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ASSESSMENT OF THE QUADRUPLE INJECTION STRATEGY OVER TRIPLE INJECTIONS TO IMPROVE EMISSIONS, PERFORMANCE AND NOISE OF THE AUTOMOTIVE DIESEL ENGINE

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Abstract. *The present study aims at investigating effectiveness of the 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).*

This comprehensive study showed that the quadruple injection strategy provides optimum results in both performance and emissions compared to the promising three triple injection strategy. The quadruple injection strategy exhibits the best BTE at all operating conditions and best BSFC at medium to high-speed zone around 0.5–1% inline to reduce combustion noise (CN) level, especially at low speeds and low to medium load of 0.2–2.2 dBA. Among triple injections, the pMa shows the best performance in BSFC, BTE, smoke and THC emissions. The epM is the best in the CO emissions and torque performance in the low-speed zone. Smoke value is marginally higher for the epMa at low to medium speed than the pMa, although average smoke emissions were the best. Taken together, the overall PM emission level was marginally better than Triple Injections, due to the impact of double pilots in combination with post-injection. In addition, NOx emissions were improved (around 3–6%) significantly with quadruple than with triple injections. The epMa injection scheduling also showed improvement in constant speed fuel economy and in pass-by-noise at the vehicle.

Key Words: *Quadruple Injections, Emission, Brake Specific Fuel Consumption, Pass-by-noise, Constant Speed Fuel Economy, Brake Thermal Efficiency*

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1. INTRODUCTION

Automotive engine out-emissions, noise and fuel economy have a significant impact on environmental pollution. Thus, the challenges are multi-fold for an engine developer/engineer (R&D), especially for the diesel engine as he needs to deal with stringent emissions norms in line with mandated fuel economy norms as per applicability [for example, heavy-duty fuel economy (HDFE) or constant speed fuel economy (CSFE) or corporate average fuel efficiency/economy (CAFE)]. Fuel economy norms are targeted to CO_2 emissions reduction (in gm/km) to control global warming. Currently, the diesel engine combustion noise (CN/radiation) has gained significant attention as it is associated with the passengers and pedestrians' discomfort along with noise pollution. Therefore, the fuel injection strategy plays a key role in the simultaneous reduction of emissions and CN without penalizing fuel economy due to the better control of the combustion process. The fuel injection strategy in combination with the common rail direct injection (CRDI) technology and heavy or high EGR is also promising low-temperature combustion (LTC) methodology [1]. The CRDI technology provides flexibility to experiment with various injection strategies based on the parameters such as injection pressure, fuel quantity and injection timing, which are linked to the engine combustion management. Furthermore, engine with a turbocharging system enables power augmentation with improved fuel efficiency at particular brake mean effective pressure [2].

A five-dimensional study has been carried out on the modern diesel engine to simultaneously improve the performance (especially fuel economy and CN) and emissions. Several studies [3-7] are focused on the effect of pilot injection (single or double/twin) or post-injection on emissions, combustion or CN. Some groups are focused on the impact of injection parameters (fuel injection pressure (FIP), injection rate, injection timing and fuel quantity) on combustion characteristics and emissions [8-9]. The influence of alternative fuel on performance, combustion and emissions has also been explored [10-11] with variation in injection parameters or injection strategies. On the other hand [12-14], the predictive model was developed based on quasi-dimensional (1D) or phenomenological and multi-dimensional (i.e., CFD) approach and validated for combustion and emissions of DI diesel engine with single and multiple injections (double, triple). A recent study [15-18] assessed the impact of multiple injections on the performance, CN, and emission characteristics of the modern diesel engine. The selective outcomes of these studies have been discussed subsequently.

Mendez et al. [15] examined the impact of multiple (double, triple and quadruple) injections on a low Compression-Ratio diesel engine with high EGR%. The study concluded that the multi-injections strategy is beneficial along with high rate EGR (~46%) to accept ignition delay with improvement in the emission level, CN and trade-off of fuel economy. D'Ambrosio et al. [16] concluded that the pilot-pilot-main-after (ppMa) strategy could improve in engine out-NOx emissions and trade-off among BSFC-NOx EGR curve compared to both the pilot-pilot-main (ppM) and pilot-main-after (pMa) strategies at mid-range loads and speeds. In addition, it reduces CN significantly compared to both triple injections. In a previous study [17], the impact of epMa injection was assessed with respect to the performance, emissions and CN level of CRDI engine with variables, such as variable main injection timing and eight different speeds and loads, for better and smoother torque, BSFC and reduced CN than baseline pMa-E. In another study [18], the superiority of epMa injection over triple (pMa) and double (pM) injections was assessed with respect to noise, performance and emissions level with fixed main injection time.

Currently, only limited literature is available on the quadruple injection strategy consisting of a double pilot and one post-injection event combined with high EGR on the heavy-duty diesel engine. Studies of the influence of multiple injection strategies upon vehicle level fuel economy and noise performance have not been reported yet. Considering this research gap, we have focused on the comprehensive assessment of four types of multiple injections, including the newest quadruple injection (Fig. 1). In the present study, the potentialities of quadruple injection schedules are evaluated over three triple injections on a classic six-cylinder heavy-duty CRDI engine at three different operating loads and eight speeds (low-to-high) using design of experiments (DOE) approach. The results of emissions (nitrogen oxides (NOx), particulate matter (PM), smoke and total hydrocarbons (THC) levels) and performance (torque, BSFC and BTE) and CN (radiated) with fixed EGR% and main injection timing were compared at various engine working conditions. The study also elucidated the impact of these injection strategies on vehicle level pass-by-noise (PBN) and CSFE. The current literature provides an insight in terms of in-cylinder characteristics.

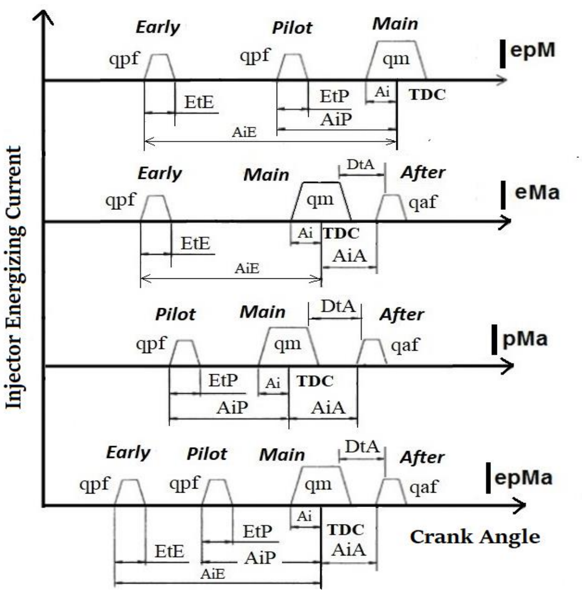

Fig. 1 Schematic representation of quadruple and three triple injection strategies

In Fig. 1 the following is 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.

2. EXPERIMENTAL SETUP AND METHODOLOGY

2.1. Experimental Setup

The experiment was conducted on a heavy-duty BS-IV diesel engine containing a cooled EGR and CRDI system. The external cooling system (turbocharged intercooler) is attached to the engine. Table 1 shows the specification of a typical engine.

Table 1 Specification of Experimental Engine

Parameters	Value
Engine type	BS-IV 6 cylinder inline, Turbocharged
Total displacement volume	5.67 L
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	120–170 MPa
EGR type	Short route cooled EGR
No. of holes at injector and tip angle	8 no. and 148°
Combustion chamber type	Shallow bowl/semi-quiescent
Boost pressure @ max power	214 kPa

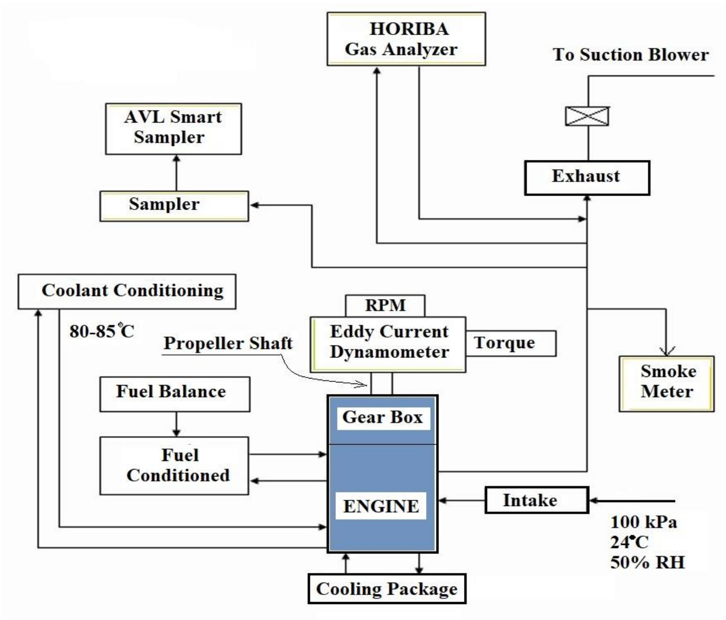

Fig. 2 Schematic layout of the experimental setup for performance and smoke emissions

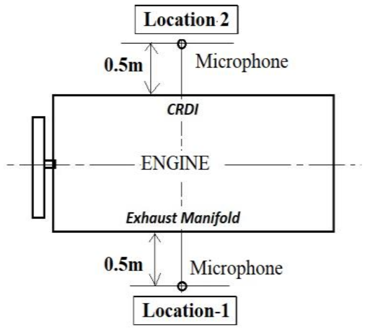

Fig. 3 Schematic layout of nearby noise test at Rig

In Test rig, the engine is propelled by an Eddy current dynamometer using a drive shaft. A 6-speed transmission is mounted with the engine. The driveshaft is connected in between the dynamometer and the transmission/gearbox. Properly conditioned and metered air and fuel were used during experiments as shown in the setup and data acquisition system (Fig. 2) for emissions and performance. Inside the testbed, engine-radiated noise was measured according to the schematic in Fig. 3, following the IS: 10399 guidelines [19].

2.2. Experimental Methodology

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 2). 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° CA BTDC, DtA 1350 ms), which meets BS-IV norms. To adopt all four injection strategies (i.e., epMa, pMa, eMa and epM), delta optimization 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 2. The experiments were conducted as per the DOE matrix shown in Table 3 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) were followed in the laboratory. The emission tests were based on European stationary cycle (ESC) with a European load response (ELR) for smoke trial and European transient cycle (ETC) standards to verify the results in reference to regulatory norms. Radiated noise/CN of engine was measured based on the IS: 10399 [19] standard on noise measurement methodology of a stationary vehicle. During the noise trial, the microphone was placed as shown in Fig. 3. Test data were acquired only after stabilization of exhaust gas temperature. Furthermore, the ambient noise of the test rig was measured before the start of the trials. PBN trial was conducted as per IS: 3028 [20] to understand the vehicle level impact. CSFC or CSFE performance of vehicle was measured based on AIS-149 [21] 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 2 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 3 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

3. RESULTS AND DISCUSSION

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.

3.1. Rig Level Tests

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 3). Torque (Tr in Nm) and fuel flow rate (FFR in kg/h) were directly measured during experimentation. BSFC (g/kWh) value was calculated using equation (1), where N is engine speed in RPM.

$$BSFC = \frac{(FER \times 1000 \times 9549.35)}{(T_r \times N)} \tag{1}$$

The average BSFC performance was the best for the quadruple injection strategy among the schemes at 100% load, although at few speeds, pMa performed better (Fig. 4). In addition, the BSFC curve was smoother with the 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. 5). 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.

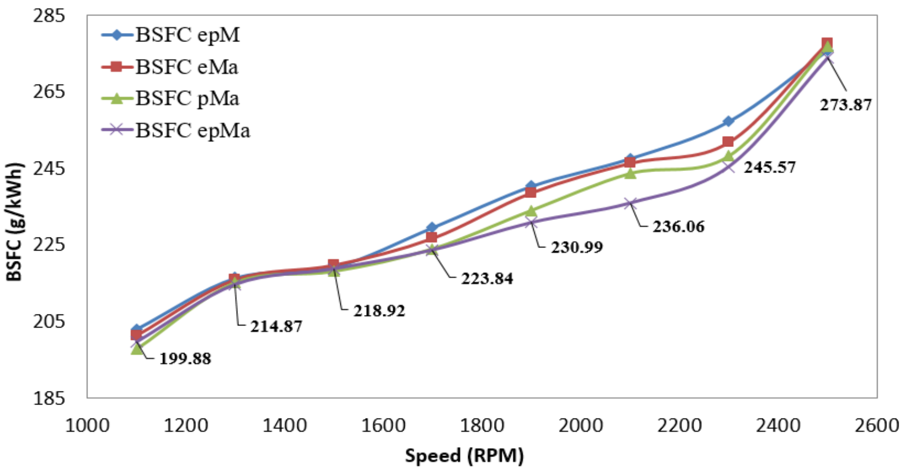

Fig. 4 Comparative BSFC graphs at 100% load

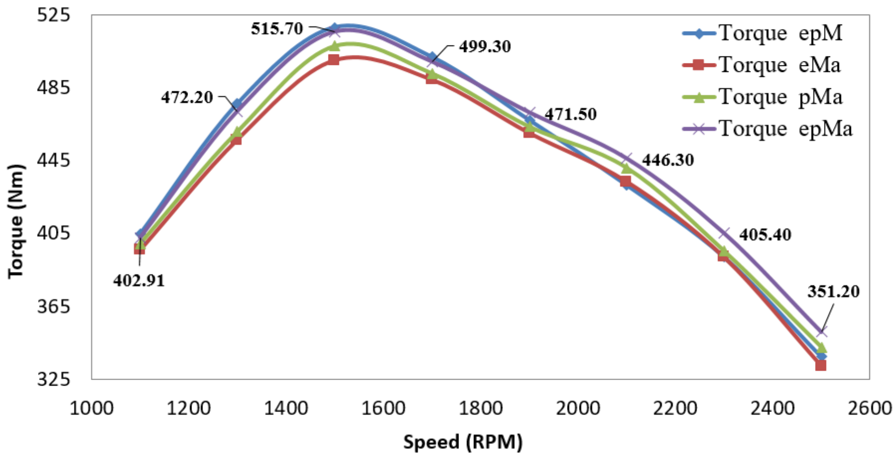

Fig. 5 Comparative torque graphs at 100% load

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. 6). The pMa injection strategy performed the best <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). 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).

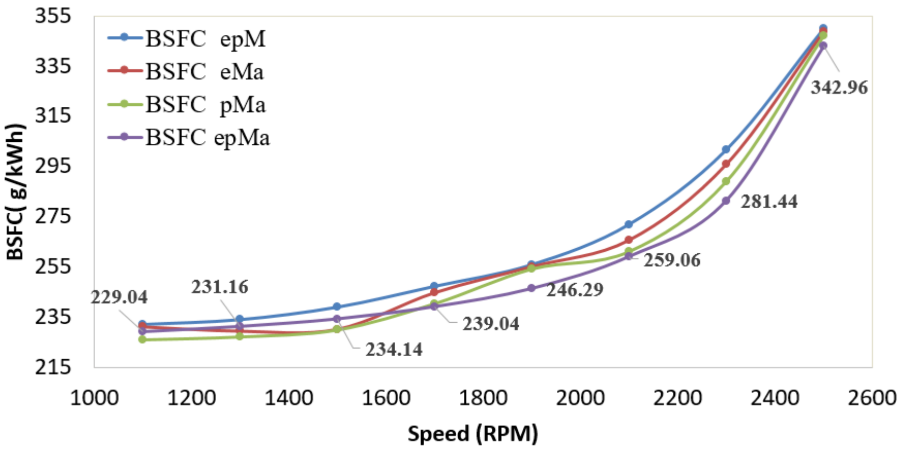

Fig. 6 Comparative BSFC graphs at 60% load

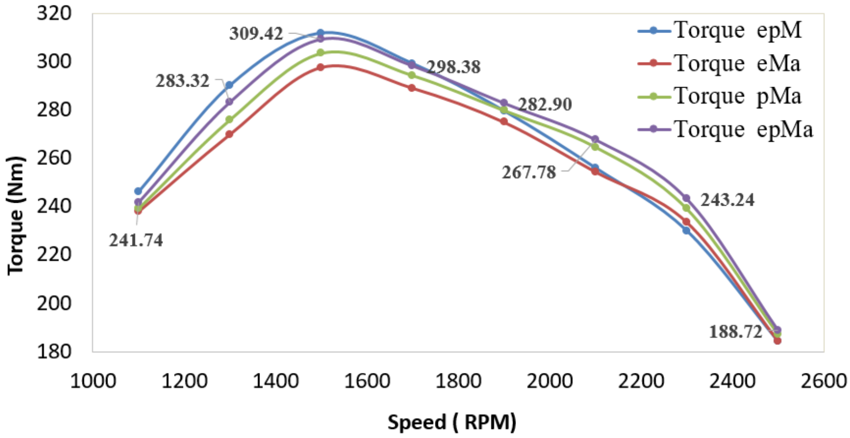

Fig. 7 Comparative torque graphs at 60% load

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. 8). 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. 8). Similarly, the torque performance is also mixed in nature at a partial load of 20% (Fig. 9). The quadruple (epMa) injection provides the optimum torque performance among the injection strategies (Fig. 9), 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.

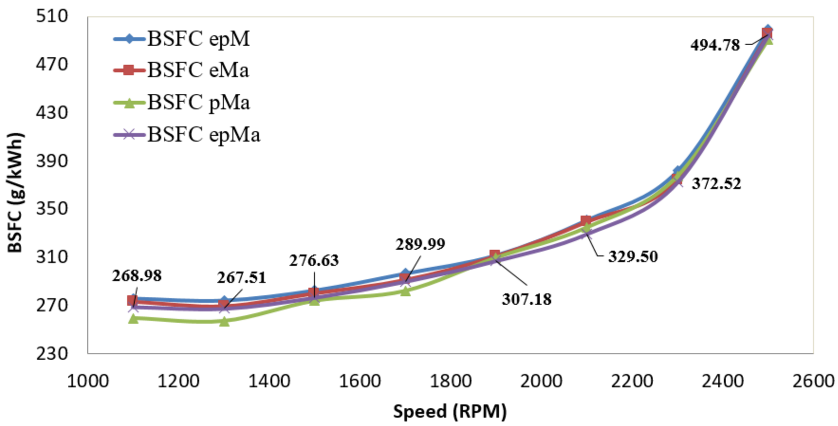

Fig. 8 Comparative BSFC graphs at 20% load

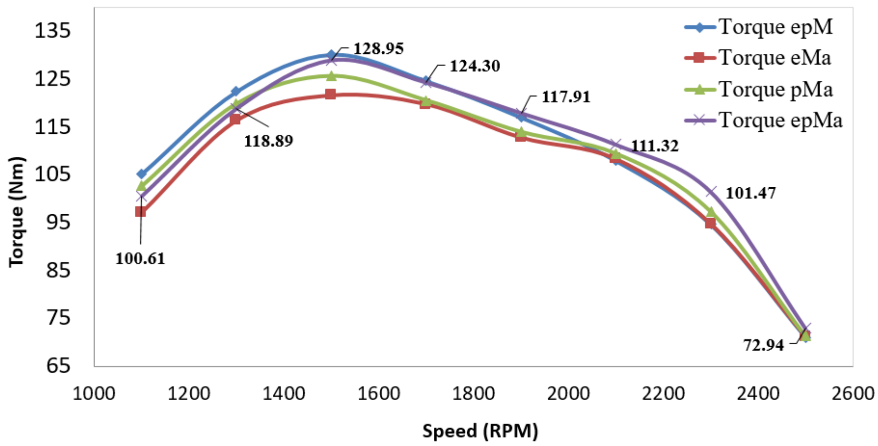

Fig. 9 Comparative torque graphs at 20% load

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 standardization report was 42.8 MJ/kg (termed LHV). The FER was fuel flow rate in kg/h. Then, brake power (BP) was calculated using the torque and speed data.

$$BTE = \frac{BP \times 3600}{FER \times CV} \tag{2}$$

where:

$$BP = \frac{T_r \times N}{9549.35} \tag{3}$$

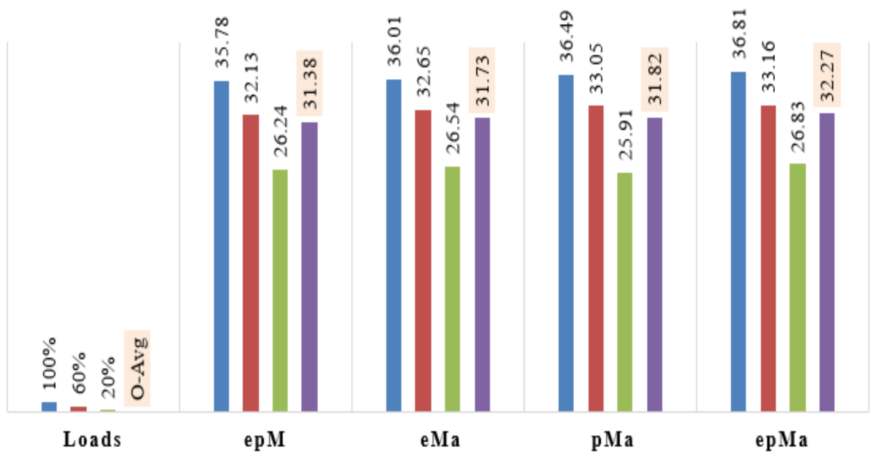

Fig. 10 Average BTE at different loads and overall average BTE of injection strategies

Fig. 10 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%.

3.1.2. Emission Tests

NOx, THC and CO emissions data have been captured following the sampling method of exhaust gases and analyzing 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. 2). In addition, regulatory emission tests were carried out following the ESC with ELR and ETC standards. 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. 11, 12 and 13). The soot concentration (St in mg/m^3) could be calculated further using the below imperial equation 4. Similarly, several correlations were available to predict the particulate matter (PM) as the summation of soot and hydrocarbons (HCs) with multiplication factors.

$$S_t = \frac{4.95 \times FSN \times e^{0.38 \times FSN}}{0.405} \tag{4}$$

The smoke (FSN) emission is the highest with epM among the multiple injection strategies at 100% load (Fig. 11). 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. 12). 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. 13). 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.

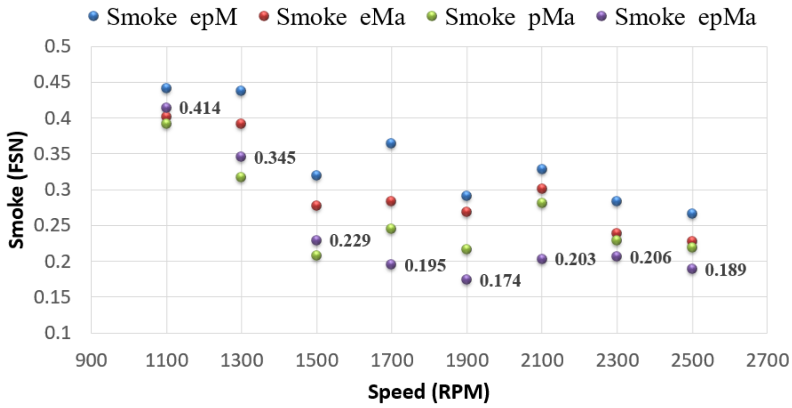

Fig. 11 Smoke test results at 100% load

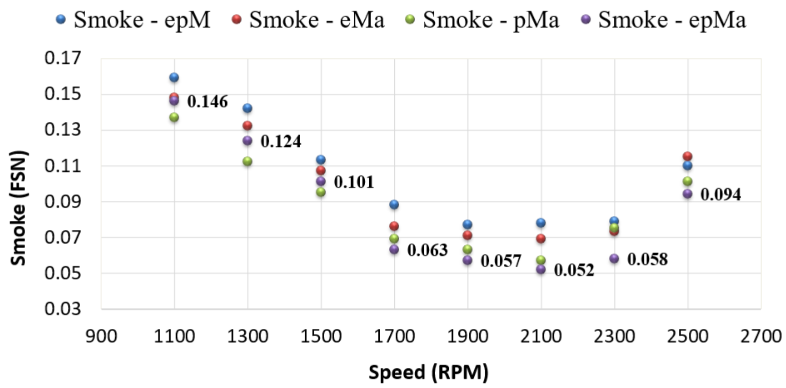

Fig. 12 Smoke test results at 60% load

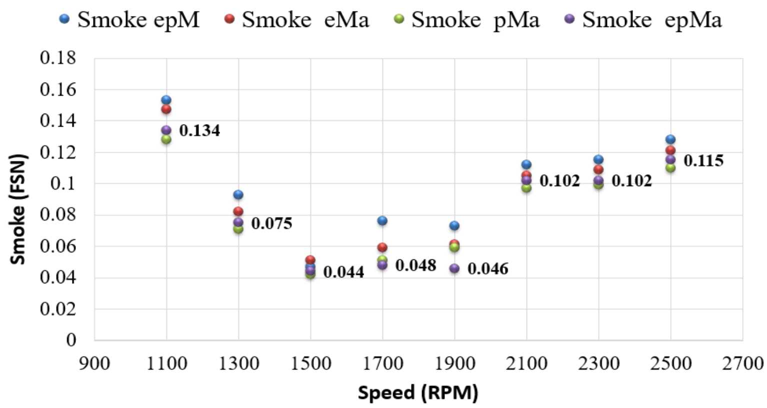

Fig. 13 Smoke test results at 20% load

The average smoke curves (Figs. 14 and 15) indicate that the epMa injection strategy is optimum and the 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.

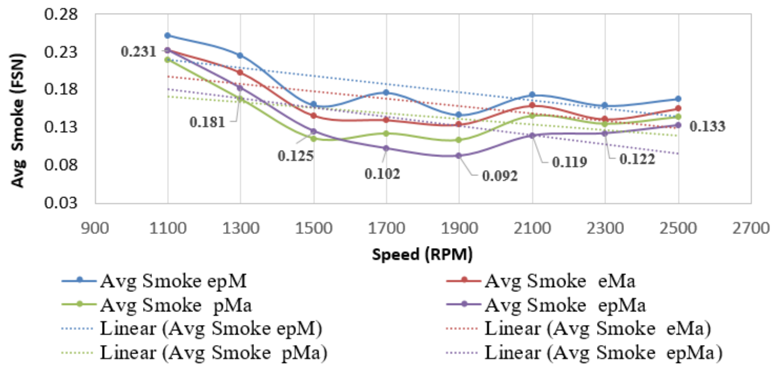

Fig. 14 Average smoke results with varying speeds

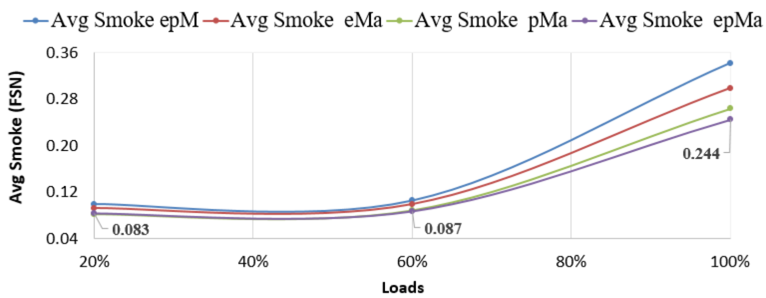

Fig. 15 Average smoke results with varying loads

Regulatory Emission Tests: 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 4 and 5, and the units are in g/kWh.

Table 4 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 5 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 4 and 5).

(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 the reduced soot content due to improved diffusion combustion duration with quadruple injection with twin pilots and a post-injection pulse.

3.1.3 Noise Tests

The CN data are captured for lower three speeds and represented in Table 6 and Fig. 16, 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 summarized in Fig. 16. 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 a rate of combustion pressure in a controlled manner owing to twin pilot injections.

Table 6 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

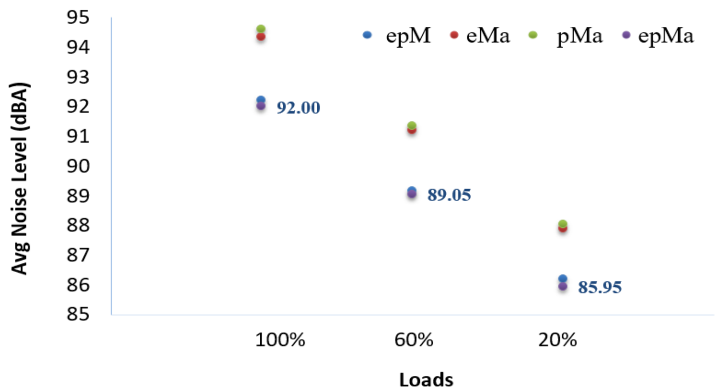

Fig. 16 Average CN reduction plot at 1100 RPM

3.2. Vehicle Level Tests

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 [20].

Test results (Table 7) 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

Table 7 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

quadruple (epMa) injection strategy delivered the best PBN results among the four injection strategies compared to the worst type (pMa as per Table 7) by 0.8 dBA (third gear) to 0.3 dBA (fifth gear).

3.2.2. Constant Speed Fuel Economy (CSFE) Testing

HDFE has been introduced to India as per the directives of the Ministry of Road Transport and Highways (MoRTH) in 2018. It provides guidelines (empirical formula) to calculate the CSFC 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 epMa displayed the best BSFC performance at medium to high speeds and load combinations (Figs. 4, 6 and 8) 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 8). The pMa injection strategy was the second best and also met the CSFE criteria (Table 8).

Table 8 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	

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 optimization was conducted at the base level calibration on the production engine to adopt all four injection strategies in order to 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 the 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 the 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 on the basis of 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 indicated mean effective pressure (IMEP) value increases and 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 the triple 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. Furthermore, only working with this epMa strategy for optimization of injection timing and injection dwell for shaping might meet further emissions with optimum performance. In addition, predictive quasi-dimensional or phenomenological combustion and emission model formulation correlated and verified the experimental data and the available scientific literature.

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