/post-injection.

7.2 Experimental Methodology

The The typical engine has EGR for in-cylinder NOx reduction and Bosch-make CRDI system. It also has a definite fuel-mass torque cycle (FMTC) where the broad outline of fuel demand for any particulate torque and speed was mapped. Calibration, diagnostics and validation activities were monitored using INCA software. The permittable smoke limit for the base engine has been outlined for partial as well as full load application with pMa injection schedule. Fuel mass (FM) and engine speed are functions of fuel injection pressure (FIP). Therefore, FIP varies within 120–170 MPa based on the FM and engine speed (RPM). In the present study, EGR% was the same as the typical production diesel engine (Table 3.1).

Herein, the key focus was on the comparative study and understanding the effect of four different multiple injection strategies on performance (mainly BSFC) and exhaust emissions trade-off and CN. The base engine also had pMa triple injection schedules (Ai variable 6 to -3° CA BTDC, AiP - 19.9° CABTDC, DtA 1350 ms), which meets BS-IV norms. To adopt all four injection strategies (i.e., epMa, pMa, eMa and epM), delta optimisation was carried out at the base level calibration to reduce variable factors in experimentation and complexity. After-treatment arrangement was carried out similarly as in production/base engine during the experiments. In this test bed, the clutch, gearbox, external cooling/intake system and engine mounts adapted from production models were used in a typical engine.

The DoE method used in this study for a systematic approach of testing was based on the inputs presented in Table 7.1. The experiments were conducted as per the DoE matrix shown in Table 7.2 for performance and emissions. The data were captured at a steady-state condition, considering an average of 20 cycles for each dataset. To deal with uncertainty in measurement data, especially for the sensitive fuel economy and emissions, NBL-141 guidelines (Issue 2, Amendment No. 3, 2000)[143] were followed in the laboratory. The emission tests were based on European stationary cycle (ESC) with an European load response (ELR) for smoke trial and European transient cycle (ETC) standards [140] to verify the results in reference to regulatory norms. Radiated noise/CN of engine was measured based on the IS: 10399 [141] standard on noise measurement methodology of a stationary vehicle. During the noise trial, the microphone was placed as shown in Fig. 3.2. Test data were acquired only after stabilization of exhaust gas temperature. Furthermore, the ambient noise of test rig was measured before the start of the trials. PBN trial was conducted as per IS: 3028 [142] to understand the vehicle level impact. CSFC or CSFE performance of vehicle was measured based on AIS-149 [144] to evaluate the real-time effect. This standard provides the guidelines to calculate the target CSFC at 40 kmph and 60 kmph speed based on engine specification, driveline configuration (e.g. 4×2) and vehicle GVW.

Table 7.1:- DoE matrix inputs: factors, level, and value

Factors	Level	Value
Triple Injection1	A	epM
Triple Injection 2	B	eMa
Triple Injection 3	C	pMa
Quadruple Injection	D	epMa
Load (%)	L1, L2, L3	20, 60, 100
Speed (rpm)	N1, N2, N3, N4, N5, N6, N7, N8	1100, 1300, 1500, 1700, 1900, 2100, 2300, 2500
Fixed Factors	EGR	45%
	Ai	2 °CA BTDC
	AiP	19 °CA BTDC
	AiE	39 °CA BTDC
	DtA	1100 ms

Table 7.2:- DoE matrix for performance and smoke emissions tests

Trial Combination		Speed (RPM)							
		N1	N2	N3	N4	N5	N6	N7	N8
epM	AL1	AL1N1	AL1N2	AL1N3	AL1S4	AL1N5	AL1N6	AL1N7	AL1N8
	AL2	AL2N1	AL2N2	AL2N3	AL2S4	AL2N5	AL2N6	AL2N7	AL2N8
	AL3	AL3N1	AL3N2	AL3N3	AL3S4	AL3N5	AL3N6	AL3N7	AL3N8
eMa	BL1	BL1N1	BL1N2	BL1N3	BL1S4	BL1N5	BL1N6	BL1N7	BL1N8
	BL2	BL2N1	BL2N2	BL2N3	BL2S4	BL2N5	BL2N6	BL2N7	BL2N8
	BL3	BL3N1	BL3N2	BL3N3	BL3S4	BL3N5	BL3N6	BL3N7	BL3N8
pMa	CL1	CL1N1	CL1N2	CL1N3	CL1S4	CL1N5	CL1N6	CL1N7	CL1N8
	CL2	CL2N1	CL2N2	CL2N3	CL2S4	CL2N5	CL2N6	CL2N7	CL2N8
	CL3	CL3N1	CL3N2	CL3N3	CL3S4	CL3N5	CL3N6	CL3N7	CL3N8
epMa	DL1	DL1N1	DL1N2	DL1N3	DL1S4	DL1N5	DL1N6	DL1N7	DL1N8
	DL2	DL2N1	DL2N2	DL2N3	DL2S4	DL2N5	DL2N6	DL2N7	DL2N8
	DL3	DL3N1	DL3N2	DL3N3	DL3S4	DL3N5	DL3N6	DL3N7	DL3N8

7.3 Results and Discussions

The experimental data are presented in tabular and graphical form. In the current study, three major tests were conducted to evaluate performance, emissions and noise sequentially. The data of comparative trials of BSFC and torque among the strategies are shown below. The measured data points have been mentioned on the epMa curve or chart for clarity.

7.3.1. *Rig Level Tests*

7.3.1.1 BSFC, Torque and BTE Performance

Performance test data are plotted in graphical format for each load and speed combination as per the DoE strategy (Table 7.2). Torque (Tr in Nm) and fuel flow rate (FFR in kg/h) were directly measured during experimentation. BSFC (g/kWh) was calculated using equation (7.1), where N is engine speed in RPM.

$$\mathrm{BSFC} = ((\mathrm{FFR\ x\ 1000})/((\mathrm{Tr\ x\ N})/9549.57)) \qquad (7.1)$$

The average BSFC performance was the best for quadruple injection strategy among the schemes at 100% load, although at few speeds, pMa performed better (Fig. 7.2). In addition, the BSFC curve was smoother with quadruple injection strategy than triple injections, while epM and eMa strategies are the bottom two performers in BSFC. The quadruple injection displays the optimum torque performance among the injection strategies (Fig. 7.3). Conversely, epM shows the best torque performance in 1200–1800 RPM zone. Herein, the torque performance of pMa strategy was second optimum, and the eMa strategy was the poorest in torque performance at 100% load at almost all speeds.

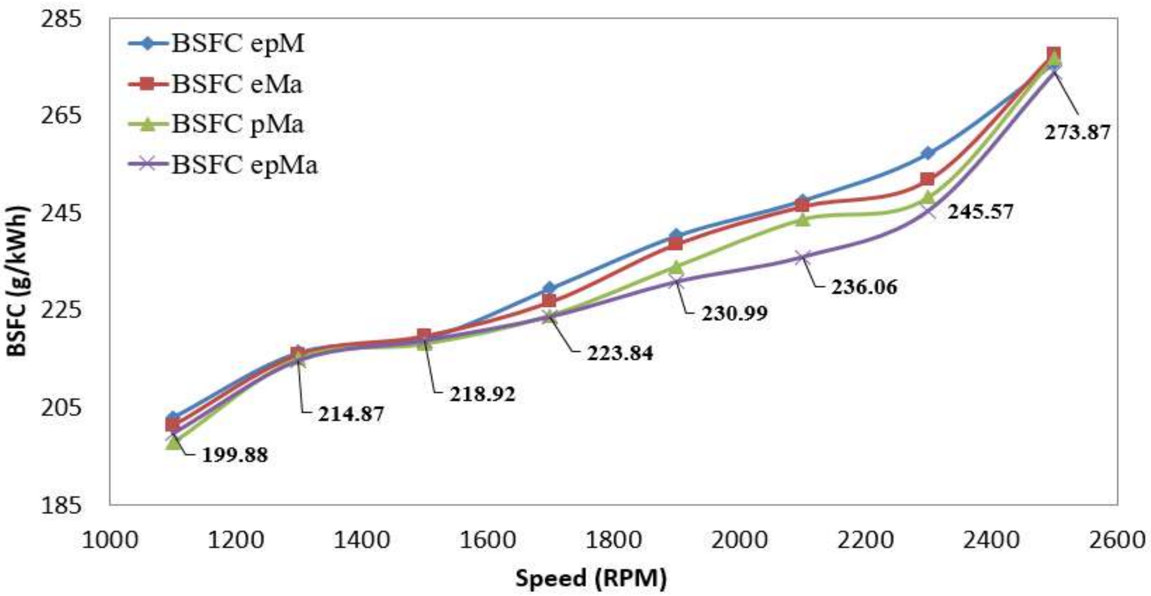


Figure 7.2:- Comparative BSFC graphs at 100% load

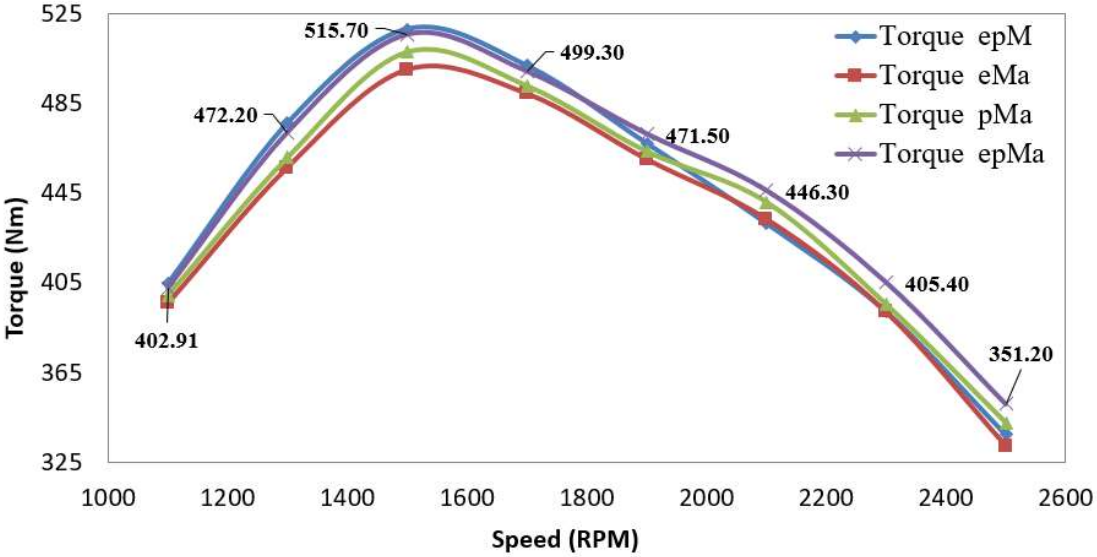


Figure 7.3:- Comparative torque graphs at 100% load

At 60% load, epMa exhibits an optimum BSFC performance but is the best between 1800 and 2500 RPM compared to the other three multiple injection strategies (Fig. 7.4). The pMa injection strategy performed the best below 1700 RPM and thus, deemed as the second best. On the other hand, the epM strategy was the poorest in BSFC performance, and the BSFC pattern/curve of epMa was smoother than that of other injection schedules. Similarly, the quadruple epMa injection shows the optimum torque performance among the injection strategies (Fig. 7.5). However, epM shows the best torque performance from 1100 to 1700 RPM. The second optimal torque performance was assessed using the pMa injection strategy. The eMa is the worst in torque performance at almost all speeds (Fig. 7.5).

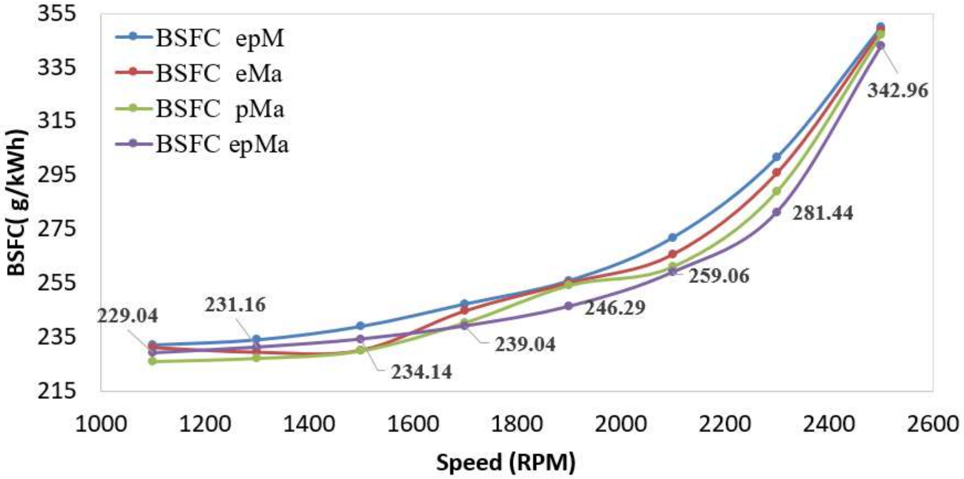


Figure 7.4:- Comparative BSFC graphs at 60% load

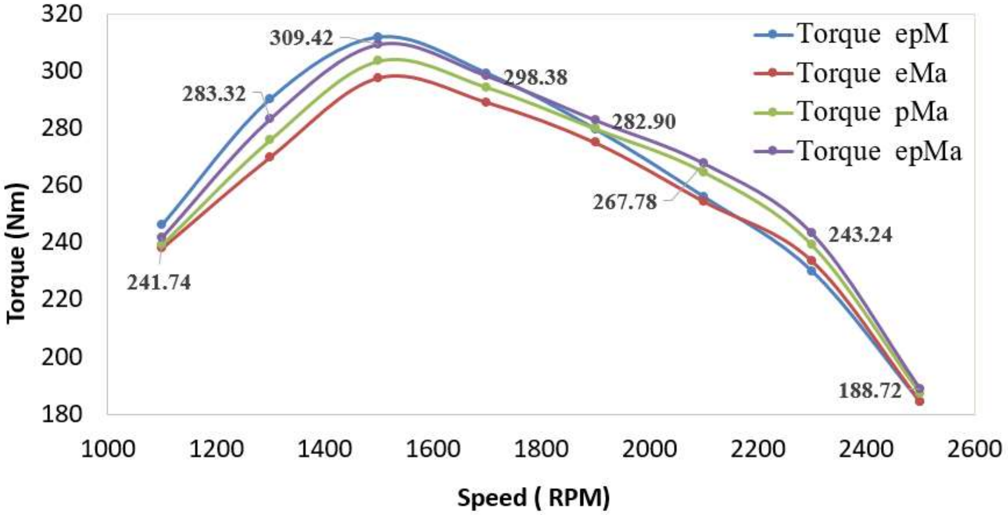


Figure 7.5:- comparative torque graphs at 60% load

At a partial load of 20%, the BSFC performance among the four multiple injection strategies could not be distinguished, especially between 2200 and 2500 RPM from the line chart (Fig. 7.6). The BSFC of the pMa is the best in the zone of 1100–1900 RPM but the BSFC curve is not smooth. On the other hand, the BSFC performance curve was smoother for the epMa and marginally better than the pMa considering the average BSFC level. The epM and eMa injections are the bottom-level performers in BSFC (Fig. 7.6). Similarly, the torque performance is also mixed in nature at a partial load of 20% (Fig. 7.7). The quadruple (epMa) injection provides the optimum torque performance among the injection strategies (Fig. 7.7), although it is the third-best in the 1100–1400 RPM zone. The epM also shows the best torque performance between 1100 and 1500 RPM. The second optimum torque performance was detected with the pMa injection strategy, and the eMa showed the most inadequate torque performance from 1100 to 2000 RPM engine speed.

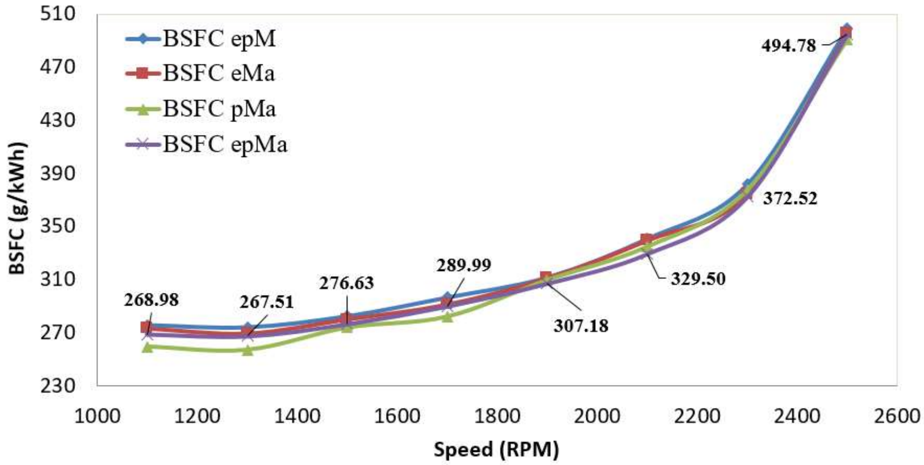


Figure 7.6:- Comparative BSFC graphs at 20% load

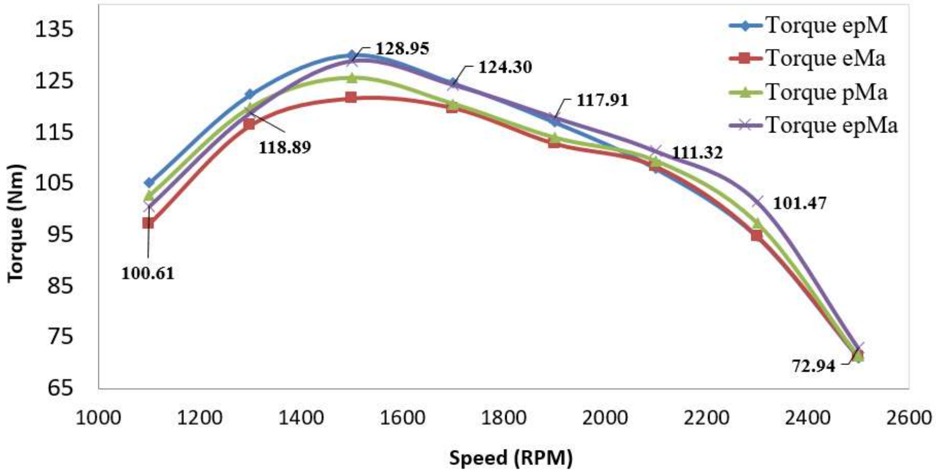


Figure 7.7:- Comparative torque graphs at 20% load

BTE is calculated based on the measured torque (Tr), engine speed (N) and FFR. The calorific value (CV) of BS-IV diesel fuel based on the standardisation report was 42.8 MJ/kg (termed LHV). The FFR was fuel flow rate in kg/h. Then, brake power (BP) was calculated using the torque and speed data.

$$BTE = \frac{BP \times 3600}{FFR \times CV} \tag{7.2}$$

Where, $$BP = \frac{T_r \times N}{9549.35} \tag{7.3}$$

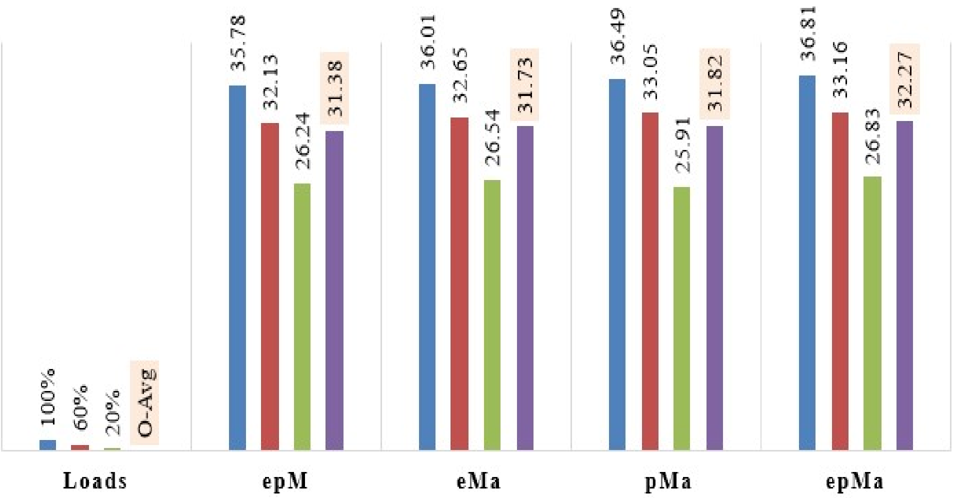


Figure 7.8:- Average BTE at different loads and overall average BTE of injection strategies

Figure 7.8 shows the trends of average BTE at different loads and the overall average BTE of each injection strategy. The average and overall average BTE was the best for epMa, while the epM was the worst. The overall average BTE of pMa was the best among triple injections, although the average BTE was the worst at 20% load. Indirectly, this study presented the combustion efficiency of each injection strategy with fixed main injection time and EGR%.

7.3.1.2 Emission Tests

NOx, THC and CO emissions data have been captured following the sampling method of exhaust gases and analysing using the Horriba Analyser. The measured smoke data are represented in terms of filter smoke number (FSN), and this parameter was measured using AVL Smoke Meter (Fig. 3.1). In addition, regulatory emission tests were carried out following the ESC with ELR and ETC standards [140]. The measured regulatory test data among the multiple injection strategies were tabulated for comparative analysis of the results.

Smoke test as per ELR: The measured smoke data are shown in the scatter chart format (Fig. 7.9, 7.10 and 7.11). The soot concentration (St in mg/m^3) could be calculated further using the below imperial equation 7.4. Similarly, several correlations were available to predict the particulate matter (PM) as the summation of soot and hydrocarbons (HCs) with multiplication factors.

$$S_t = \frac{4.95 \times FSN \times e^{0.38 \times FSN}}{0.405} \qquad (7.4)$$

The smoke (FSN) emission is the highest with epM among the multiple injection strategies at 100% load (Fig. 7.9). On the other hand, the epMa shows the best performance from medium to high speed, whereas the pMa is the best in smoke reduction from 1100 to 1500 RPM. At 60% load, the smoke (FSN) emission pattern is similar to 100% load except for the values (Fig. 7.10). Herein, the epMa displays the best smoke emission from 1700 to 2500 RPM zone, whereas the pMa is the finest in smoke reduction from 1100 to 1500 RPM, and the epM is the worst in smoke performance with a marginal difference. At 20% partial load, the smoke (FSN) emission is the highest with the epM among the multiple injection strategies but has a narrow margin at maximum speeds (Fig. 7.11). On the other hand, the pMa is the best except at few random speeds and optimum in smoke emission, wherein the quadruple injection exhibits the second-best smoke performance.

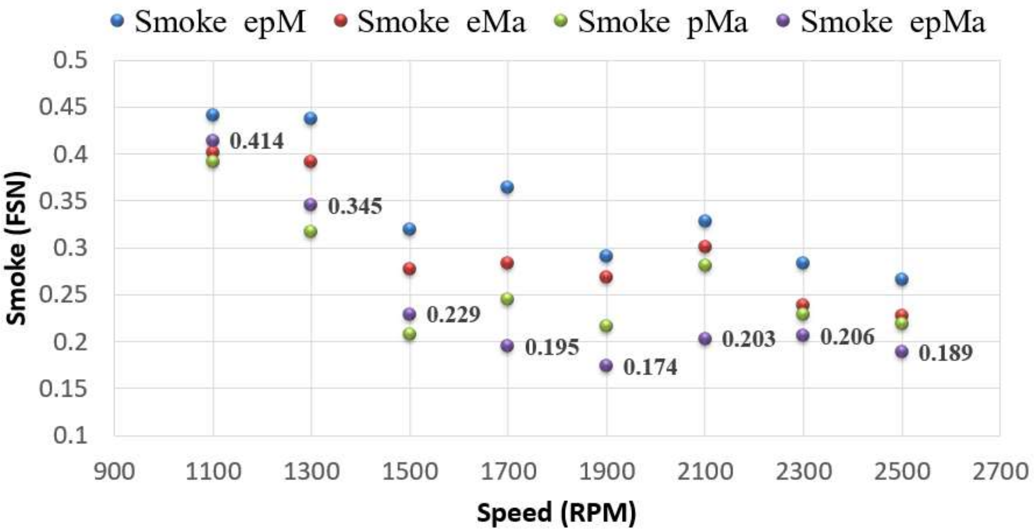


Figure 7.9:- Smoke test results at 100% load

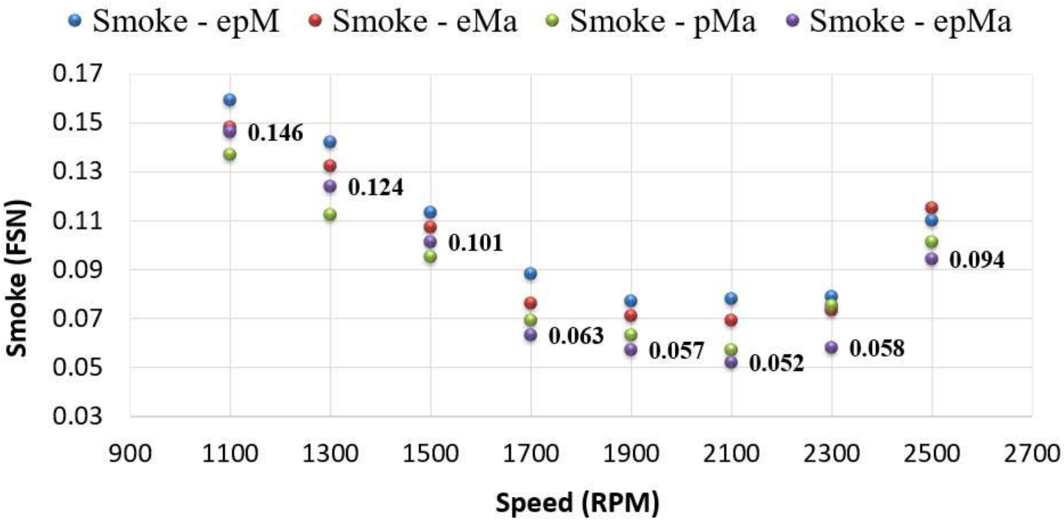


Figure 7.10:- Smoke test results at 60% load

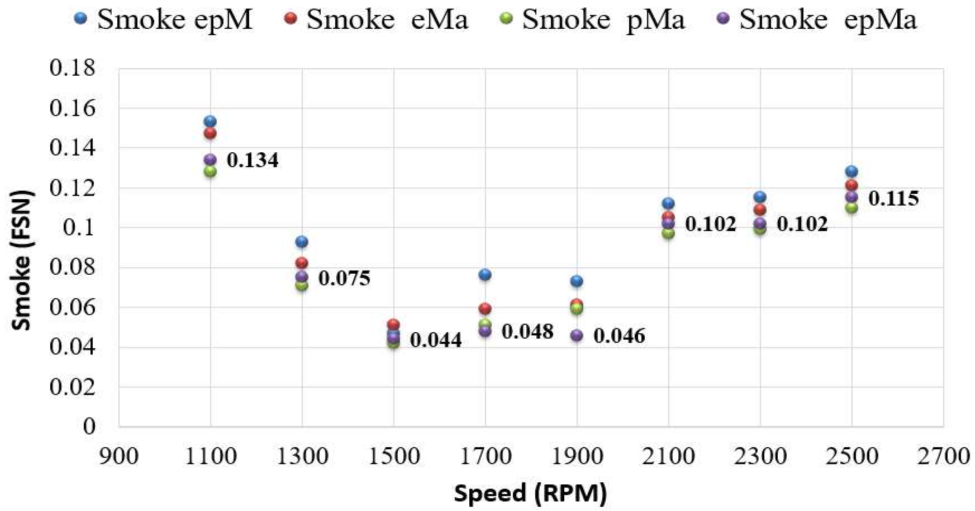


Figure 7.11:- Smoke test results at 20% load

The average smoke curves (Figs. 7.12 and 7.13) indicate that the epMa injection strategy is optimum and best in the smoke reduction for a wide speed zone except from 1100 to 1500 RPM. Herein, the high fuel-air mixture and diffusive combustion duration play a vital role in smoke or soot formation. Post-injection pulse also has a major impact on soot oxidation, which helps in smoke/soot reduction. Thus, the epM injection strategy is found the worst, while the pMa is the best in average smoke reduction from 1100 to 1500 RPM at low and medium loads.

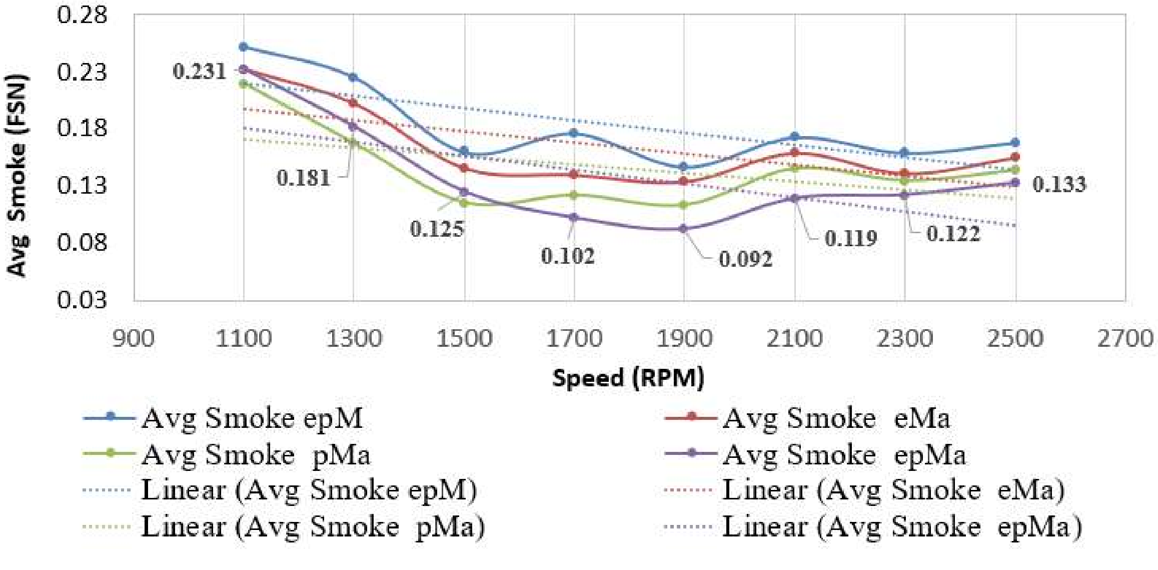


Figure 7.12:- Average smoke results with varying speeds

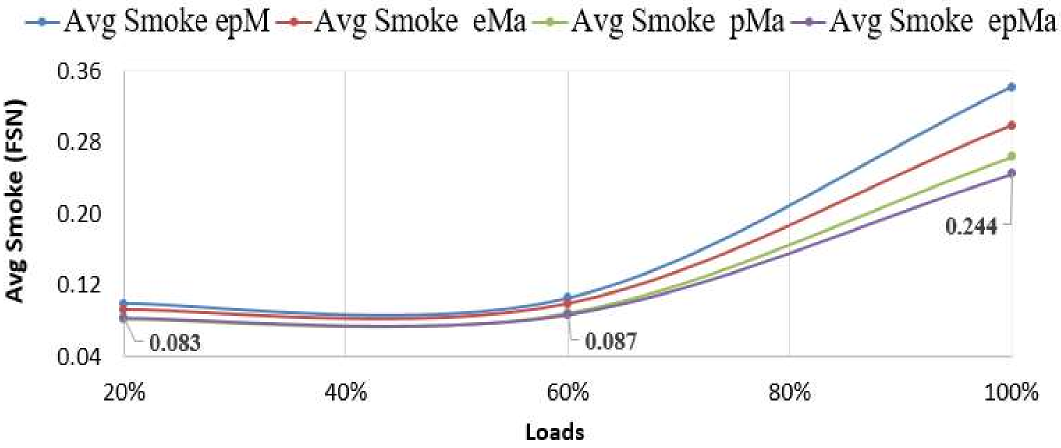


Figure 7.13:- Average smoke results with varying loads

The emission tests have been carried out according to the ESC and ETC standards for each injection strategy. The measured data are presented in Tables 7.3 and 7.4, and the units are in g/kWh.

Table 7.3:- ESC Test Results

	epM	eMa	pMa	epMa	BS-IV Limits	BS-V Limits
PM	0.019	0.018	0.015	0.014	0.020	0.020
NOx	3.208	3.312	3.278	2.971	3.500	*2.000*
THC	0.068	0.056	0.043	0.051	0.460	0.460
CO	0.053	0.087	0.077	0.061	1.500	1.500

Table 7.4:- ETC Test Results

	epM	eMa	pMa	epMa	BS-IV Limits	BS-V Limits
PM	0.026	0.025	0.021	0.019	0.030	0.030
NOx	3.263	3.501	3.291	3.014	3.500	*2.000*
THC	0.092	0.084	0.056	0.063	0.550	0.550
CO	0.065	0.090	0.087	0.051	4.000	4.000

The epMa injection comprising of twin pilots and one post-injection pulse produces optimum emissions compared to the other three triple injection strategies (Tables 7.3 and 7.4). The major interferences from the study as follows

(1) The epMa injection strategy consisted of both advanced and retreaded pilot injection events combined with a high EGR rate producing the lowest NOx emission due to low burn gas temperature, early termination of the first injection event and controlled heat release rate. The epM shows the second-best performance due to its similar double pilot feature. The eMa is the third in NOx emissions due to early injection and prolonged duration between early injection and main injection schedule that causes the lower bulk gas temperature inside the combustion chamber compared to the pMa.

(2) The double pilot-injection strategies gave rise to higher THC emissions due to the rich fuel mixture during the ignition delay period than the single pilot (or early) injection combustion. In addition, the ignition delay has a significant impact on THC that compensates for the overall results. Hence, the THC formation of these injection strategies in ascending order is pMa<epMa<eMa<epM. Furthermore, the highest ignition delay may cause the second high THC formation by the eMa injection strategy.

(3) The CO emission is the highest from the eMa injections due to the prolonged ignition delay with less gas temperature inside the combustion chamber. On the other hand, the epM produces the lowest CO emissions due to the shortest ignition delay with high in-cylinder temperature. The epMa is the second-best in CO emissions, while the CO emission of pMa is the second-highest among the injection strategy.

(4) The epMa reduces the PM maximally among the injection strategies, although it produces higher THC than the pMa. This phenomenon could be attributed to reduced soot content due to improved diffusion combustion duration with quadruple injection with twin pilots and a post-injection pulse.

7.3.1.3 Noise Tests

The CN data are captured for the lower three speeds and represented in Table 7.5 and Fig. 7.14, which show that the twin pilot injection had a significant impact on CN reduction, especially at low loads and idle or lower speeds. The average noise data at 1100 RPM are summarised in Fig. 7.14. Herein, both the double pilot (epM and epMa) injection strategies show improved results in the nearby noise trial. The epMa injection strategy was best in the nearby noise test and superior by 2.2 dBA compared to the worst type (i.e., pMa) at 1100 RPM and 20% load. This might be due to the raised rate of combustion pressure in a controlled manner owing to twin pilot injections.

Table 7.5:- Rig Level Nearby Noise Test Results

Injection Strategy	Location/Speed	Load 20%			Load 60%			Load 100%		
		1100	1300	1500	1100	1300	1500	1100	1300	1500
epM	1	86.4	87.6	89.4	89.3	91.0	91.4	92.4	93.2	94.5
	2	86.0	87.2	89.1	89.0	90.7	91.1	92.0	92.9	94.2
eMa	1	88.2	89.6	91.0	91.4	92.9	93.3	94.6	95	96.1
	2	87.6	89.1	90.6	91	92.6	92.9	94.1	94.6	95.8
pMa	1	88.4	89.7	91.2	91.7	93.1	93.5	94.8	95.3	96.4
	2	87.7	89.3	90.8	91.3	92.8	93.2	94.4	94.9	96.0
epMa	1	86.1	87.4	89.3	89.2	90.8	91.2	92.1	92.9	94.3
	2	85.8	87	88.8	88.9	90.5	90.9	91.9	92.7	93.9

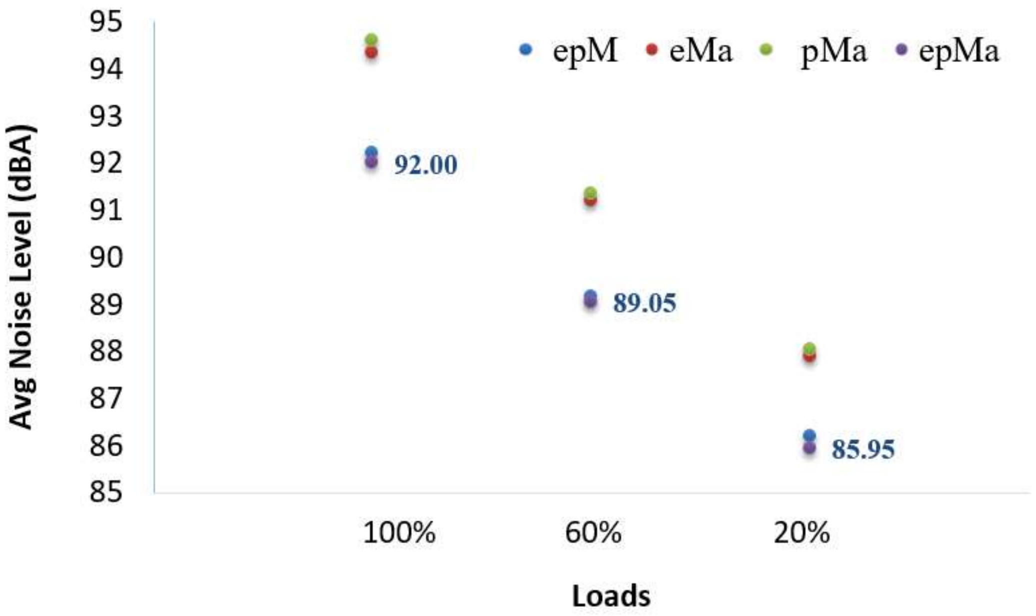


Figure 7.14:- Average CN reduction plot at 1100 RPM

7.3.2 Vehicle Level Tests

7.3.2.1 PBN Testing

Vehicle PBN level is captured successively with all the injection strategies on a typical 16T vehicle with six-speed gearbox and 10×20 size based on IS: 3028 [142].

Test results (Table 7.6) indicate that the injection strategies with double pilots (epM and epMa) are better in vehicle level PBN reduction, similar to the nearby noise trial. The quadruple (epMa) injection strategy delivered the best PBN results among the four injection strategies while pMa gave the worst (as per Table 7.6) by 0.8 dBA (third gear) to 0.3 dBA (fifth gear).

Table 7.6:- PBN test results

Injection Strategy	Gear No.	Engine RPM		Vehicle Speed		Average Noise (dBA)
		At POS AA’	At POS BB’	At POS AA’	At POS BB’	
epM	3rd	1870	2800	20	30	80.3
	4th	1870	2700	30	38	80.4
	5th	1870	2300	40	45	79.7
eMa	3rd	1870	2800	20	30	80.8
	4th	1870	2700	30	38	80.6
	5th	1870	2300	40	45	79.8
pMa	3rd	1870	2800	20	30	81
	4th	1870	2700	30	38	80.7
	5th	1870	2300	40	45	79.9
epMa	3rd	1870	2800	20	30	80.2
	4th	1870	2700	30	38	80.4
	5th	1870	2300	40	45	79.6

7.3.2.2 Constant Speed Fuel Economy (CSFE) Testing

Heavy Duty Fuel Economy (HDFE) has been introduced in India as per the directives of the Ministry of Road Transport and Highways (MoRTH) in 2018. It provides guidelines (empirical formula) to calculate the CSFE for 12–49 ton GVW vehicle at 40 and 60 kmph based on driveline configuration. Similar guidelines were followed for doing the trials on a typical 16 ton- 4×2 truck of tyre size 10×20 and rear axle ratio 5.28. The Vehicle is used in other study as well in this research work.

The epMa displayed the best BSFC performance at medium to high speeds and load combinations (Figs. 7.2, 7.4 and 7.6) compared to triple injection strategies Thus, this quadruple injection exerts a good impact on CSFC trials and displays the best performance to meet the CSFE norms (Table 7.7). The pMa injection strategy was the second best and also met the CSFE criteria (Table 7.7).

Table 7.7:- CSFC Trial Results

Injection Strategy	Vehicle Speed 40 km/h		Vehicle Speed 60 kmph		Remarks
	CSFC Limit (L/100 km)	Measured value	CSFC Limit (L/100 km)	Measured value	
epM	16.19	16.25	21.79	21.80	pMa and epMa meet CSFC target
eMa		16.21		21.75	
pMa		15.99		21.71	
epMa		15.93		21.65	

7.4. Conclusion

The quadruple (epMa) injection strategy has been compared to the best three triple injection strategies (eMa, pMa and pMa) on a typical six-cylinder BS-IV diesel engine featuring 45% EGR rate to assess the potential benefits in performance (BSFC, torque and CSFC), emissions and noise (CN and PBN) at eight different speeds and three load conditions (20%, 60% and 100%). Prior to this experimental investigation, delta optimisation was conducted at the base level calibration on the production engine to adopt all four injection strategies maintain the same percentage of EGR. All the testing environments were formulated based on the Taguchi DOE approach and regulatory norms. Also, vehicle level trials have been carried out for real-time performance (fuel economy and PBN). The outcomes of this study were as follows:

1. CN is decreased at about 0.2–2.2 dBA with quadruple injection (epMa) strategy compared to all three triple injection strategies (eMa, pMa and pMa) at lower RPM and higher to lower loads. The eMa is marginally better than the pMa injection strategy in CN reduction. This finding indicates that the rate of cylinder pressure rise is well-controlled due to a shorter ignition delay with double pilots (i.e., e and p). At vehicle level PBN evaluation, the epMa exhibits an average of 0.3 dBA of noise reduction with respect to the pMa and eMa injection strategies.

2. The epMa injection strategy is optimal in average smoke reduction and reduces the smoke at wide-ranging speed except for 1100–1500 RPM. The high fuel-air mixture, diffusive combustion duration and soot oxidation rate post-injection affect the smoke or soot formation. The pMa is the second-best in average smoke reduction and the best at low speeds from 1100 to 1500 RPM. On the other hand, the epM injection strategy shows the worst smoke emissions due to the unavailability of any post-injection pulse. A prolonged AiE might cause the second-worst smoke performance by the eMa.

3. Overall PM emission is marginally better for quadruple injection strategy compared to pMa and is also better than the other two (i.e., epM and eMa) triple injections. Both pilot and post-injection have a significant impact on the combustion phases to control the soot/smoke formation and HC. The PM is a mixture of soot and HC. A better smoke performance may cause marginal improvement in PM reduction by the epMa injection strategy. The epM and eMa strategies are the least effective in PM reduction.

4. A significant reduction was observed in exhaust-out NOx emission level with quadruple injection scheme as this reduces the flame or bulk gas temperature inside the cylinder as well as the heat release rate (HRR). The epMa strategy is exhibited at 3–6% NOx reduction over epM, eMa and pMa but fails to meet the BS-V emission target for NOx.

5. In epM injections, the combination of both advanced and retreaded injection timing at a high EGR rate produced the lowest CO emissions compared to epMa, eMa and pMa. The epMa reported as second best in CO emissions. This becomes the favorable condition for reduced CO level due to a relatively high temperature inside the cylinder (in-Cylinder) with a shorter ignition delay period and enhanced the oxidation rate of CO. Reportedly, the eMa has the highest CO emission among the four strategies due to its advanced injection (i.e., 39° CA BTDC) schedule in combination with high EGR%.

6. The double pilot (epMa) injection strategy formed slightly higher emissions of THC level than the single-pilot injection schedule (eMa and pMa) due to the availability of richer fuel mixture during the ignition delay phase. At the same time, Double pilots reduce the ignition delay, which has a significant impact on THC reduction. Thus, the final THC formation sequence is found as pMa<epMa<eMa<epM.

7. BSFC performance is optimal and the best with a smoother curve for quadruple (epMa) injection strategy among all the schemes but marginally inferior at medium to low loads and speeds compared to pMa. The pMa injection schedule provides the second-best results. Taken together, the epMa exhibits better results (BSFC) at medium to high speeds and loads combination as proved based on the vehicle-level CSFC test results.

8. The average BTE and overall average BTE is the best for the epMa injection strategy, whereas the epM was the worst. Among the triple injection strategies, the pMa shows the best overall average BTE and average BTE except at 20% load. The literature indicates that in the presence of two pilot injections with a post-injection pulse, the IMEP value increases and Coefficient of variation of IMEP (COV_{-IMEP}) value decreases compared to single-pilot injection, which can be indirectly correlated to the results, indicating an improvement in combustion efficiency.

9. Furthermore, the torque value, restricted by exhaust out smoke number of engine, was enhanced by pilot injection with advanced injection schedule/timing in addition to a reduction in CN. Interestingly, twin pilot (e and p) injections (epMa) with advancement in injection timing display a marked improvement of torque at all loads (especially low to medium loads). The inside-cylinder pressure and HRR are high in twin pilot e and p) injections with advancement in injection timing, which underlies the improvement in the torque of the engine without crossing the smoke number. The epM produce marginally more smoke than other injection schedules due to the absence of post-injection.

The present study showed that the quadruple injection scheme has significant potential over triple injection strategy to trade-off among NOx-PM/Smoke, CNBSFC, torque-BSFC, BSFC-NOx and optimum outcome to correlate the test results with scientific literature in a specific research domain. Furthermore, only working with this epMa strategy for optimisation of injection timing and injection dwell for shaping might meet further emissions with optimum performance.

Chapter -8

Effect of Quadruple Injections with different pilot and post injection timing

8.1 Objective of this Work

Multiple injections in association with suitable (High/heavy) exhaust gas recirculation (EGR) is a promising technique to achieve low temperature combustion (LTC) regime in modern CRDI (common rail direct injection) diesel engine. This helps in simultaneous reduction of NOx and Soot to meet the stringent emission norms without penalizing the fuel efficiency and overcome the drawbacks of EGR-LTC. There are limited insights available which discuss about the potentiality of latest Quadruple injection (early-pilot-main-post/after; epMa) strategy in combination with high EGR and different injection timing over triple injections (pilot-main-after; pMa) at wide operating conditions. This chapter deals with the study on the effect of Quadruple injection (epMa) strategy on performance, emissions and noise with different Pilot injection timing and post injection dwell combinations (8 Nos) on a CRDI diesel engine with high EGR and fixed main injection schedule at 4 operating loads and 5 speeds.

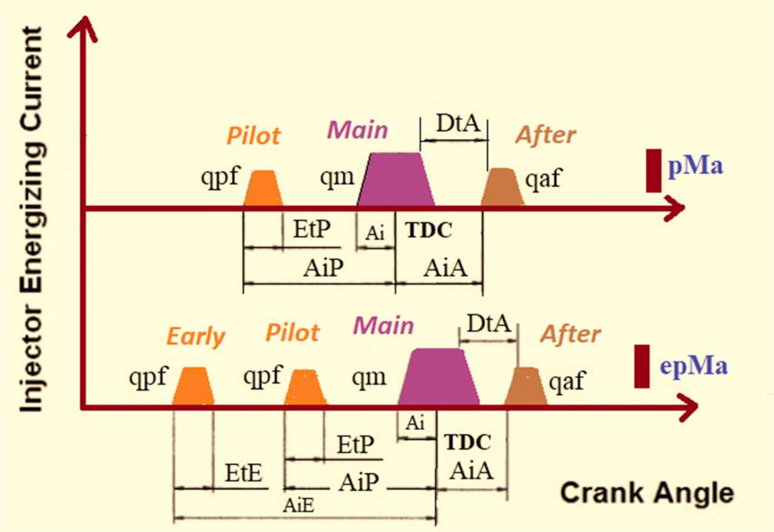


Figure 8.1:- Quadruple Injection Strategy (epMa; early–Pilot-main-after) and Triple injection strategy (pMa; Pilot-main-after); TDC – Top dead Centre, Ai – Main injection advance w.r.t TDC, AiE - early injection advance w.r.t TDC, AiP- pilot injection advance w.r.t TDC, AiA - After injection w.r.t TDC, CA - crank angle, p - Pilot or Pilot2 injection, e - Pilot injection 1 or early injection; DtA-after/post injection Dwell, qpf- quantity of fuel at pilot or early pilot injection, qm- quantity of fuel at main injection , qaf- quantity of fuel at after/post injection

8.2 Experimental Methodology

The the typical engine is with EGR system for in-cylinder NOx reduction and Bosch-make CRDI system. It has a definite FMTC (fuel-mass torque cycle) where broad outline of fuel demand for any particulate torque and speed are mapped. Calibration, diagnostics and validation activities are monitored using INCA software. Fuel Mass (FM) and engine speed are interrelated with fuel injection Pressure (FIP). Therefore, FIP varies based on the fuel mass and engine speed (RPM). The fuel injection pressure (FIP) range is in between 120- 170 MPa. The permissible smoke limit for the base line/ production engine has been outlined for full as well as part load application.

EGR percentage kept same as 45% as existing typical production engine to achieve LTC regime and to compare with the base/production version Triple Injections. Hence, EGR variation is not part of present study. Here, key focus given on comparative study and understanding the effect of eight different quadruple injection combinations (variable injection timing and dwell) on performance (BSFC, BTE and torque) and exhaust emissions trade off and combustion noise. As mentioned, the base engine is with pMa triple injection schedules, which meet BS-IV norms. This has following specifications- Ai 6 to -3 °CA BTDC; AiP 19.9° CA BTDC; AiE 39.9° CA BTDC; qpf – 1.5 mg/hub ; qaf – 2 mg/hub and DtA 1350 ms . Minor optimization done on base level engine calibration to implement quadruple injection strategy and main injection timing fixed to reduce complexity.

Table 8.1:- DoE matrix inputs –Factors, Level and Value

Factors	Description	Level	Value
Carry over Factors	Triple Injection strategy	pMa-E [Study-2]	pilot - main-after
Fixed Factors	EGR	fixed	45%
	Quantity of fuel at pilot or early pilot injection	qpf	1.5 mg/hub
	Quantity of fuel at after or post injection	qaf	2 mg/hub
	Quadruple Injections	epMa	early-pilot -main-after/post
	Main Injection Timing	Ai	1.5°CA BTDC
Variable Factors	Post or After Injection Dwell (DtA)	DA1, DA2	1100ms, 1300ms
	Early or Pilot1 injection timing (AiE) w.r.t TDC	E1, E2	39° & 35°CA BTDC
	Pilot or Pilot2 injection timing (AiP) w.r.t TDC	P1, P2	19° & 15° CA BTDC
Operating Conditions	Engine Load (%)	L1,L2, L3,L4	25, 50, 75, 100
	Engine Speed (RPM)	N1,N2,N3,N4, N5	1200, 1500, 1800,2100,2400

Table 8.2- DoE matrix for Performance and smoke emissions Tests for post injection dwell – (a) DA1 and (b) DA2 . These tables show the number of trials associated for Performance and smoke emissions evaluation.

Load- Speed Combination	(a) Injection Timing Combination with DA1-1100 ms			
	E1P1	E1P2	E2P1	E2P2
L1N1	*L1N1 E1P1*	*L1N1 E1P2*	*L1N1 E2P1*	*L1N1 E2P2*
to				
L1N5	*L1N5 E1P1*	*L1N5 E1P2*	*L1N5 E2P1*	*L1N5 E2P2*
L2N1	*L2N1 E1P1*	*L2N1 E1P2*	*L2N1 E2P1*	*L2N1 E2P2*
to				
L2N5	*L2N5 E1P1*	*L2N5 E1P2*	*L2N5 E2P1*	*L2N5 E2P2*
L3N1	*L3N1 E1P1*	*L3N1 E1P2*	*L3N1 E2P1*	*L3N1 E2P2*
to				
L3N5	*L3N5 E1P1*	*L3N5 E1P2*	*L3N5 E2P1*	*L3N5 E2P2*
L4N1	*L4N1 E1P1*	*L4N1 E1P2*	*L4N1 E2P1*	*L4N1 E2P2*
to				
L4N5	*L4N5 E1P1*	*L4N5 E1P2*	*L4N5 E2P1*	*L4N5 E2P2*

Load- Speed Combination	(b) Injection Timing Combination with DA2- 1300 ms			
	E1P1	E1P2	E2P1	E2P2
L1N1	*L1N1 E1P1*	*L1N1 E1P2*	*L1N1 E2P1*	*L1N1 E2P2*
to				
L1N5	*L1N5 E1P1*	*L1N5 E1P2*	*L1N5 E2P1*	*L1N5 E2P2*
L2N1	*L2N1 E1P1*	*L2N1 E1P2*	*L2N1 E2P1*	*L2N1 E2P2*
to				
L2N5	*L2N5 E1P1*	*L2N5 E1P2*	*L2N5 E2P1*	*L2N5 E2P2*
L3N1	*L3N1 E1P1*	*L3N1 E1P2*	*L3N1 E2P1*	*L3N1 E2P2*
to				
L3N5	*L3N5 E1P1*	*L3N5 E1P2*	*L3N5 E2P1*	*L3N5 E2P2*
L4N1	*L4N1 E1P1*	*L4N1 E1P2*	*L4N1 E2P1*	*L4N1 E2P2*
to				
L4N5	*L4N5 E1P1*	*L4N5 E1P2*	*L4N5 E2P1*	*L4N5 E2P2*

DoE method is used in this experimental research work for systematic approach of testing. Tests are conducted as per the DoE matrix shown in Table -8.2 for performance and smoke emissions. The emission testing was carried out based on European stationary cycle (ESC) with a European load response (ELR) for smoke trial and European transient cycle (ETC) standards [140] to validate the results in reference to regulatory limits. The engine test laboratory is NABL accredited [143] which is estimation of uncertainty in measurement. Minimum five numbers of trial has been taken in accordance to the NABL guideline. Engine radiated/nearby noise level (combustion Noise) was measured following the IS: 10399 [141] standard for lower speeds (N1 and N2) and Loads (L1 and L2) using the Sound level meter (B&K, Model-2250-S) as per the schematic of Fig.3.2. Also, Vehicle PBN measurement done to authenticate the efficacy multiple injection strategies to improve noise reduction in assistance of IS 3028 standard [142]. The vehicle level noise at moving state is called as pass by noise (PBN).

Uncertainty Analysis

The uncertainty of measurement is calculated as per the NABL-141 [143] guidelines and details mentioned in chapter 3 .

8.3. Results and Discussion

This experimental research work consists of three major trials namely performance tests, emission tests, noise tests respectively. These are represented in tabulated and graphical format sequentially for better understanding below.

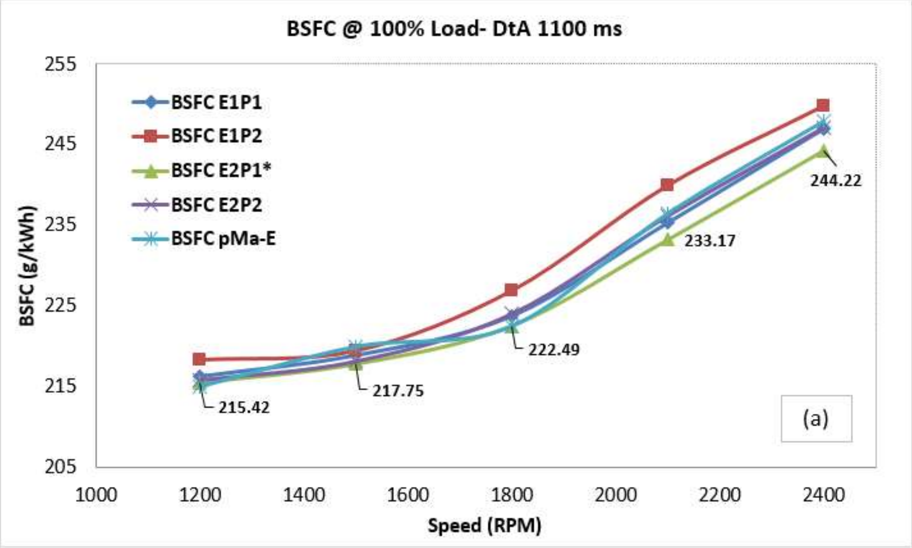
8.3.1 Performance Results

Performances tests were conducted as per DoE table 8.2 and comparative test data among the injection combinations are shown below vide graphical form.

8.3.1.1 BSFC Performance

BSFC value calculated using measured date of Torque (To in Nm), engine speed (N in RPM) and Fuel flow rate (FFR in kg/hr) and below equation.

$$\mathrm{BSFC} = ((\mathrm{FFR\ x\ 1000})/((\mathrm{To\ x\ N})/9549.57)) \qquad (8.1)$$



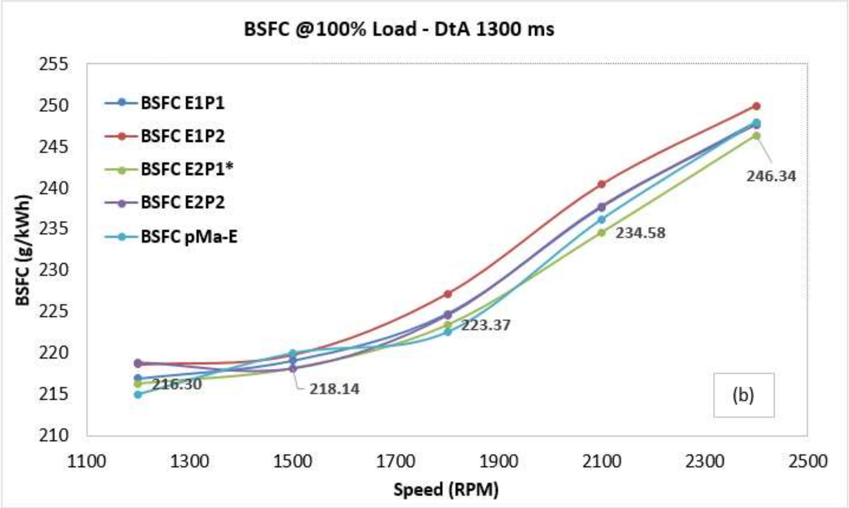


Figure 8.2:- Comparative BSFC results at 100% load- (a) DtA 1100ms and (b) DtA 1300ms

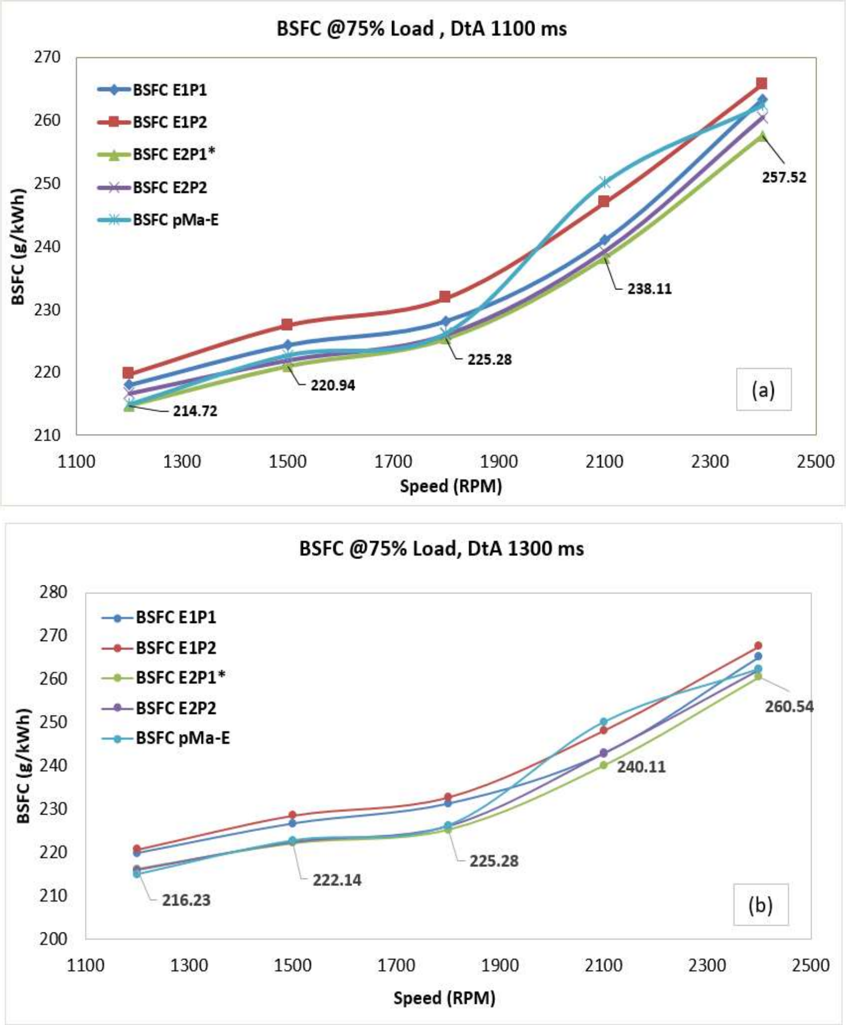


Figure 8.3:- Comparative BSFC results at 75% load- (a) DtA 1100ms and (b) DtA 1300ms

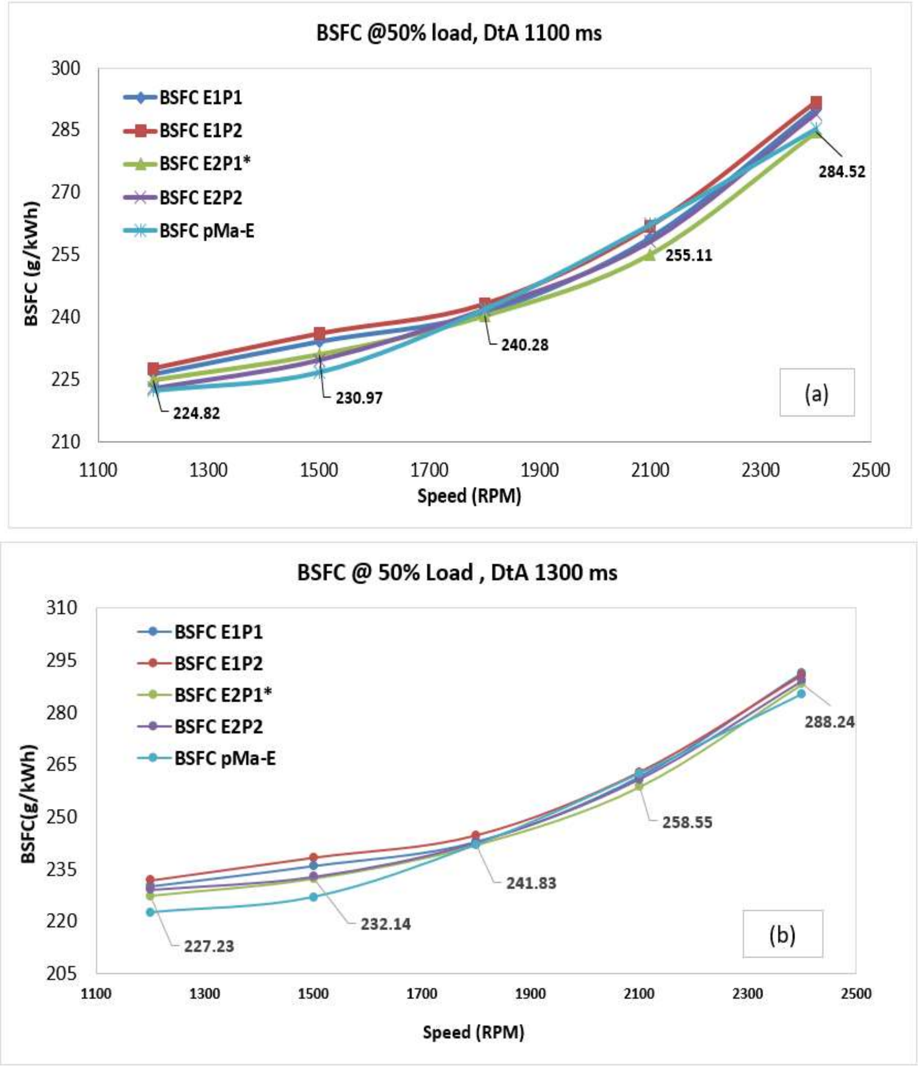
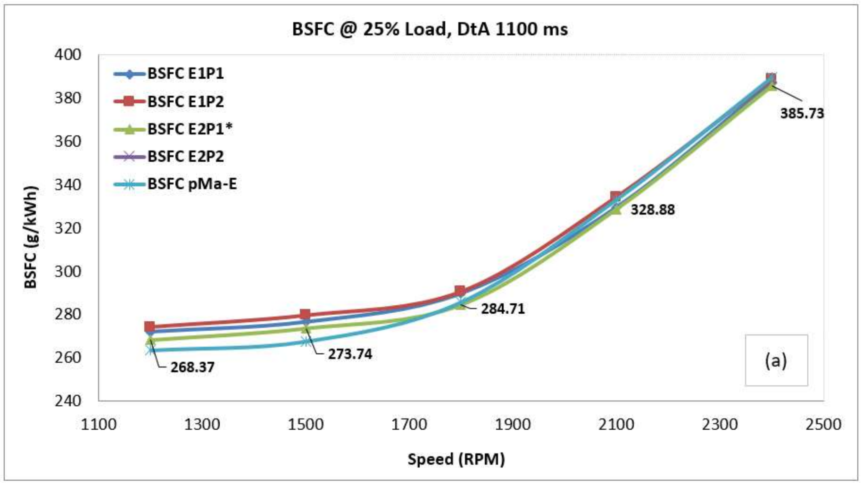


Figure 8.4:- Comparative BSFC results at 50% load- (a) DtA 1100ms and (b) DtA 1300ms



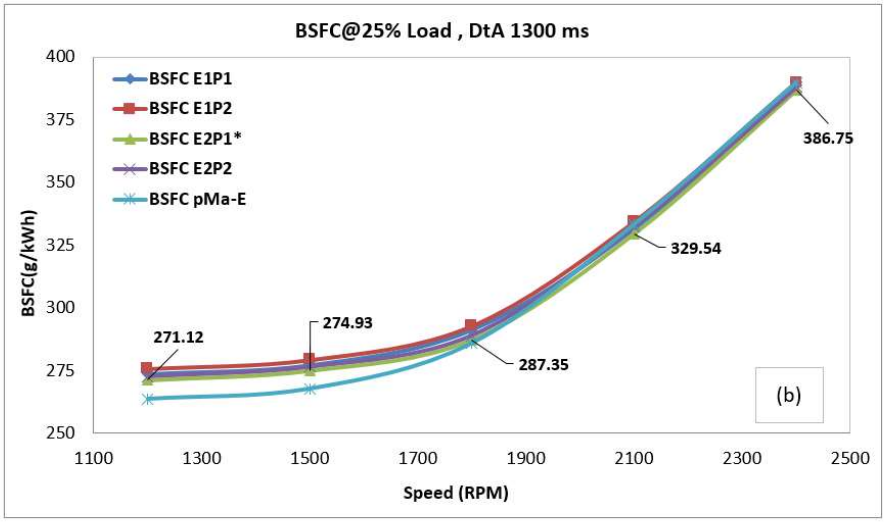


Figure 8.5:- Comparative BSFC results at 25% load- (a) DtA 1100ms and (b) DtA 1300ms

The BSFC results (ref Fig.8.2 to 8.5) indicates the strong influence of the early injection timing and marginal influence of the after/post injection dwell with fixed main injection timing for quadruple injections (epMa) with LTC regime. This injection timing helps for better combustion control by means of improvement in ignition delay, diffusion combustion phase. The pMa-E injection strategy shows best performance only from 1200 to 1800-RPM zone and at lower loads (25% and 50%). BSFC Performance of epMa-E2P1 with shorter post injection dwell 1100 ms is the best than all injection timing combination of the epMa and pMa-E whereas the epMa-E1P2 shows comparatively worst result especially with longer post injection dwell 1300ms though curve smoother than pMa-E. This may due to the adavaced early injection event with faraway pilot injection event. The BSFC Curves of all eight quadruple injection (epMa) combinations (epMa-E1P1, epMa-E2P2, epMa-E2P1, epMa-E2P2) are is considerably smoother than base line triple injections at all load conditions. The BSFC level of epMa- E1P2 with both post injection dwell (1100 ms and 1300 ms) are found worst among the trial combinations. The epMa-E2P2 – DtA 1100ms (or DA1) is the second best quadruple (epMa) injection configuration and it is at per lower with base line data for all load cases. The epMa-E1PI is the third best quadruple (epMa) injection configuration for both dwell times. This BSFC results are indicating the improtance of injection timing specially both the pilot injections (early and pilot) event and post injection dwell for newest quadruple injection strategy at LTC regime on CRDI diesel engine. The epMa-E2P1-DA1 is found superior in average BSFC by around 0.2 to 1.31% in comparision with base level triple (pMa-E) injection from low to high loads.

8.3.1.2 Torque Performance

Torque comparison data of all eight-injection timing combination of quadruple injection strategy are shown in figs. 8.6-8.9 for each load case sub- sequentially. These data are directly measured during the trials.

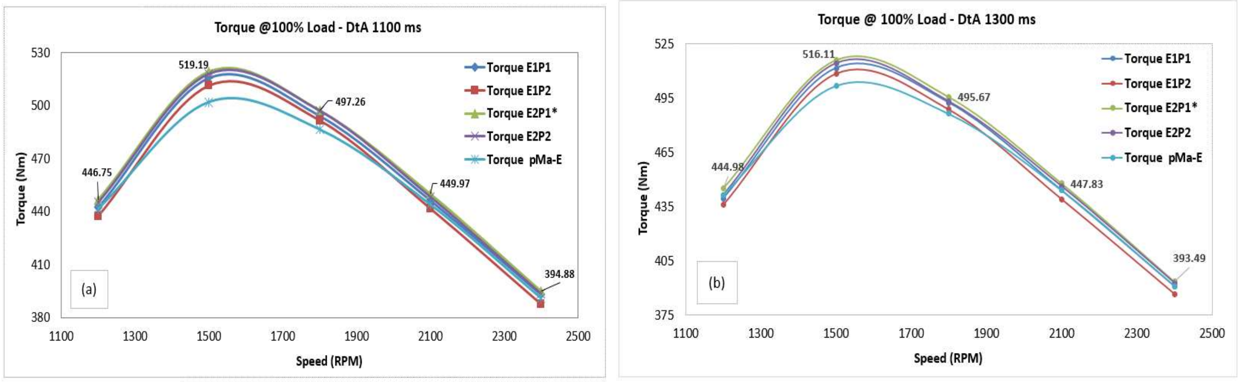


Figure 8.6:- Comparative Torque results at 100% load-(a) DtA 1100ms and (b) DtA 1300ms

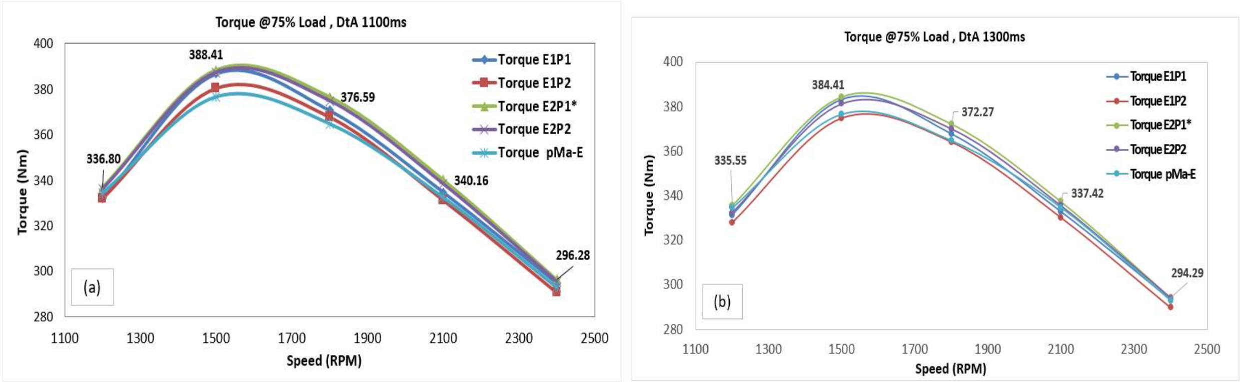


Figure 8.7:- Comparative Torque results at 75% load-(a) DtA 1100ms and (b) DtA 1300ms

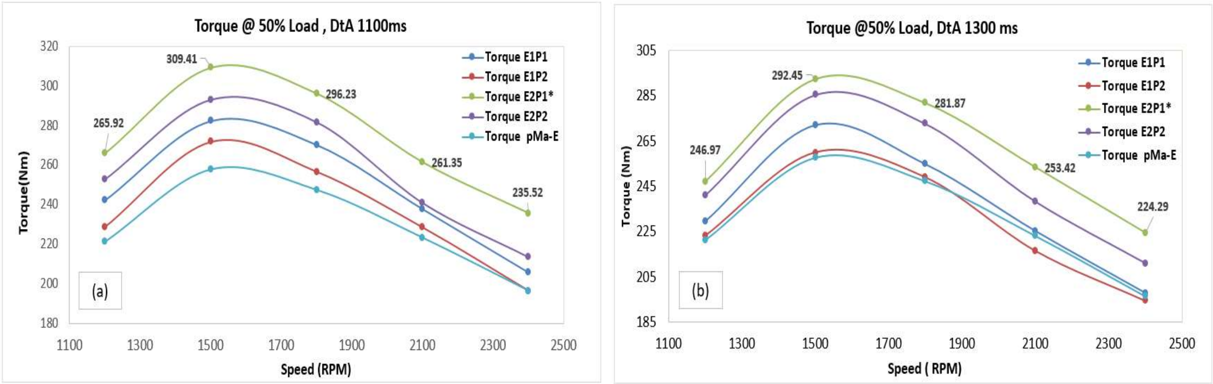


Figure 8.8:- Comparative Torque results at 50% load-(a) DtA 1100ms and (b) DtA 1300ms

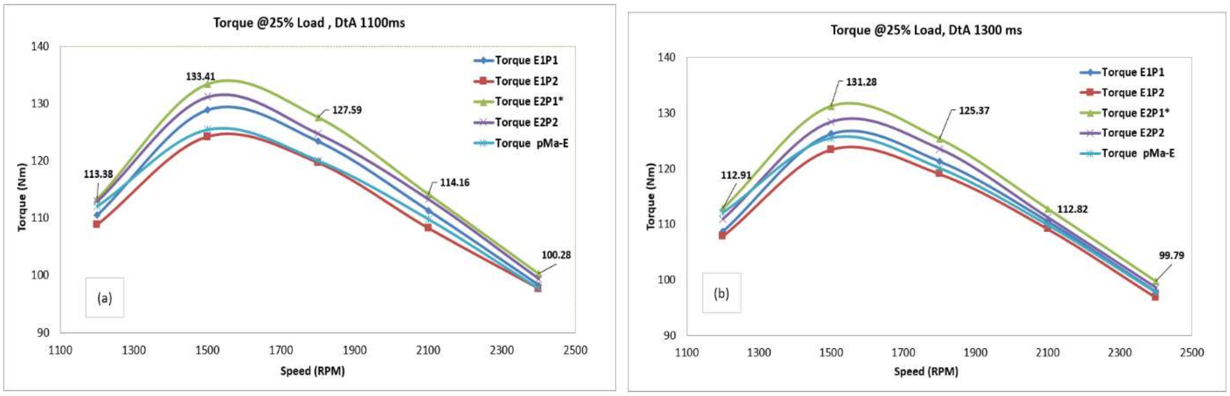


Figure 8.9:- Comparative Torque results at 25% load-(a) DtA 1100ms and (b) DtA 1300ms

The epMa-E2P1, epMa-E2P2 and epMa-E1P1 are better in torque performance among all injection timing combination of epMa for both post injection dwell as well w.r.t base pMa-E injection. The epMa-E2P1- DtA (both DA1 and DA2) found the best in torque performance. The existing pMa-E is better than epMa-E1P2 with both post injection dwell at few speed zone of higher loads (100%, 75%, 50%) and best at 25%. The torque performance of epMa-E1P2 found worst averagely than other epMa injection-timing combination (ref Fig. 8.6 to 8.9). Overall torque performance indicates that the quadruple (epMa) injection with delayed early (or Pilot 1), advanced pilot (or pilot 2) and closed post injection dwell combination is best torque performance than other combination as well as in reference to existing triple injection data. This may due to the better combustion control, which affects the ignition delay, heat release rate, pressure rise inside the combustion chamber []. The heat released by additional pilot injection pulse aids the combustion of the pre-injection, and henceforth the main combustion can be improved. As a outcome, a persistent net Torque/power was produced from the engine irrespective of the injection timing combinations. Due to improved IMEP results twin-pilot-injection strategies could enhanced the fuel conversion efficiency during the central combustion phase. The combustion stability which can be evaluted by studying the $COV_{IMEP;}$ are very low for the multiple-injection strategies having twin pilot injections []. Thus, a lower COV_{IMEP} can be expected in combustion of multiple-injections specially with this epMa qudrauple injections.

8.3.1.3 Brake Thermal Efficiency (BTE)

Brake thermal efficiency is calculated based on measured Torque, engine speed and FFR. In addition, Calorific Value (CV) of BS-IV Diesel fuel taken from Standardization Report.

$$\mathrm{BTE} = ([\mathrm{To \ x \ N \ x \ 3600}]/9549.57)/(\mathrm{FFR \ x \ CV}) \qquad (8.2)$$

Figure 8.10:- Average BTE data with variation of Load and post injection dwell (a) 1100 ms & (b) 1300 ms

This average BTE and overall average data indicates that epMa-E2P1 is best among the quadruple injection combination especially with closed post injection dwell (Refer Fig. 8.10). Around 0.84 to 1.5% improvement observed in BTE with the epMa- E2-35°CABTDC, P1-19°CABTDC and DtA-1100ms combination w.r.t pMa-E (base line). The epMa- E2P2 and epMa-E1P1 are found at par for some load cases in reference to existing triple injection. Average BTE is better for epMa with shorter post injection dwell of 1100ms then longer one (i.e- 1300 ms). BTE has been drived from torque and FER or BSFC. Better combustion control , Combustion efficency and Lower COV_{IMEP} can be the reason behind the improved BTE []. Injection timing of pilots and post injection pulses specially the twin pilots plays the key role in igintion delay, pre-mixed combustion and diffusion combustion phase.

8.3.2 Noise Test

8.3.2.1 Rig level Noise Test

The engine radiated (CN) noise are measured based on IS: 10399 [141] standard for lower two loads and speeds and represented in Table 8.3 , 8.4 and Figs 8.11, 8.12. Prior to start of engine, laboratory inside ambient noise level data were recorded at four locations (1, 2, 3 and 4) around the engine as shown in Fig.4. The average noise level inside the engine laboratory found 63.3 dBA. Minimum five sets of data were captured for each as per the NABL -141 guidelines [143].

Table 8.3:- Nearby Noise trial results with DtA-1100ms

Load- Speed -Location Combination	epMa -injection Timing Combination with DtA-1100ms				Base Line /Existing data
	L1- 25% Load , L2-50% load , N1- 1200 RPM, N2-1500 RPM E1- 39 °CA BTDC, E2- 35 °CA BTDC, P1- 19 °CA BTDC, P2- 15 °CA BTDC				
	E1P1	E1P2	E2P1	E2P2	pMa-E [24]
L1N1 Y	86.4	86.6	86.8	87	88.8
L1N1 Z	86.0	86.2	86.4	86.6	88.4
Avg.L1N1	*86.2*	*86.4*	*86.6*	*86.8*	*88.6*
Avg. Improvement	2.4	2.2	2.0	1.8	NA
L1N2 Y	89.3	89.6	89.7	89.9	91.4
L1N2 Z	88.9	89	89.1	89.3	91.0
Avg. L1N2	*89.1*	*89.3*	*89.4*	*89.6*	*91.2*
Avg. Improvement	2.1	1.9	1.8	1.6	NA
L2N1 Y	90.5	90.7	90.9	91.1	92.7
L2N1 Z	90.1	90.3	90.6	90.8	92.2
Avg. L2N1	*90.3*	*90.5*	*90.75*	*90.95*	*92.35*
Avg. Improvement	2.05	1.85	1.6	1.4	NA
L2N2 Y	91.3	91.5	91.7	91.9	93.2
L2N2 Z	90.9	91.1	91.2	91.4	92.8
Avg.L2N2	*91.2*	*91.3*	*91.45*	*91.65*	*93.0*
Avg. Improvement	1.8	1.7	1.55	1.35	NA

Table 8.4:- Nearby Noise trial results with DtA-1300ms

Load- Speed -Location Combination	epMa -injection Timing Combination with DtA-1300ms				Base Line /Existing data
	L1- 25% Load , L2-50% load , N1- 1200 RPM, N2-1500 RPM E1- 39 °CA BTDC, E2- 35 °CA BTDC, P1- 19 °CA BTDC, P2- 15 °CA BTDC				
	E1P1	E1P2	E2P1	E2P2	pMa-E [24]
L1N1 Y	86.3	86.4	86.6	86.8	88.8
L1N1 Z	85.9	86.0	86.3	86.4	88.4
Avg.L1N2	*86.1*	*86.2*	*86.45*	*86.6*	*88.6*
Avg. Improvement	2.5	2.4	2.15	2.0	NA
L1N2 Y	89.2	89.3	89.5	89.7	91.4
L1N2 Z	88.8	88.9	89.1	89.2	91.0
Avg. L1N2	*89*	*89.2*	*89.3*	*89.45*	*91.2*
Avg. Improvement	2.2	2.0	1.9	1.75	NA
L2N1 Y	90.2	90.4	90.6	90.9	92.7
L2N1 Z	89.9	90	90.1	90.5	92.2
Avg. L2N1	*90.05*	*90.2*	*90.35*	*90.7*	*92.35*
Avg. Improvement	2.3	2.15	2	1.65	NA
L2N2 Y	91.1	91.2	91.5	91.6	93.2
L2N2 Z	90.8	90.9	91.1	91.2	92.8
Avg.L2N2	*90.95*	*91.05*	*91.3*	*91.4*	*93.0*
Avg. Improvement	2.05	1.95	1.7	1.6	NA

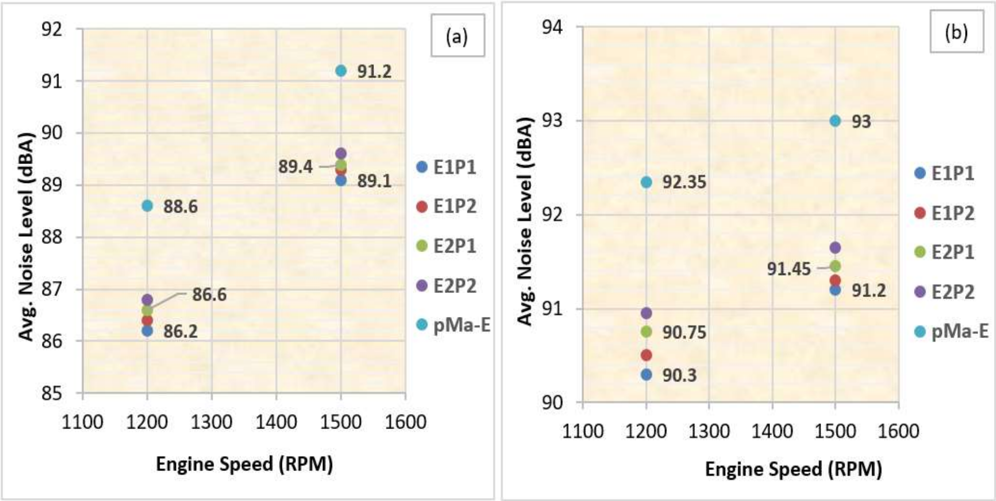


Figure 8.11:- Average Noise level at DtA -1100 ms - (a) 25% Load and (b) 50% load

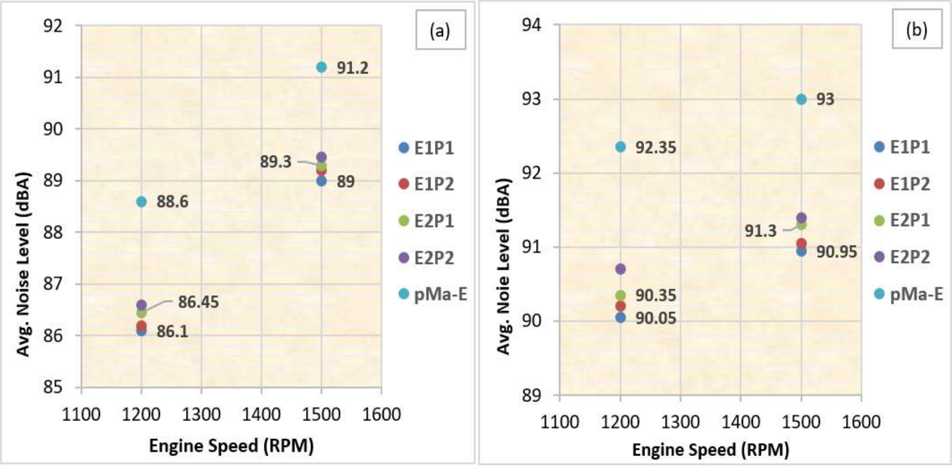


Figure 8.12:- Average Noise level at DtA -1300 ms - (a) 25% Load and (b) 50% load

From these results, it observed maximum 2.05- 2.5 dBA of noise reduction with epMa –E1-39 °CA BTDC P1 –19 °CA BTDC and DtA-1300 ms at lower loads and speeds with respect to existing pMa-E [Study 2]. This provides the best outcome among the injection timing combinations of epMa and base data [pMa-E]. This may due to the advaced Pilot1 (early) injection and longer 2nd pilot and post injection which helps to control the HRR and sudden combustion presure rsise post igintion delay phase. Actually, all the epMa shows CN reduction in comparison to existing Triple injection. The double pilot (i.e. - e and p) injection plays the key role to achieve noise reduction for epMa referring to literatures. The post inject Dwell have marginal impact as well on CN (refer Table 8.3 and 8.4; Fig 8.11 and 8.12). The epMa – E1-39 °CA BTDC, P2 –15 °CA BTDC and DtA-1300 ms combination found second best in noise reduction among all . The epMa-E2P2-DtA-1100ms exhibits the poor results in CN reduction among different injection timing combination of quadruple injections. The epMa- E2P1 DtA-1100 ms combination which is best in BSFC, Torque and BTE, is the 4th best combination in CN reduction. This injection strategy can reduce the CN by 1.55 -2.0 dBA in comparision to the existing triple injections. This is also indicating the benefits of multiple injections specially the quadruple injections in combination with high EGR –LTC to improve (reduction) CN and fuel efficency.

8.3.2.2 Vehicle level Noise Test

The vehicle PBN is the combination of vehicle noise and exterior noise [134]. Tire-road frictional and Wind noise are the contributor of exterior noise. Similarly, Engine, Intake, Exhaust, Transmission/drive line and cabin insulation are the key giver of vehicle noise. Among these engine noise is louder, which contains combustion/radiated noise (CN), piston slap noise and fan belt noise primarily. Also, Exhaust system has significant contribution in PBN performance. Here, exhaust system carried over from production version model where the engine in use for apple-to-apple comparison (refer Fig.8.13). The vehicle have 16T GVW with 6-speeds transmission, Rear Axle Ratio-5.85 and 10x20 size tyres.

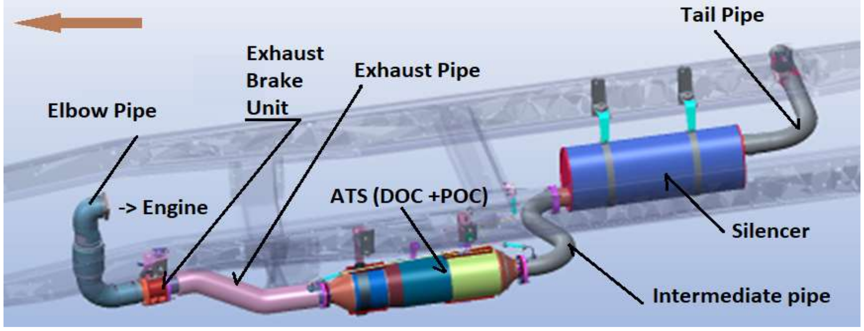


Figure 8.13:- Exhaust Layout of vehicle

Vehicle PBN measurement has been conducted based on IS 3028 [142] for best three Quadruple Injections (epMa- E2P1-DA1 [best in BSFC, BTE], epMa- E1P1-DA2 and epMa- E1P2-DA2) along with base line triple injections (pMa-E). During the PBN trial, the ambient noise and temperature were 52 dBA and 33.5°C respectively. The test results (Table 8.5) exhibited superiority of the quadruple injections in vehicle level noise or PBN performance. The epMa- E2P1 DtA-1100 ms combination has improved the PBN by 0.7 dBA whereas 0.9 dBA reduction shown by the epMa-E1-39 °CA BTDC P1-19 °CA BTDC and DtA-1300 ms injection timing combination w.r.t base injection strategy. This is found the best among the epMa combinations.

Table 8.5 Vehicle level Noise trial results

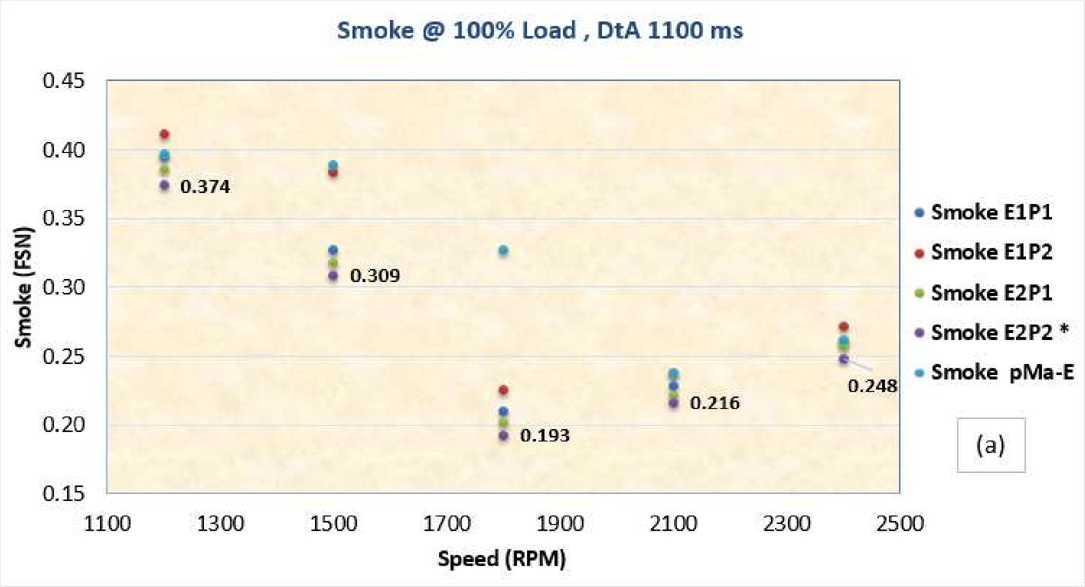
Injection Strategy	Gear No.	Engine RPM		Vehicle Speed		Average Noise (dBA)
		At POS AA’	At POS BB’	At POS AA’	At POS BB’	
epMa-E1P1-DA2	3rd	1800	2600	23	32	78.4
	4th	1800	2350	30	45	78.6
epMa-E1P2-DA2	3rd	1800	2600	23	32	78.5
	4th	1800	2350	30	45	78.7
epMa-E2P1-DA1	3rd	1800	2600	23	32	78.6
	4th	1800	2350	30	45	78.8
pMa-E	3rd	1800	2600	23	32	79.3
	4th	1800	2350	30	45	79.5

8.3.3 Emission Test

Emissions (NOx, THC and CO) measurement done by sampling of exhaust gases and analysing the same using Analyzer. Smoke value characterize in terms of FSN and it was measured using AVL Smoke Meter as shown in schematic (Fig 3.1). Regulatory related emission tests done based on the ESC with ELR and ETC standards (Applicable upto BS-V). Measured regulatory Test data among the injection timing combinations for quadruple injections are represented in tabulated format below for comparative analysis w.r.t base Triple injections.

8.3.3.1 Smoke Test

Measured smoke data shown in bubble chart format below for each load case and speeds as per Table 8.2.



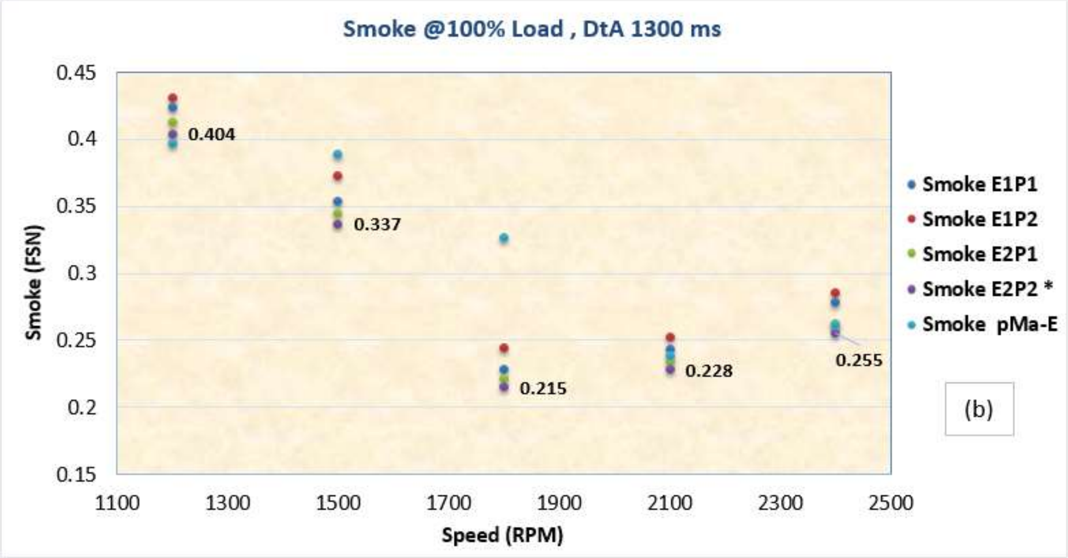


Figure 8.14:- Smoke test results at 100% load-(a) DtA 1100ms and (b) DtA 1300ms

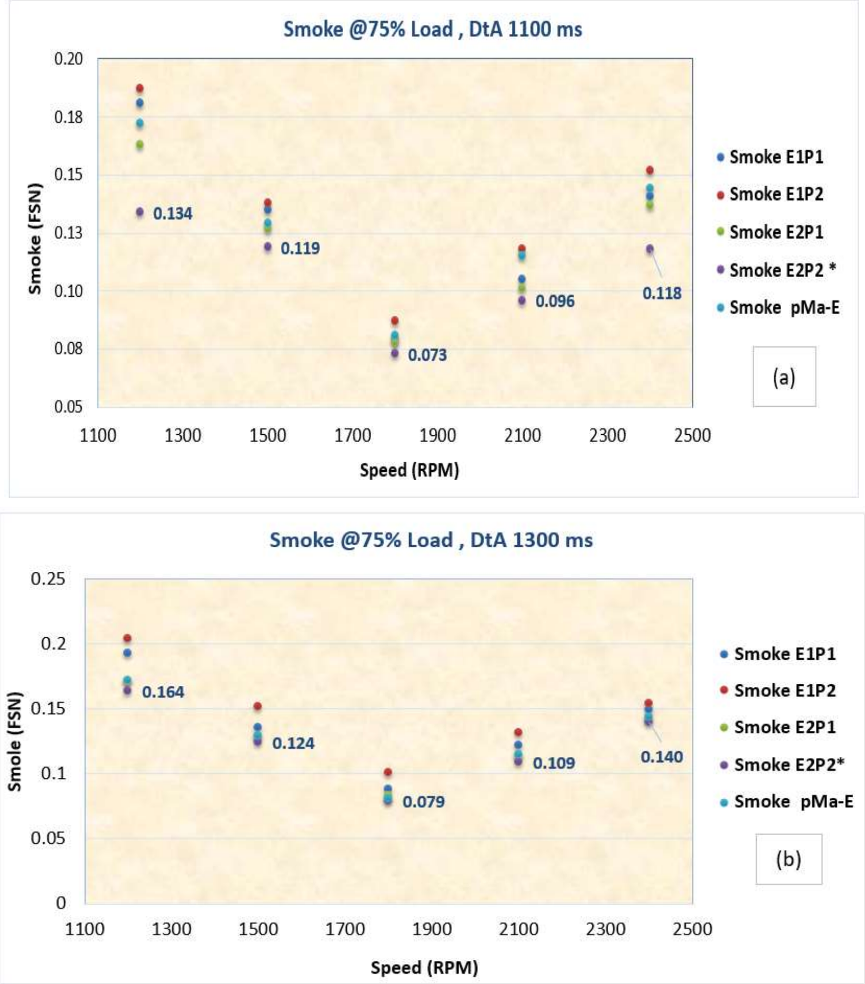
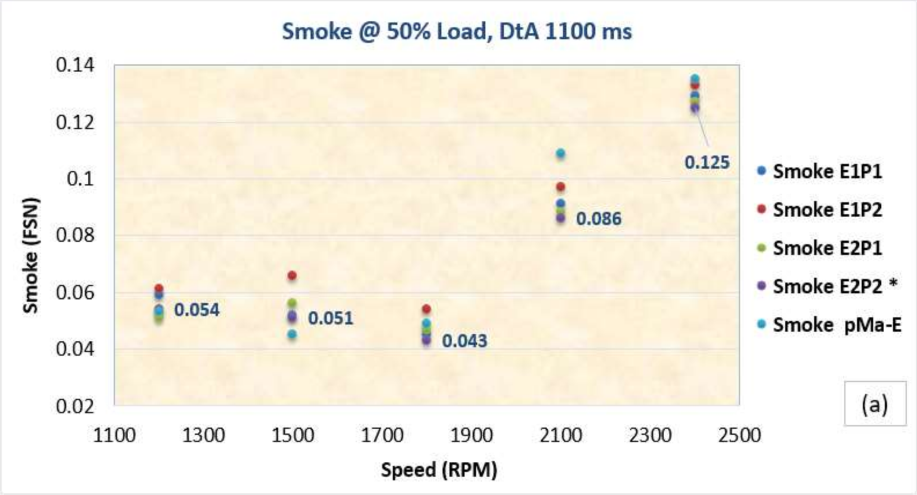


Figure 8.15:- Smoke test results at 75% load-(a) DtA 1100ms and (b) DtA 1300ms



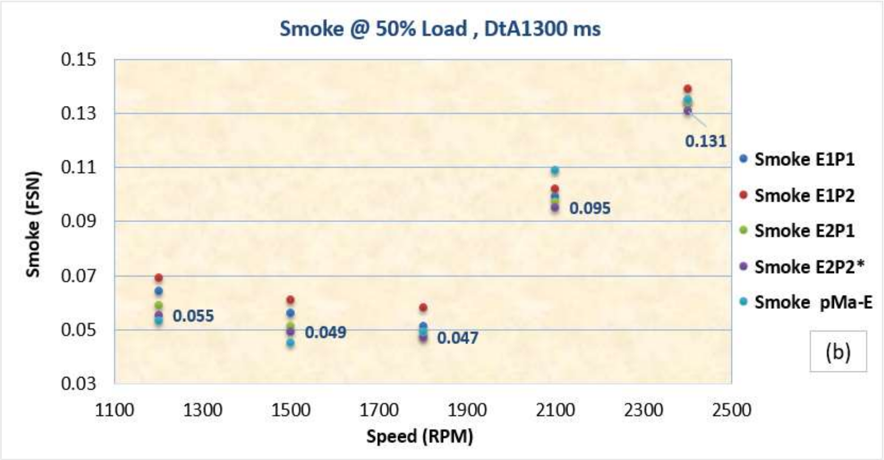


Figure 8.16:- Smoke test results at 50% load-(a) DtA 1100ms and (b) DtA 1300ms

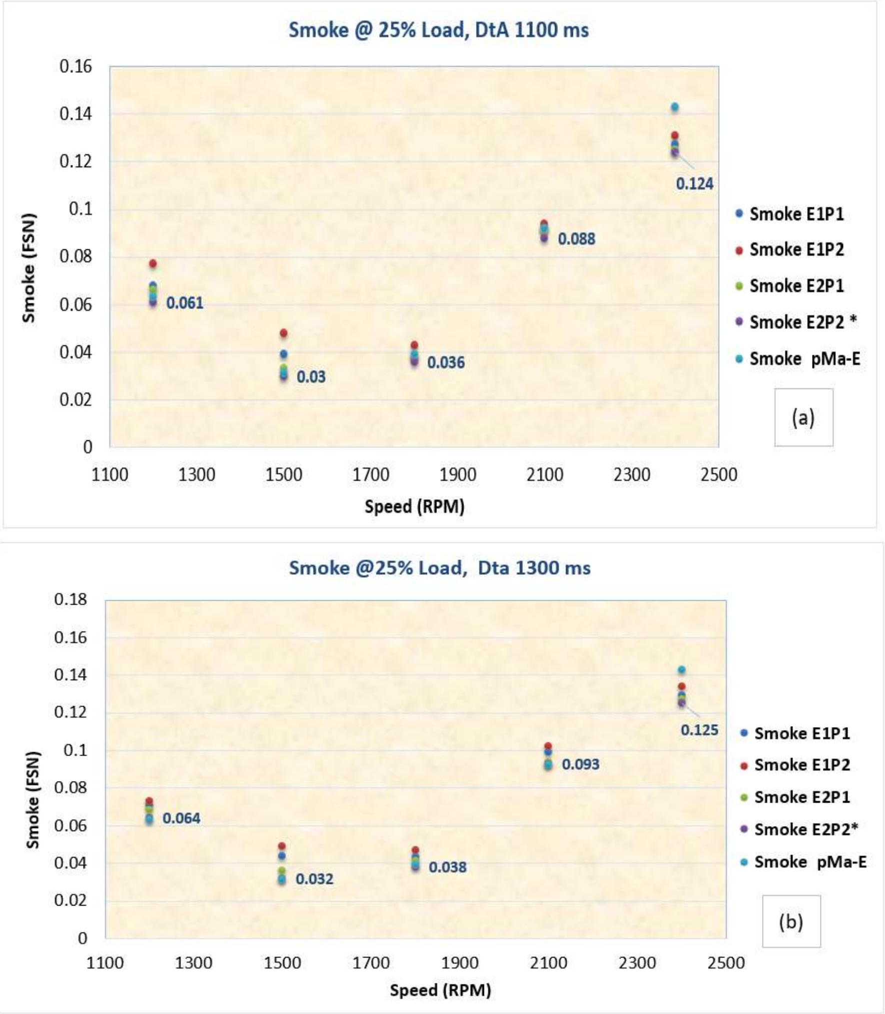


Figure 8.17:- Smoke test results at 25% load-(a) DtA 1100ms and (b) DtA 1300ms

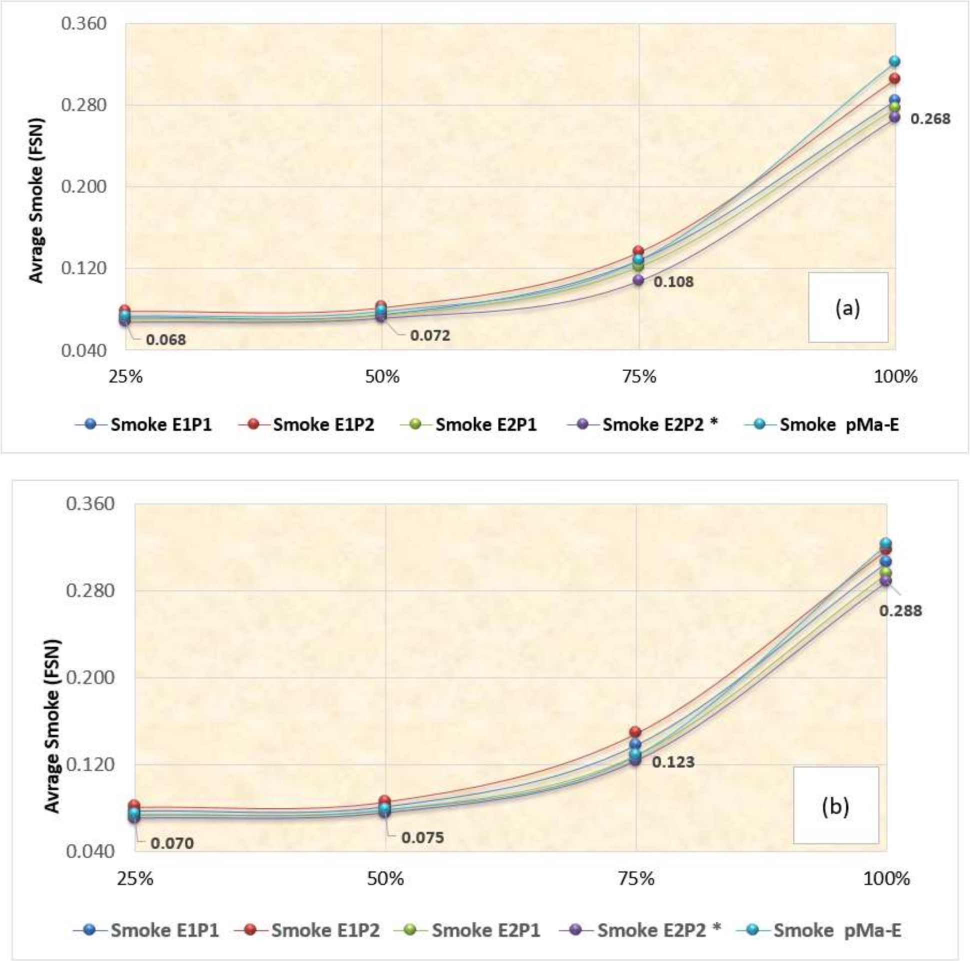


Figure 8.18:- Average smoke with increasing Loads (a) DtA 1100ms and (b) DtA 1300ms

From the smoke charts (Refer Fig 8.14- 8.18), it observed that smoke level improved with closer /shorter post injection dwell. The average smoke graphs (refer Fig 8.18) are showing that the epMa-E2P2 strategy with both the injection dwell is best in smoke reduction. In other hand, the epMa-E2P1 is second best combination. The smoke performance better with the epMa- E2-35°CABTDC, P1-19°CABTDC and epMa- E2-35°CABTDC, P2-15°CA BTDC scheduling specially in combination with inject dwell of 1100ms. The post/after injection enhances the late-cycle mixing of engine combustion at low-temperature combustion (LTC) regime which helps to reduce the soot /smoke formation. Furthermore, among the different quadruple (epMa) injection combinations closed to main injection or retarded pilots (both e and p) are effective in smoke reduction. This is due to increase of bulk temperature of gases inside the chamber with delayed double pilots for epMa injection strategy. In other hand, the epMa injection strategy with advanced twin pilots cause for reduction of bulk temperature of gases inside the chamber thus smoke or soot content increase. The injection timing between both the pilots (i.e. - AiE - AiP) is also important. Due to above reasons, best smoke performance observed with the epMa-E2P2 and worst one with the epMa-E1P2. The smoke level of existing triple injections are fourth and 3rd best respectively w.r.t the quadruple injection combinations with shorter (i.e. - 1100ms) and longer (i.e.-1300ms) after injection dwell. This (pMa-E) strategy shows very good performance at low speed. The epMa-E1P2 is worst one among the combinations and in reference to base line pMa-E.

8.3.3.2 Overall Emission Tests (ESC and ETC)

Emission level investigation as per ESC and ETC standards [146] are represented in tabulated format below

Table 8.6:- ESC Test Results with DtA-1100ms

	pMa-E	epMa-E1P1	epMa-E1P2	epMa-E2P1	epMa-E2P2	BS-IV Limits	BS-V Limits
PM	*0.015*	0.014	0.017	0.013	0.012	0.02	0.02
NOx	*3.13*	2.978	2.973	3.009	3.274	3.5	2
THC	*0.059*	0.063	0.069	0.055	0.058	0.46	0.46
CO	*0.065*	0.06	0.063	0.057	0.056	1.5	1.5

Table 8.7:- ETC Test Results with DtA-1100ms

	pMa-E	epMa-E1P1	epMa-E1P2	epMa-E2P1	epMa-E2P2	BS-IV Limits	BS-V Limits
PM	*0.016*	0.015	0.018	0.014	0.013	0.03	0.03
NOx	*3.133*	3.014	3.011	3.017	3.313	3.5	2
THC	*0.072*	0.074	0.077	0.072	0.07	0.55	0.55
CO	*0.087*	0.075	0.079	0.061	0.059	4	4

Table 8.8:- ESC Test Results with DtA-1300ms

	pMa-E	epMa-E1P1	epMa-E1P2	epMa-E2P1	epMa-E2P2	BS-IV Limits	BS-V Limits
PM	*0.015*	0.015	0.018	0.014	0.013	0.02	0.02
NOx	*3.13*	2.973	2.969	3.006	3.274	3.5	2
THC	*0.059*	0.064	0.071	0.06	0.059	0.46	0.46
CO	*0.065*	0.061	0.064	0.059	0.058	1.5	1.5

Table 8.9:- ETC Test Results with DtA-1300ms

	pMa-E	epMa-E1P1	epMa-E1P2	epMa-E2P1	epMa-E2P2	BS-IV Limits	BS-V Limits
PM	*0.016*	0.016	0.02	0.015	0.014	0.03	0.03
NOx	*3.133*	3.011	3.003	3.014	3.311	3.5	2
THC	*0.072*	0.076	0.079	0.073	0.072	0.55	0.55
CO	*0.087*	0.077	0.081	0.067	0.066	4	4

Emmision test results are showing that the epMa injection strategy is superior in overall emission performance with most of injection timing combination though THC is slightly higher side in comparison to existing Triple injections (refer Table 8.6, 8.7, 8.8 and 8.9). The particulate matter emissions are better for epMa even though marginal higher THC and smoke at lower Speeds. This may due to the improved ignition delay, diffusion combustion phase, better-controlled heat release rate, combustion gas temperature (bulk) and late cycle mixing due to after/post injection inside the combustion chamber at high EGR-LTC regime . Comparatively closer post injection (1100 ms and 1300 ms from 1350ms) also help to compensate the soot emission for epMa when compared with existing pMa-E due to improvemet of late cyclice mixing and exhaust gas temerature. The epMa- E2-35°CABTDC, P1-19°CABTDC and DtA-1100ms is found optimum in emissions though the epMa-E2P1 is best in PM, THC and CO emissions among the eight injection combinations of epMa. Similarly, the epMa- E1-39°CABTDC, P2-15°CABTDC and DtA-1300ms deliver the best NOx reduction among all. The results are indicating stretched post injection dwell affect the degradation of PM, THC and CO marginally with delta improvement in NOx emissions. The emission analysis is also indicate the benfit of adopting the multiple injections specially the newest quadruple injection strategy with twin pilots with high EGR to compensate the draw back of high EGR-LTC like CO emission .

8.4. Conclusion

This experimental study carried out to understand the effect of newest quadruple injections (early-pilot-main-after/post) with different injection timing (both pilots and post/after) combination on emissions, performance (BSFC, Torque, BTE) and combustion noise (CN) with fixed main injection timing and high EGR on a Heavy duty CRDI BS-IV diesel engine. Further, Comparative analysis done in comparison to existing triple injections (pMa-E) to evaluate the potentially of the Quadruple (epMa) injections at four different loads and five speeds condition. From the experimental results and understanding from available scientific literatures, following conclusions can be emerged.

(i) In association with high EGR –LTC regime, all eight quadruple injection (epMa) combinations (epMa-E1P1, epMa-E2P2, epMa-E2P1, epMa-E2P2) are considerably smoother than base line triple injections at all operating conditions. The epMa- E2-35°CABTDC, P1-19°CABTDC with shorter post injection dwell (DtA-1100 ms) exhibits the best BSFC performance among the combinations and existing triple injections (pMa-E). The average BSFC of this is superior by 0.2 to 1.31 % from low to high Load. On other hand, the epMa-E1P2 shows relatively worst result especially with longer post injection dwell 1300ms. The BSFC performance of quadruple injection strategy indicates the influence of early (or pilot1) and Pilot (or Pilot 2) injection timing and post injection dwell on fuel economy performance with fixed main injection timing at high EGR-LTC. Injection timing of both the pilots (AiE, AiP) and post injection pulse specially the twin pilots plays the key role in igintion delay, pre-mixed combustion and diffusion combustion phase.

(ii) From the torque performance graphs , it is clear that the quadruple (epMa- E2P1-DtA 1100ms) injection with delayed early (or Pilot 1), advanced pilot (or pilot 2) and closed post injection dwell combination is best in torque performance among the injection timing combinations (8 nos) and existing triple injection. This may due to the better combustion control, which is affected by the ignition delay, heat release rate, pressure rise rate and bulk gas temperature inside the combustion chamber. The qudrapule injections having twin pilots help to improve combustion efficinecy, combustion stability and reduce $COV_{IMEP.}$ The epMa-E2P2 shows the second best

Torque performance whereas the epMa-E1P2 exhibits worst outcome especially with longer post/after injection- dwell. The existing pMa-E is found bottom liner in torque performance.

(iii) The overall average and average Brake thermal efficiency (BTE) which depends upon BSFC or FER and Torque, shows that the epMa-E2P1 is best among the quadruple injection combination especially with short post/after injection dwell (Refer Fig. 8.10). This provides improved BTE of around 0.84 to 1.5% compared to base line pMa-E. The epMa- E2P2 found better with DtA 1100ms and at par with DtA 1300ms as compared to pMa-E. These results also indicating that average BTE is better for quadruple injection (epMa) in combination with smaller post/after injection dwell then longer one. This could be outcome of better combustion control , Combustion efficency and Lower COV_{IMEP} .

(iv) This epMa strategy is found better in reduction of engine combustion Noise (CN) due to double pilot (early and pilot) injection pulses especially at low loads and speeds; than existing triple injection strategy. The quadruple injection strategy (epMa- E1-39°CABTDC, P1-19°CABTDC and DtA-1300ms) featuring advanced twin pilots with delayed post injection dwell exhibits the best CN reduction of around 2.05- 2.5 dBA at rig level. Similarly it helps in PBN reduction of around 0.9 dBA w.r.t the base line. The epMa-E2P2 –DtA 1100 ms is worst in CN reduction among the injection strategies /timing combinations. The epMa- E2P1 DtA-1100 ms combination is the 4th best in CN reduction (1.55 to 2 dBA) as well in PBN reduction (0.7 dBA).

(v) The average smoke graphs are showing that the epMa-E2P2 is best and the epMa-E2P1 is second best combination in smoke reduction respectively specially with DtA 1100ms. The retarded pilots (early and pilot) along with closer after injection dwell showed significant influence in smoke reduction.

(vi) The epMa injection strategy is superior in overall emission performance with most of injection timing combination though THC is slightly higher side in comparison to existing Triple injections. The particulate matter emissions are better for epMa even though marginal higher THC and smoke at lower Speeds. This may due to the improved ignition delay, diffusion combustion phase, better-controlled heat release rate, combustion gas temperature (bulk) and late cycle mixing due to post injection. Comparatively closer post injection (1100 ms and 1300 ms from 1350ms) also help to compensate the soot emission for epMa when compared with existing pMa-E. The epMa- E2-35°CA BTDC, P1-19°CA BTDC and DtA-1100ms is found optimum in emissions though the epMa-E2P1 is best in PM, THC and CO emissions among the eight injection combinations of epMa. Similarly, the epMa- E1-39°CA BTDC, P2-15°CA BTDC and DtA-1300ms delivers the best NOx reduction among all.

(vii) Test results show the importance of twin pilots (early and pilot) and post injection timing on performance (BSFC , Torque, BTE) , emissions (smoke, NOx, PM, THC and CO) and Combustion Noise in assocation with high EGR-LTC. The condition (i.e-injection Timing combination) which is fevourable for NOx & CN ; gives adverse effect on smoke , PM , THC and CO. Though, this study shows that marginal impact of post injection dwell on CN. The period between early (or Pilot 1) and Pilot (Pilot2) injection pulse have signficant impact on combustion control which ultimately has the influence on perfromance , emissions and CN. The stretched post/after injection dwell degrades the smoke, PM, THC emissions with marginal improvement in NOx level. This study shows that no such significant impact of post injection dwell on CN. Optimize injection timing of both the pilots (early and pilot) and closer post injection dwell w.r.t main injection, plays the key role in improvemt of BSFC performance.

Finally, these results display the importance of adopting Multiple fuel injection strategies with high EGR-LTC for simultaneous reduction of emissions and combustion noise along with improved performance (BSFC, Torque, BTE) in modern diesel engine because of its better commends on combustion process which helps to overcome the drwaback of high EGR-LTC process. Newest Quadruple injections featuring twin pilot and post injection pulse and variable injection parameters; are promising to meet the strict emission norms and fuel economy goal. This study done with fixed main injection timing and high EGR rate of 45% on a production version of 6-cylinder inline CRDI BS-IV diesel engine having Triple (pMa-E) injections with modification of claibration. Thus, this investigation does not covered the impact of further high or heavy EGR and injection rate shaping and variable main injection timing. Even though at high EGR-LTC condition, the Quadruple injection strategy shows the potentiality with diffrent injection timing (Pilots and post injection Dwell) over proven Triple injections scheduling on emissions, combustion noise and Performance (BSFC, Torque, BTE).

Chapter -9

Conclusions

Conclusions

9.1 Overall Conclusions

In this thesis, primarily experimental based research objectives have been identified and achieved (section 2.3, Fig 2.17) taking consideration of research gap analysis (section 2.2). The quadruple (epMa) injection strategy has been compared to the best three triple injection strategies (eMa, pMa and pMa), baseline triple injections (pMa-E) , two double injections (pM & Ma) and single injection on a typical six-cylinder BS-IV diesel engine featuring 45% EGR rate. This is to assess the potential benefits in performance (BSFC, torque and BTE, CSFC (in few case), emissions and noise (CN and PBN (in few case)) at different operating speeds and load conditions. Prior to each experimental investigation, delta optimisation was conducted at the base level calibration on the production engine to adopt the needed injection strategies and maintain the same percentage of EGR. All the testing environments were formulated based on the Taguchi DoE approach and regulatory norms [139-144]. Also, vehicle level trials have been carried out for real-time performance (fuel economy and Pass by noise[PBN]) evaluation. The outcomes of this investigation are as follows

1. Multiple injections featuring with pilot injection pulse is effective in combustion noise reduction at lower speeds. Double pilot injections are more impactful to reduce the combustion noise as it controls the rate of heat release and pressure rise inside the combustion chamber.

2. Multiple injections (double, triple, quadruple) are better than single injection in performance (BTE, Torque & BSFC) particulate matter (Soot , Smoke) reduction than single injection

3. The Ma (double) injection strategy is worst among the multiple injections in Smoke emission/ soot concentration level

4. The torque value, restricted by exhaust out smoke number of engine, was enhanced by pilot injection having advanced injection schedule/timing in addition to a reduction in CN. Interestingly, twin pilot (e and p) injections (epMa) with advancement in injection timing display a marked improvement of torque at all loads (especially low to medium loads). The inside-cylinder pressure and HRR are high in twin pilot (e and p) injections with advancement in injection timing, which underlies the improvement in the torque of the engine without crossing the smoke number.

5. The BSFC performance of quadruple injection strategy indicates the influence of early (or pilot1) and Pilot (or Pilot 2) injection timing and post injection dwell on fuel economy performance with fixed main injection timing at high EGR-LTC. Injection timing of both the pilots (AiE, AiP) and post injection pulse (post injection dwell) specially the twin pilots plays the key role in igintion delay, pre-mixed combustion and diffusion combustion phase.

6. The qudrapule injections having twin pilots (ep) help to improve combustion efficinecy, combustion stability and reduce $COV_{IMEP.}$ The epMa-delayed early (e) and adavanced pilot (p) with closed/shorter post injection dwell combination shows the best Torque and BSFC performance.

7. The overall average and average Brake thermal efficiency (BTE) which depends upon BSFC or FER and Torque, shows that the epMa-E2P1[delayed early (e) and adavanced pilot (p)] is best among the quadruple injection combination especially with short post/after injection dwell

8. The double pilot (epMa) injection strategy formed slightly higher emissions of THC level than the single-pilot injection schedule (pM, eMa and pMa) due to the availability of richer fuel mixture during the ignition delay phase. At the same time, Double pilots reduce the ignition delay, which has a significant impact on THC reduction. Thus, the final THC formation sequence is found as pM<pMa<epMa<eMa<epM.

9. The epMa was second best in CO emissions in comparison with best three triple injections (epM, pMa, eMa). The twin pilot's help to create the favorable condition for reduce CO level due to relatively higher temperature inside the cylinder with a shorter ignition delay period and enhanced the oxidation rate of CO. Thus epM is best in CO emissions.

10. Significant reduction was observed in exhaust-out NOx emission level with quadruple injection scheme as this reduces the flame or bulk gas temperature inside the cylinder as well as the heat release rate (HRR). The epMa strategy is exhibited at 3–6% NOx reduction over pM, epM, eMa and pMa but fails to meet the BS-V emission target for NOx.

11. Overall PM emission is marginally better for quadruple injection strategy compared to pMa and other (i.e., epM and eMa) triple injections and double injections (pM). Both pilot and post-injection have a significant impact on the combustion phases to control the soot/smoke formation and HC. The PM is a mixture of soot and HC. A better smoke performance may cause marginal improvement in PM reduction by the epMa injection strategy.

12. The present study showed that the quadruple injection scheme has significant potential over triple and double injection strategy to trade-off among NOx-PM/Smoke, CN-BSFC, torque-BSFC, BSFC-NOx and optimum outcome to correlate the test results with scientific literature in a specific research domain.

13. Importance of injection timing specially the dwell between early and pilot ; pilot and main and lastly main and post/after injection pulse are well established from experimental results.

9.2 Future scope of work

The comprehensive study shows the potentiality of newest Quadruple injection strategy(epMa) over other multiple injections (doubl and triple) on CRDI diesel engine. Also, the outcomes display the significance of implementing Multiple fuel injection strategies with high EGR-LTC for simultaneous reduction of emissions and combustion noise along with improved performance (BSFC, Torque, BTE) in modern diesel engine because of its better control on combustion process which helps to overcome the drwaback of high EGR-LTC process. Newest Quadruple injections featuring twin pre-injections (early and Pilot) and post injection pulse are further promising to meet the strict emission norms and fuel economy goal. All the investigations done with either fixed main injection timing or varable main injection mapping with high EGR rate of 45% on a production version of 6-cylinder inline CRDI BS-IV diesel engine having Triple (pMa-E) injections with modification of claibration. Thus, this investigation does not cover the impact of further high or heavy EGR and injection rate shaping or variable main injection timing, even though at high EGR-LTC condition, the Quadruple injection strategy shows the potentiality with diffrent injection timing (Pilots and post injection Dwell, main injection timing) over proven Triple injections (pMa) scheduling as well as other (epM, eMa, pM, Ma) on emissions, combustion noise and Performance (BSFC, Torque, BTE).

As further scope of study, injection rate shaping of main injecton along with heavy EGR-LTC can be worked out to reduce the emissions further. In addition, there is a scope to work with newest Quadruple injection strategy in combination with alternative fuels or felxi fuel mode as per upcoming government regulation. Combustion noise 3D plot (cambell diagram) and frequency analysis are also can be worked out after upgradtion of noise measurement setup.

Also, Development low order (0D or quasi-dimensional/ Phenomenological (1D)) combustion model (heat release, in cyclinder pressure and emissions) and its validation with experimental results can be planned.

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Appendix-A

Appendix-A: Smoke, Soot and PM correlation and its measurement

Generally, Soot or carbonaceous particulate matter is produced during premixed or diffusion combustion of fuel rich mixtures. High concentration of soot in the exhaust can be visible as black smoke. Fuel composition also has impact in soot formation. Same factors affect both soot formation/ oxidation and smoke. Engine torque rating and maximum brake mean effective pressure limited by the permissible smoke emissions. Smoke value is measured in terms of opacity or FSN (filter Smoke number) or HSU (Hartridge Smoke Unit) or BSU (*Bosch Smoke Unit*). All these units have correlation among them and with PM (particulate matter). FSN unit is used for smoke measurement in present work. Particulate matter is combination of soot and unburned hydrocarbons absorbed on soot of exhaust. Hence, Soot content can be roughly estimated from smoke measurement using the correlation developed by SAE [144]. Considering the complexity of PM measurement, simplified correlations developed by different researchers to estimate particulate matter, using smoke and unburned hydrocarbons absorbed on soot.

Alkidas [141] has established a correlation between the soot concentration (mg/m^3) and FSN from the exhaust measurements

$$\rho_c = 581.4\,\{ln[10/(10 * FSN)\,]\}1.413 \quad \text{………………………………………………………} \; (A.1)$$

Greeves et al.[142] have given a correlation for calculating particulate mass (mg/m^3) by knowing the soot and unburned hydrocarbon concentration in the exhaust.

$$\rho_p = 1.024\rho_c \; + 0.505\,\rho_{HC} \quad \text{………………………………………………………} \; (A.2)$$

J. Arregale et al.[143] have given a correlation based on smoke opacity, FSN and HC measurements for predicting particulate matter and proposed a relation between FSN and smoke opacity values.

$$\rho_p = 4.78\,FSN + 9.14\,FSN^{1.83} + 0.28\,\rho_{HC} \quad \text{…………………………………………} \; (A.3)$$

Also, smoke opacity can be measured with AVL 439 smoke meter and FSN values are estimated from smoke opacity values using Figure A.1.

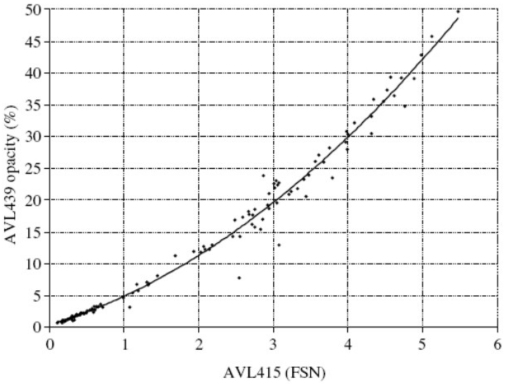

Figure A.1:- Opacity Vs FSN of AVL Smoke meter