Indian Journal of Engineering & Materials Sciences
Vol. 12, June 2005, pp. 169-181

Optimizing diesel engine parameters for low emissions using Taguchi method: variation risk analysis approach—Part I

M Nataraj*, V P Arunachalam & N Dhandapani

Department of Mechanical Engineering, Government College of Technology, Coimbatore 641 013, India

Received 18 June 2004; accepted 2 March 2005

An experimental study has been carried out to simultaneously optimize several diesel engine designs and operating parameters for low exhaust emissions using Taguchi method. A single cylinder (DPF make) diesel engine equipped with a high pressure, cam driven mechanical injector has been used in this experiment. The effects of changes in engine design/operating parameters–nozzle spray holes, piston–to–head clearance, nozzle protrusion, injection control pressure, start of injection timing and swirl level on diesel engine emissions have been investigated at two engine operating conditions, i.e., 40% of maximum load and 80% of maximum load using Taguchi design of experiment methods. Emissions are quantified and optimum parameter setting has been arrived. Measurement of exhaust emissions for the optimized engine showed that CO, HC and smoke emissions are significantly lower than those obtained for the baseline engine. Taguchi method has been found to be a useful technique for the simultaneous optimization of several engine parameters and also for predicting the effect of various design parameters on diesel exhaust emissions.

IPC Code: F02B

Extensive research into the mechanisms governing diesel combustion and emissions has already been reported[1-4]. However, in spite of many studies conducted in the area of diesel combustion and emissions, these processes are still not well understood due to the complex interrelationships that exist between combustion system parameters and fuel injection system parameters.

Exhaust emissions from a diesel engine are highly dependent on the combustion process, which is influenced by the design of the combustion chamber as well as the fuel injection system. Often changes in design parameters which result in the improvement of one emission characteristic may result in the deterioration of another. For example, high injection pressures, and small spray hole diameters and high swirl will achieve good fuel atomization, but result in higher emission. To reduce exhaust emission, it is important to gain a good understanding of the relationships between the various design parameters and how they influence the combustion process and the resulting emissions. This understanding becomes extremely important, when optimizing conflicting emission requirements such as CO, HC and smoke.

In an attempt to gain a better understanding of these relationships, Taguchi's orthogonal array (OA) design of experiment (DOE) methods were used in this research work to investigate the effects of changes in several engine design parameters on diesel combustion and resulting emissions. Taguchi developed multivariate experimental techniques[5,6] using orthogonal design arrays, which allow one to isolate the effect of a single parameter on a particular response characteristic.

To evaluate the effects of all of these factors on diesel emissions using conventional "one-factor-at-a-time" methods would require a large number of experiments which would be very time consuming and costly. As an alternative, the Taguchi method combines experimentation with statistical analysis to study several factors simultaneously and requires only a few experiments to evaluate the cause and effects of those factors. Hence, the time required to run the experiments is considerably less and costs are substantially reduced. The Taguchi method can also be used to investigate the effects of interactions between the various factors, which can be easily missed when using conventional methods.

Although Taguchi methods have been most extensively used in industrial and manufacturing sectors, their application to investigate diesel combustion and emissions has been very limited[7, 8]. Therefore, the purpose of this study was to examine the effects of changes in several key combustion and fuel injection system parameters using Taguchi methods with the aim of acquiring a better

---

*For correspondence: (E-mail : m_natanuragct@yahoo.com) understanding of how these changes affect the diesel combustion and emission formation processes.

Problem Definition/Identification

Conventional design of experiments deals with averages only, while Taguchi design of experiments deals with averages and variability. Diesel engines must be designed and developed to meet emission values below the standards to allow for variability in manufacturing processes and for deterioration during useful engine life. Taguchi method can be used to identify those factors, which affect the average emission level as well as those which affect variations.

Classical methods for design of experiments, which include a full variety of statistical design techniques, have existed for some time[9]. However, engineers have generally avoided these techniques because they were too cumbersome to implement due to the high level of statistical sophistication required to use them. In this work, the desired function is to minimize exhaust emissions.

Taguchi concept for quality improvement

Taguchi simplified the statistical design efforts by using OA and statistical analyses to evaluate experimental data. OA allows the researcher to make evaluations on parameter or system design settings with respect to their optimum values. Taguchi's DOE are most extensively used to determine the parameter values or setting required to achieve the desired function. Taguchi[10] defined a "figure of merit" called the signal-to-noise (S/N) ratio which takes both the average and variation into account. The S/N ratio is an evaluation of the stability of performance of an output characteristic such as emissions or fuel economy. When the quality characteristic is classified as "smaller-the-better", the analytical expression for the S/N ratio is given by Eq. (1)

$$\text{SN Ratio (dB)} = -10\left[\log 1/n\sum_{i=1}^{i=n} Y_i^2\right] \quad \ldots(1)$$

where n is the number of responses and Y_i is the response characteristics at level i. Using the DOE based OA, the parametric levels having the highest SN ratio decides the optimum combination of settings.

Problem formulation

Figure 1 shows a flow chart of the Taguchi method implemented in this study. The method consisted of mainly eight steps: (i) defining the goal, (ii) selecting the parameters, (iii) selecting the orthogonal array, (iv) conducting the experiment, (v) statistical analysis, (vi) finding optimum settings, (vii) predicting emissions at optimum settings and (viii) running confirmation experiments.

Defining the goal

The first step in the Taguchi process was to define the goal. The goal in this experiment was to identify and to quantify those parameters, which have the greatest potential for reducing diesel exhaust emissions and to optimize selected design and operating parameters for low emissions.

Selecting the parameters

The second step was to select the design parameters, which were most likely to influence diesel exhaust emissions. A parameter design experiment typically involves two types of factors; control factors and noise factors. A control factor is one whose level can be set and maintained while a noise is a one whose level cannot be maintained, yet which could affect the performance of the response characteristic. Six key engine design and operating parameters[11] shown in Table 1 were selected. These parameters were believed to have a significant effect on diesel emissions and could be tested using the available engine hardware. Due to the non-linearity of the diesel exhaust emissions over the normal speed and load operating range of the engine, two levels for nozzle spray holes (A) and three levels for the remaining parameters were considered. The emission response variables included are CO, HC and smoke.

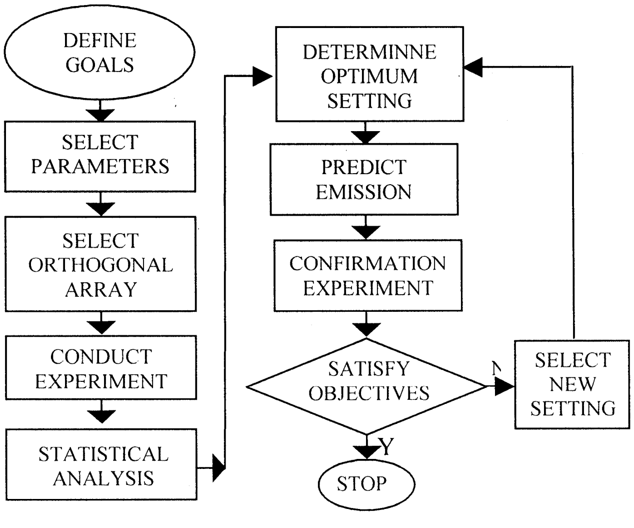


Fig 1—Flow chart of the Taguchi method

Two sets of data were taken for each test configuration to verify repeatability and to include the effect of variability in the statistical analysis.

Selection of orthogonal array

The third step in the Taguchi process was to select the appropriate OA required to investigate the one parameter at two levels and five parameters at three levels. Six factors were assigned to specific column in the OA for analyzing the main effects. Table 2 shows the mixed L_{18} ($2^1 \times 3^7$) OA for the experimental work. Table 3 provides the information regarding control factors assignments in the L_{18} orthogonal array.

Conducting the experiment

The fourth step in the Taguchi process was to conduct the experiment. Steady state tests were performed on a single cylinder engine which was built into 18 different hardware configurations during the experiment.

Table 1—Parameter with levels

	Parameters	Level 1	Level 2	Level 3	Units
A	Nozzle spray hole	One	Two	–	–
B	Piston-to-head clearance	1.25	1.35	1.5	mm
C	Nozzle protrusion	0.95	1.35	2.3	mm
D	Start of injection timing (bTDC)	Retarded (15.8)	Baseline (18.8)	Advanced (21.8)	degree
F	Injection control pressure	130	140	150	atm
G	Swirl level	¼ throttle open (Low)	½ throttle open (Medium)	Full throttle (High)	–

Table 2—Mixed orthogonal arrays [L_{18} ($2^1 \times 3^7$)]

Trail No.	Control factors assignment								SN Ratio
	A	B	C	D	F	G	e_1	e_2	
1	1	1	1	1	1	1	1	1	SN_1
2	1	1	2	2	2	2	2	2	SN_2
3	1	1	3	3	2	3	3	3	SN_3
4	1	2	1	1	2	2	3	3	SN_4
5	1	2	2	2	3	3	1	1	SN_5
6	1	2	3	3	1	1	2	2	SN_6
7	1	3	1	2	1	3	2	3	SN_7
8	1	3	2	3	2	1	3	1	SN_8
9	1	3	3	1	3	2	1	2	SN_9
10	2	1	1	3	3	2	2	1	SN_{10}
11	2	1	2	1	1	3	3	2	SN_{11}
12	2	1	3	2	2	1	1	3	SN_{12}
13	2	2	1	2	3	1	3	2	SN_{13}
14	2	2	2	3	1	2	1	3	SN_{14}
15	2	2	3	1	2	3	2	1	SN_{15}
16	2	3	1	3	2	3	1	2	SN_{16}
17	2	3	2	1	3	1	2	3	SN_{17}
18	2	3	3	2	1	2	2	1	SN_{18}

To perform a comprehensive analysis of the involved phenomena, a test rig has been set up for conducting the study with the aim of measuring the CO, HC and smoke levels from the engine emissions. The test rig has been installed in Thermal Engineering Laboratory at Government College of Technology, Coimbatore, comprising of fuel tank, manometer, air tank, electronic temperature measuring unit, fuel injection system and exhaust gas analyzer. The engine used to conduct the experiment was a single cylinder, direct injection diesel engine (DPF make). The bore and stroke were 114 mm × 140 mm respectively. The fuel injection system consists of a cam driven mechanical unit injector with an 8.5 mm plunger diameter. A schematic of the test rig with hardware is shown in Fig. 2.

One of the major concerns associated with this experiment was the possibility of introducing engine variability when changing hardware configurations. Each time the injector unit was removed to change the nozzle/nozzle protrusion. Extra precautions were taken to ensure that each part was re–installed according to specifications.

Engine operating parameters such as nozzle spray holes, piston to head clearance, nozzle protrusion,

Table 3— Mixed orthogonal arrays [L_{18} ($2^1 \times 3^7$)]

Column No.	1 No. of holes	2 Piston to head clearance (mm^2)	3 Nozzle protrusion (mm)	4 Injection control pr. (atm)	5 Start of inj. timing (degree)	6 Swirl level
1	One	1.25	0.95	130	15.8bTDC	Low
2	One	1.25	1.35	140	18.8bTDC	Medium
3	One	1.25	2.30	150	21.8bTDC	High
4	One	1.35	0.95	130	18.8bTDC	Medium
5	One	1.35	1.35	140	21.8bTDC	High
6	One	1.35	2.30	150	15.8bTDC	Low
7	One	1.50	0.95	140	15.8bTDC	High
8	One	1.50	1.35	150	18.8bTDC	Low
9	One	1.50	2.303	130	21.8bTDC	Medium
10	Two	1.25	0.95	150	21.8bTDC	Medium
11	Two	1.25	1.35	130	15.8bTDC	High
12	Two	1.25	2.30	140	18.8bTDC	Low
13	Two	1.35	0.95	140	21.8bTDC	Low
14	Two	1.35	1.35	150	15.8bTDC	Medium
15	Two	1.35	2.30	130	18.8bTDC	High
16	Two	1.50	0.95	150	18.8bTDC	High
17	Two	1.50	1.35	130	21.8bTDC	Low
18	Two	1.50	2.303	140	15.8bTDC	Medium

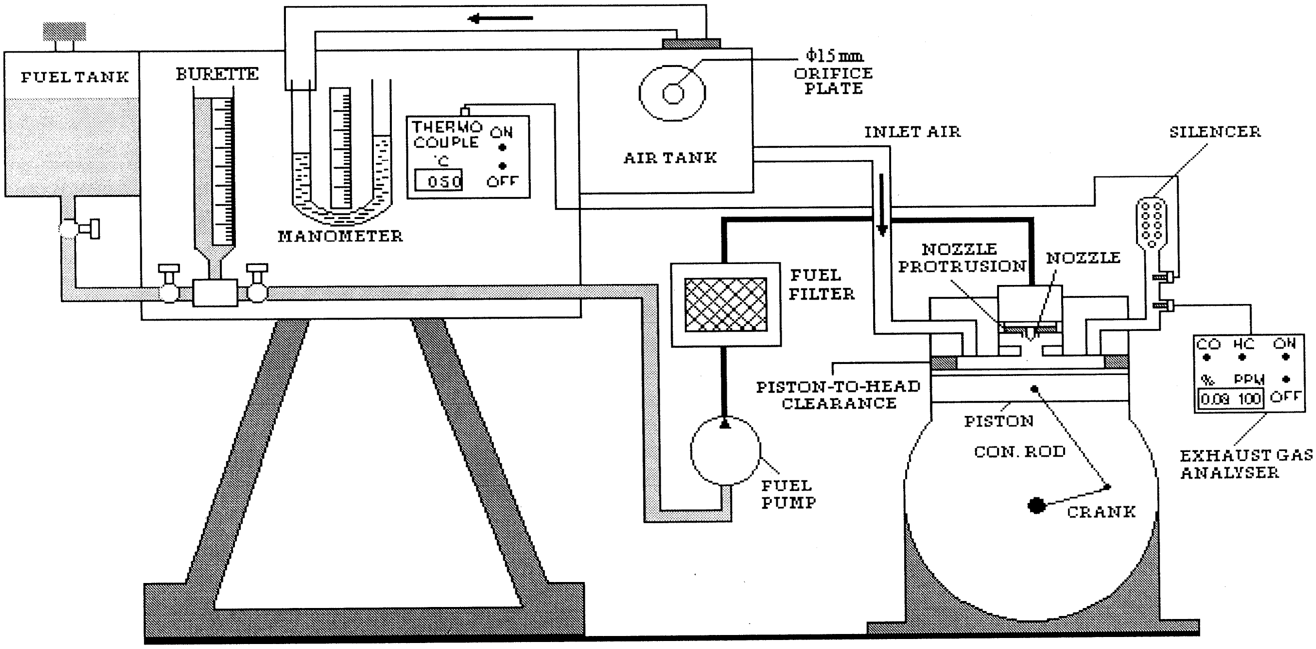


Fig 2— Diesel engine test rig

Table 4 —F_0 and % of contribution for CO, HC, smoke at 40% W_{max}

Parameters	CO (%)		HC (PPM)		SMOKE (HSU)	
	‘F_0’ Test value	ρ (%)	‘F_0’ Test value	ρ (%)	‘F_0’ Test value	ρ (%)
A	4.564***	14.94	0.197	1.11	4.844***	15.23
B	0.071	0.46	0.686	7.71	3.739*	23.51
C	0.085	0.55	0.376	4.22	4.107**	25.82
D	3.539*	23.17	2.199†	24.72	0.535	3.36
F	3.601**	23.57	2.228†	25.06	0.522	3.28
G	2.700†	17.67	0.307	3.45	1.581	9.94
(e)	–	19.63	–	33.73	–	18.86
Total	–	100.00	–	100.00	–	100.00

injection control pressure, start of injection timing and swirl level were set consistently to the specified conditions and carefully monitored throughout the tests. Nozzle spray holes were varied by changing the nozzle. Nozzle protrusion was varied by changing the thickness of washer used for seating the injector unit. Piston to head clearance was varied by changing the various thicknesses of gaskets. Injection control pressure was varied by using the nozzle tester. Start of injection timing was varied by using tapered nut located under the fuel injection pump. Swirl level was varied by adjusting the butterfly valve plate angle located in the air intake port. A total of 216 data points were recorded for this experiment. CO, HC and smoke emission responses were obtained for the 18 engine configurations at 40% W_{max} and 80% W_{max} load from the exhaust gas analyzer. The emissions responses are summarized in Table A1 (see Appendix).

Statistical analysis

The fifth step in the Taguchi process was to perform a statistical analysis using the data obtained from the L_{18} Experiment. The average emission responses and the S/N ratios for each control factor computed and are listed in Tables A2, A3 and A4 (see Appendix). Using the data from these tables, an analysis of variance (ANOVA) was performed to identify the most significant control parameters and to quantify their effects on CO, HC and smoke. Tables 4 and 5 summarize the ANOVA results for each emission response; at 40% W_{max} and 80% W_{max} respectively.

Tables 4 and 5 give the relative percent contribution (ρ) attributable and source of variance

Table 5 —F_0 and % of contribution for CO, HC, smoke at 80% W_{max}

Parameters	CO (%)		HC (PPM)		SMOKE (HSU)	
	F_0 value	ρ (%)	F_0value	ρ (%)	F_0 value	ρ (%)
A	0.648	2.40	2.025†	2.76	1.778	4.60
B	0.252	1.87	17.57***	47.89	3.880*	20.06
C	0.367	2.72	0.841	2.29	4.776*	24.70
D	1.610	11.95	2.343*	6.39	1.060	5.48
F	0.595	4.42	7.447**	20.30	0.618	3.20
G	7.322***	54.36	4.477**	12.20	5.116**	26.45
(e)	–	22.28	–	8.17	–	15.51
TOTAL	–	100.00	–	100.00	–	100.00

(e)–pooled error [e_1+e_2] ***most significant **more significant *significant † less significant

(F_o) of the each control parameters to the total variation observed in the emission results.

At 40% of W_{max}

In CO emissions the most significant influential control parameters are injection control pressure accounted for 23.57% followed by start of injection timing for 23.17%; swirl level for 17.67% and nozzle spray holes for 14.94% of the observed variation.

For HC emissions, injection control pressure was the most significant parameter with 25.06% of variation followed by start of injection timing producing 24.72% of the observed variation followed by piston to head clearance at 7.71%; nozzle protrusion at 4.22%; swirl level at 3.45% and nozzle spray holes with 1.11% respectively. It is interesting to note that the injection control pressure and start of injection timing were more significant effect on CO and HC emissions. Swirl level and nozzle spray holes are influential parameters in CO emission but not so in HC emission.

Smoke emission was mainly dependent on nozzle protrusion accounted for 25.82% followed by piston to head clearance at 23.51%; nozzle spray holes at 15.23% and swirl level with 9.94%. It seems that start of injection timing and injection control pressure which are dominant in HC and CO emissions, is not having significant influence in smoke emission.

At 80% W_{max}

In CO emissions, the most significant influential parameters are swirl level accounted for 54.36%, start of injection timing for 11.95% and injection control pressure with 4.42%.

For HC emission, piston-to-head clearance was the most significant parameter with 47.89% of the variation followed by injection control pressure producing 20.3% of the observed variation; swirl level at 12.2%; start of injection timing at 6.39%. Nozzle spray holes (2.76%) and nozzle protrusion (2.29%) are less significant parameters for the HC emissions. It is interesting to note that the start of injection timing; injection control pressure and swirl level were more significant effect on CO and HC emission. Piston-to-head clearance has more significant effect on HC emission but not so in CO emission.

Smoke emissions were mainly dependent on swirl level accounted for 26.45% of observed variation and followed by nozzle protrusion at 24.7%, piston-to-head clearance with 20.06%. It seems that start of injection timing, injection control pressure having considerable influence in CO and HC emissions, isolatable influence in smoke emission.

Finding parametric combination for optimal emission level

Step six in the Taguchi process was to find the optimum parameter settings. Using the results from the ANOVA, S/N ratio and response curve analysis the optimum combination of control factor levels were arrived.

Response curve analysis

Response curves are graphical representations of change in performance characteristics with the variation in process parameter level. The curves give a pictorial view of variation of each factor and describe what the effect on the system performance would be when a parameter shifts from one level to another. This analysis is aimed at determining influential parameters and their optimum levels. Figs 3 and 4 show significant effects for each emission response at each factor level for 40% W_{max} and 80%W_{max} respectively. The S/N ratios for the different emission responses were calculated at each factor level and the average effects were determined by taking the total of each factor level and dividing by the number of data points in that total. The greater

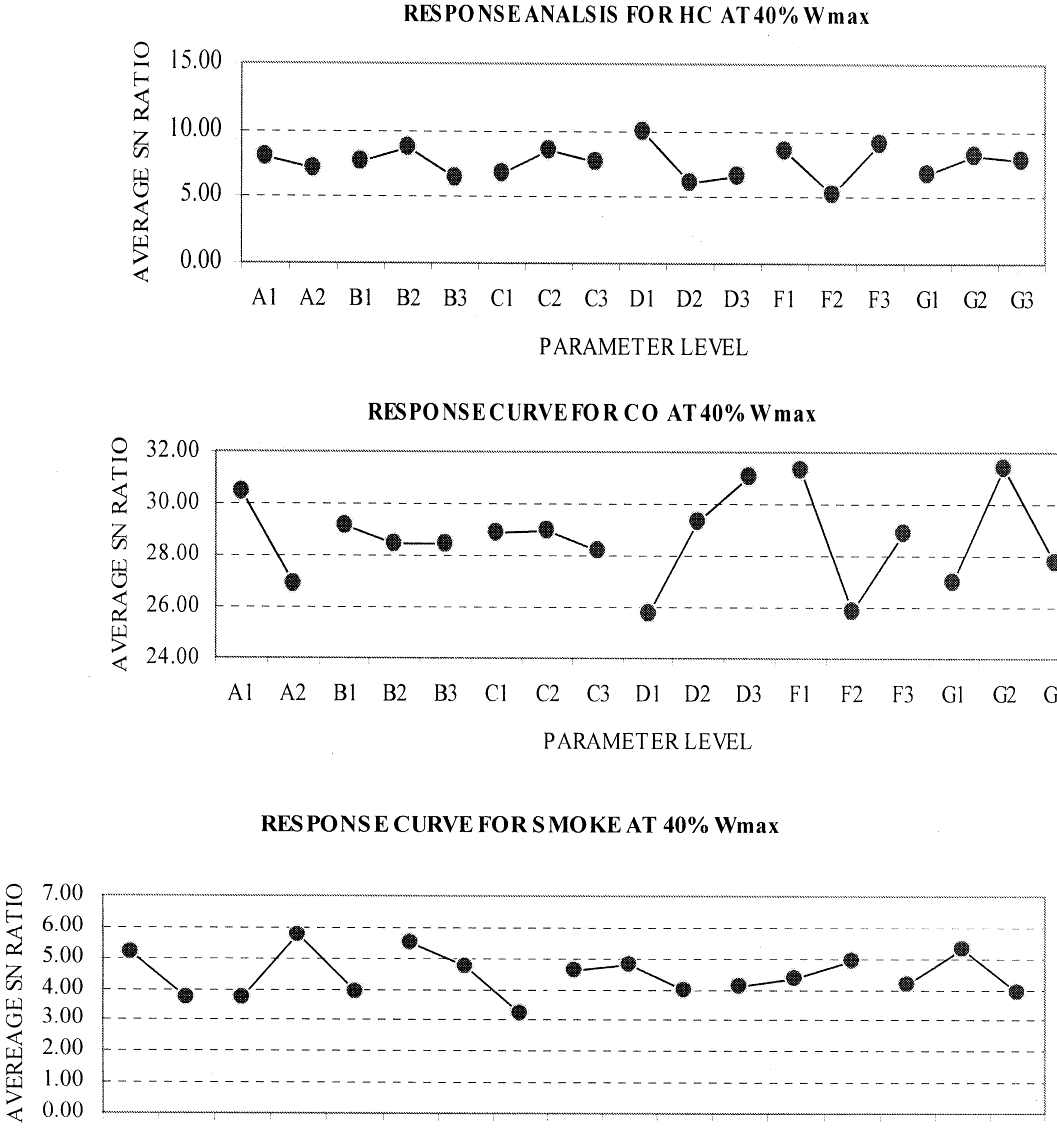


Fig 3— Response curve for 40% W_{max}

difference between the levels, the parametric influence will be more. Recall that, the parameter level having the highest S/N ratio corresponds to the parameters setting for lowest emission.

In the response curve (Fig. 3) at 40% W_{max} for the CO emissions, the highest S/N ratio was observed at nozzle spray holes (one), piston-to-head clearance (1.25 mm), nozzle protrusion (1.35 mm), start of injection timing (21.8 before TDC), injection control pressure (130 atm) and swirl level (medium). Similarly the optimum parameter setting for lowest HC emissions were found to be a nozzle spray hole (one), piston-to-head clearance (1.35mm), nozzle protrusion (1.35 mm), start of injection timing (15.8 before TDC), injection control pressure (150 atm) swirl level (medium). Smoke emissions were lowest at nozzle spray holes (one), piston-to-head clearance (1.35 mm), nozzle protrusion (0.95 mm), start of injection timing (18.8 before TDC), injection control pressure (150 atm) and swirl level (medium).

In the response curve (Fig. 4), looking 80% W_{max} for the CO emissions, the highest S/N ratio was observed at nozzle spray holes (one), piston-to-head clearance (1.5 mm), nozzle protrusion (1.35 mm), start of injection timing (18.8 beforeTDC), injection control pressure (130 atm) and swirl level (medium).

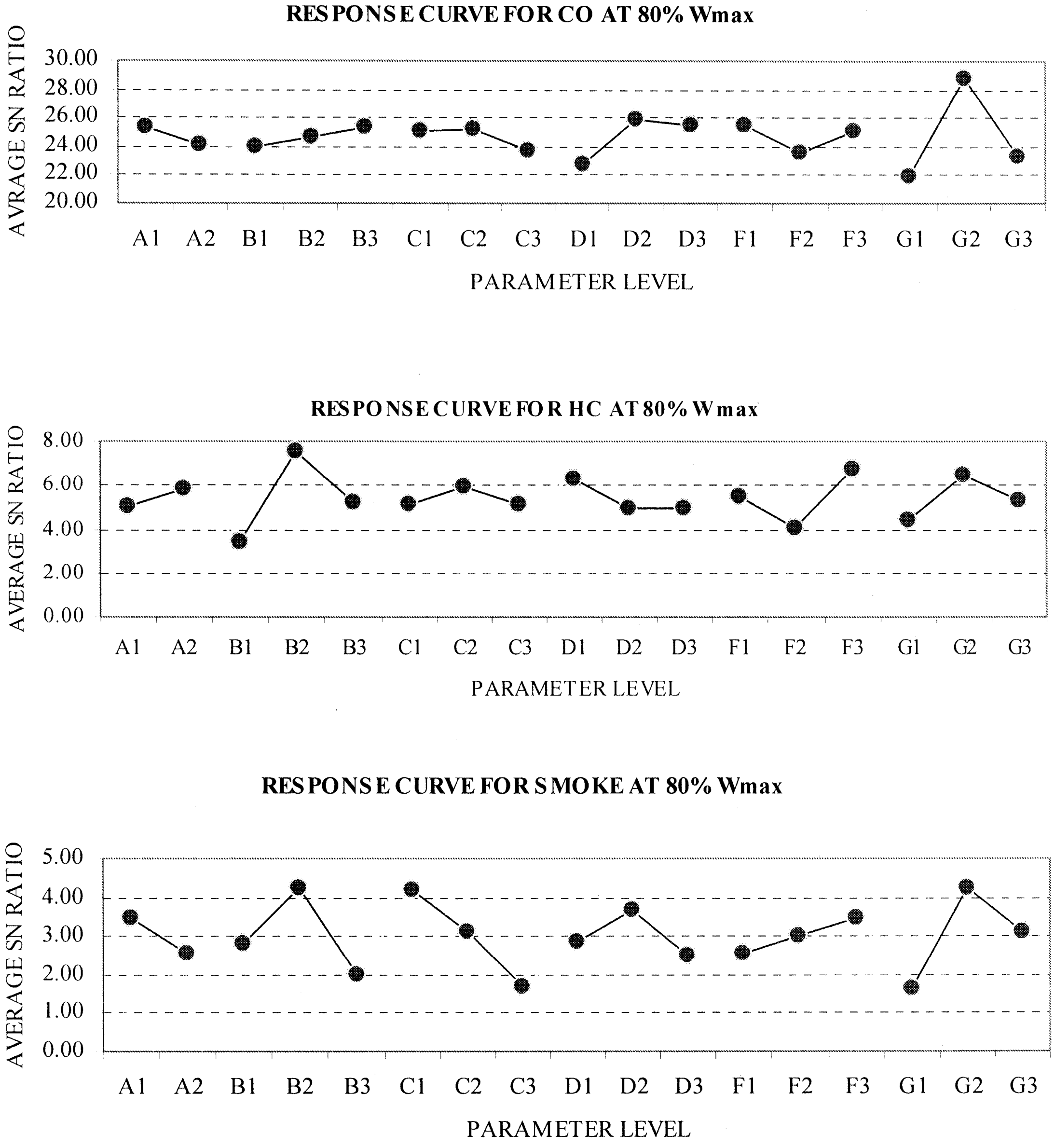


Fig 4— Response curve for 80% W_{max}

Average HC emission was lowest for nozzle spray holes (two), piston-to-head clearance (1.35 mm), nozzle protrusion (1.35 mm), start of injection timing (15.8 before TDC), injection control pressure (150 atm) and swirl level (medium). Smoke emission was lowest at nozzle spray holes (one), piston-to-head clearance (1.35 mm), nozzle protrusion (0.95 mm), start of injection timing (18.8 before TDC), injection control pressure (150 atm) and swirl level (medium).

Choosing optimum combination of parameter levels

Tables 6 and 7 summarize the optimum parameter setting determined for each response at 40% W_{max} and 80% W_{max} respectively. Note that the term optimum reflects only the optimal combination of the parameters defined by this experiment.

Table 6 needs to be constructed, in which only the level sums of SN ratio of significant factors appear. The optimum setting is determined by choosing the level with the highest SN ratio. Control factor A is more significant in CO than in smoke. So the optimum condition is A1. For factors D and F, more than one response is significant. However, since factors D and F are less meaningful in HC emission than CO emission. So it is confirmed that D3 and F1 are the optimal conditions. In respect of control factor

Table 6—Overall summary table for optimal conditions at 40%W_{max}

Parameters	Levels	Sum of S/N ratio for CO A***F**D*G†	Sum of S/N ratio for HC D†F†	Sum of S/N ratio for smoke A***C**B*	Overall optimum
	1	274.164		46.656	
A	2	242.083		33.632	A1
	–				
	1			22.383	
B	2			34.362	B2
	3			23.544	
	1			32.734	
C	2			28.381	C1
	3			19.173	
	1	154.31	6.065		
D	2	175.810	36.742		D3
	3	186.205	39.968		
	1	187.856	50.917		
F	2	155.026	31.071		F1
	3	173.365	54.787		
	1	161.661			
G	2	188.313			G2
	3	166.272			

Table 7 —Overall summary table for optimal conditions AT 80% W_{max}

Parameters	Levels	Sum of S/N ratio for CO G***	Sum of S/N ratio for HC B***F**G**D*A†	Sum of S/N ratio for smoke G**C*B*	Overall optimum
A	1		44.923		A2
	2		52.296		
	–		–		
B	1		20.493	16.707	B2
	2		45.489	25.403	
	3		31.237	12.058	
C	1			25.220	C1
	2			18.717	
	3			10.231	
D	1		37.691		D1
	2		29.629		
	3		29.899		
F	1		32.693		F3
	2		24.103		
	3		40.422		
G	1	131.555	26.381	9.924	G2
	2	172.907	39.001	25.425	
	3	140.014	31.837	18.818	

***most significant **more significant *significant † less significant

B, C and G; factors B, C and G are significant only in smoke emission and CO emission respectively. Hence, B2, C1 and G2 being predicted as the optimal parameters. Therefore, the optimal combination of control factors at 40% W_{max} is A1 B2 C1 D3 F1 G2 for minimum level of CO, HC and smoke in the emission for the engine under investigation. Table 7 is constructed for 80% W_{max} in a similar way as in 40% W_{max}. The optimal combination of control factor at 80% W_{max} is A2 B2 C1 D1 F3 G2.

Predict emission at optimum settings

The seventh step in the process was to predict the emission responses at the optimum parameter settings to check the reproducibility of the results obtained from this experiment. An estimate of the emission response at the optimum conditions was made using the following expressions. Effective number of replications (n_{eff})

$$n_{\text{eff}} = N/[1+(\text{Total d.o.f. associated with items used in } \hat{\mu} \text{ estimate})] \qquad \ldots(2)$$

Estimate of error variance (V_e)

$$V_e = \frac{\text{Pooled variation of non} - \text{significant sources}}{\text{Pooled degrees of freedom of non} - \text{significant sources}}$$

To allow for the possibility of an over estimate due to error of variances, only parameters which have a strong effect on the emission response were used in calculating the estimate. Sample calculations of the predicted emissions using this formula are presented in the appendix.

Confirmation experiments

The final step in the process was to run confirmation experiments to verify the engine parameter settings really produce optimum emissions and to evaluate the predictive capability of the Taguchi method for diesel emission. The optimum parameters were set at nozzle spray holes (one), piston-to-head clearance (1.35 mm), nozzle protrusion (0.95 mm), start of injection timing (21.8 bTDC), injection control pressure (130 atm), and swirl level (medium) for 40% W_{max}.

Similarly, the optimum parameters were set at nozzle spray holes (two), piston-to-head clearance (1.35 mm), nozzle protrusion (0.95 mm), start of injection timing (15.8 bTDC), injection control pressure (150 atm) and swirl level (medium) for 80% W_{max}.

Emission responses for CO, HC and smoke were recorded at 40% W_{max} and 80% W_{max}. S/N ratios were calculated and presented in Tables 8 and 9.

Tables 10 and 11 show the comparison of the actual S/N ratios, computed from the measured emission responses and the predicted S/N ratios computed using Eqs (2) and (3). The ranges shown for the predicted S/N values were computed using a 99.995% confidence interval about the mean. In general, all three emission responses fell within their predicted ranges which indicated good reproducibility and confirmed that the experiment results were valid.

Results and Discussion

The baseline engine comprises of a pump-line-nozzle injection system with a nozzle spray holes (one) and a nozzle protrusion (1.35 mm), piston-to-head clearance (1.25 mm), start of injection timing (18.8 deg before TDC), injecton control pressure (140 atm), swirl level (high).

For the optimized engine, these above control parameters were adjusted 18 combinations limit the emission levels in the engine exhaust.

Figure 5 shows visually the composition of CO, HC and smoke in emissions for the baseline and optimized engine at 40% W_{max} and 80% W_{max}. CO level in the emission varies proportionally with the load for the baseline engine. But it remains at same level whatever be the load for the optimized engine. Looking for HC level, it proportionally varies with the load in the baseline. But there is appreciable reduction with increasing load in optimized engine.

Smoke level slightly increases with rise in load for the baseline and optimized engine. However comparing baseline engine with optimized engine variation in smoke level is higher for the increasing load (4 HSU at 40% W_{max}, 6 HSU at 80%W_{max}). The results indicate that for the optimized engine there was a remarkable and significant reduction in both HC and CO but not that much in smoke emission.

Table 8— Results from confirmation experiment at optimum parameter setting for 40% W_{max}

Emissions	Run # 1	Run # 2	Run # 3	S/N ratio (dB)
CO (%)	0.02	0.02	0.02	33.98
HC (ppm)	20	20	40	–29.03
Smoke (HSU)	63	59	61	–35.71

Table 9— Results from confirmation Experiment at optimum parameter setting for 80% W_{max}

Emissions	Run # 1	Run # 2	Run # 3	S/N ratio (dB)
CO (%)	0.02	0.02	0.02	33.98
HC (ppm)	40	30	10	–29.38
Smoke (HSU)	56	60	58	–35.27

Table 10 —Comparison of predicted and actual S/N ratios using optimum setting for 40% W_{max}

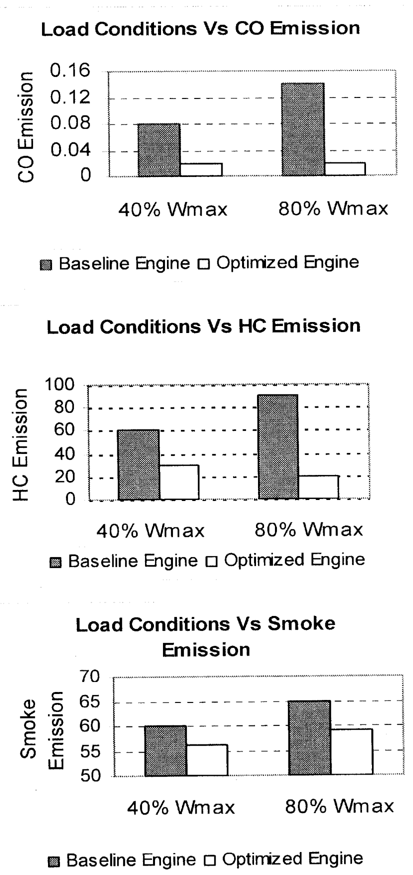
Emissions	Predicted range of S/N ratio(99.995% confidence)	Actual S/N ratio
CO (%)	29.55 to 46.75	33.98
HC (ppm)	–26.31 to – 42.31	–29.38
Smoke (HSU)	–27.90 to – 35.58	–35.27

Table 11— Comparison of predicted and actual S/N ratios using optimum setting for 80% $_{max}$

Emissions	Predicted range of S/N ratio(99.995% confidence)	Actual S/N ratio
CO (%)	19.55 to 35.02	33.98
HC (ppm)	–28.81 to – 37.39	–29.03
Smoke(HSU)	–28.76 to – 38.26	–35.71

Table 12— Control factors significance with load variation

Dependent on load variation		Independent on load variation	
Control factors influencing emission with 40 % W_{max}	Control factors influencing emission with 80 % W_{max}	For 40 % W_{max}	For 80 % W_{max}
1. Nozzle protrusion	1. Nozzle spray hole	1. Nozzle spray hole	1.Piston–to–head clearance
2. Start of inj. timing	2. Nozzle protrusion	2. Piston–to–head clearance	
3. Inj. control pressure	3. Start of inj. timing		
4. Swirl level	4. Inj. control pressure		
	5. Swirl level		



Emissions	Baseline	40% W_{max}	Baseline	80% W_{max}
CO (%)	0.08	0.02	0.14	0.02
HC (PPM)	60	30	90	20
Smoke HSU)	60	56	65	59

Fig 5— Emission levels

Conclusions

The feasibility of using the Taguchi method to optimize selected diesel engine design parameters for low emissions was investigated using a single cylinder, research diesel engine. The conclusions from this work are summarized as follows: (i) The Taguchi method was found to be an efficient technique for quantifying the effects of six engine design and operating parameters on exhaust emissions. (ii) Engine constitutions were mostly depending on engine load. The control factors significance with load variation are presented in Table 12. (iii) At 40% W_{max}, CO emission was mostly affected by changes in nozzle protrusion, injection control pressure, start of injection timing and swirl level. HC emission was mostly affected by injection control pressure and start of injection timing. Smoke emission was mostly affected nozzle spray holes followed by nozzle protrusion and piston-to-head clearance. (iv) At 80%W_{max}, CO emission was mostly affected by only injection control pressure. HC emission was mostly affected by piston-to-head clearance followed by injection control pressure and swirl level. Smoke emission was affected by changes in swirl level, nozzle protrusion and piston-to-head clearance. (v) CO, HC and smoke emission results obtained from the confirmation experiments using the optimum parameter combination showed excellent agreement with the predicted results.

References

1 Zelenka P, Kriegler W, Herzop P L & Cartellieri W P, *SAE Paper No.900602*, (1990) 722-731.
2 Gill A P, *SAE Paper No. 880350* (1988) 461-473.
3 Cartellieri W P & Herzop P L, *SAE Paper No. 880342* (1988) 379-390.
4 Hunter C E, Cikanek H A & Gardner T P, *J Eng Gas Turbines Power,* 111 (1989) 916-929.
5 Antony J, *Int J Adv Manufact Technol*, 17 (2001) 134-138.
6 Sung H Park, *Robust design and analysis for quality engineering,* (Chapman and Hall India, London), 1996.
7 Hames R J, Merrion D F & Borman G L, *SAE Paper No. 710671*, (1971) 738-751.
8 Williams T J & Tindal M J, *SAE Paper No. 800027*, (1980) 113-126.
9 Davies O L, *Design and analysis of industrial experiments*, 2nd Ed, (Hafner Publishing Co., New York), 1956.
10 Taguchi Genichi, *Introduction to quality engineering* (Kraus International Publications, Whiter Plains, New York), 1986.
11 Ganesan V, *Internal combustion engines* (Tata McGraw–Hill Publising Company, New Delhi), 2002.

Appendix

Predicting emissions at optimum conditions for 40% W_{max}

The parameter setting for the optimum conditions (Table 6) are

Parameters	Levels
A. No. of holes (one hole)	A1
B. Piston-to-head clearance (1.35 mm)	B2
C. Nozzle Protrusion (0.95 mm)	C1
D. Start of Injection Timing (21.8 deg bTDC)	D3
F. Injection Control Pressure (130 atm)	F1
G. Swirl Level (medium)	G2

For CO emission

To estimate the emission responses at the optimum conditions, Eq. (2) can be used;
Effective number of replications (n_{eff})

n_{eff} = N/[1+(Total d.o.f. associated with items used in $\hat{\mu}$ estimate)]

Estimate of error variance (V_e)

$$V_e = \frac{\text{Pooled variation of non – significant sources}}{\text{Pooled degrees of freedom of non – significant sources}}$$

In calculating the emission response, only the parameters with a strong effect on the emission response are used to allow for experimental error (variance). The S/N ratios for each emission response level are listed in Table A3.

For CO emission, the parameters with the strongest effects were: $A_1\, D_3\, F_1\, G_2$

The average S/N ratio for CO ($\bar{T}$) was determined using the values shown in Table A3 for nozzle spray holes as:

$$\bar{T} = (274.164 + 242.083) / 2 = 516.246$$

$$\hat{\mu} = \hat{\mu}\,(A_1D_3F_1G_2) = A_1 + D_3 + F_1 + G_2 - 3\,\bar{T}$$

$$= \frac{274.164}{9} + \frac{186.205}{6} + \frac{187.856}{6} + \frac{188.313}{6} - \frac{3(516.246)}{18}$$

$$= 38.15$$

$$n_{eff} = \frac{18}{1+(1+2+2+2)} = 2.25$$

$$V_e = \left[\frac{S_B}{18} + \frac{S_C}{18} + \frac{S_{e1}}{18} + \frac{S_{e2}}{18}\right] \Big/ 10$$

$$= \left[\frac{31.82}{18} + \frac{38.202}{18} + \frac{862.182}{18} + \frac{490.738}{18}\right] \Big/ 10 = 7.91$$

A 99.995% confidence interval for CO was determined by;

t (Φ, α) = t (10, 0.0005) = 4.587 (from t – Distribution Table)

$\hat{\mu}$ ±t(Φ, α) = 38.15±t(10,0.0005)

$$= 38.15 \pm 4.587 \left[\sqrt{\frac{V_e}{n_{\text{eff}}}}\right] = 38.15 \pm 4.587 \left[\sqrt{\frac{7.91}{2.25}}\right]$$

$$= 29.55 \text{ to } 46.75$$

The confirmation test is conducted to check that the obtained optimal condition ($A_1\, B_2\, C_1\, D_3\, F_1\, G_2$). The CO emission data are 0.02, 0.02, and 0.02.
SN Ratio for these observations (CO emission) is

Table A1— Experimental data

Trial run No.	AT 40% W_{max}						AT 80% W_{max}					
	CO data (%)		HC data (ppm)		Smoke data (HSU)		CO data at 80% W_{max} (%)		HC data at 80% W_{max} (ppm)		Smoke data at 80%W_{max} (HSU)	
	Trial 1 (X1)	Trial 2 (X2)	Trial 1 (X1)	Trial 2 (X2)	Trial 1 (X1)	Trial 2 (X2)	Trial 1 (X1)	Trial 2 (X2)	Trial 1 (X1)	Trial 2 (X2)	Trial 1 (X1)	Trial 2 (X2)
1	0.04	0.02	60	60	63	63	0.08	0.08	110	110	77	77
2	0.02	0.02	50	60	62	62	0.04	0.04	100	100	68	68
3	0.02	0.02	50	40	69	70	0.04	0.04	100	90	76	74
4	0.04	0.04	50	50	29	29	0.04	0.02	70	80	35	36
5	0.04	0.02	70	50	40	40	0.04	0.06	70	70	42	43
6	0.02	0.02	40	50	60	60	0.10	0.08	100	80	92	90
7	0.02	0.02	90	80	65	64	0.04	0.06	100	100	75	73
8	0.04	0.06	110	100	63	62	0.06	0.06	130	130	92	89
9	0.06	0.06	20	40	60	62	0.08	0.06	50	60	79	76
10	0.02	0.02	90	70	61	62	0.04	0.04	110	100	62	62
11	0.08	0.08	20	30	63	60	0.10	0.10	100	80	72	70
12	0.10	0.08	140	120	74	74	0.14	0.10	160	140	85	84
13	0.08	0.06	50	30	49	49	0.06	0.08	50	60	62	62
14	0.02	0.02	40	60	61	61	0.02	0.04	40	50	65	65
15	0.08	0.08	60	70	92	92	0.12	0.12	60	80	98	96
16	0.06	0.06	90	90	65	65	0.08	0.08	100	90	71	70
17	0.04	0.04	50	50	66	65	0.08	0.06	80	60	97	95
18	0.02	0.02	80	70	63	64	0.02	0.02	90	90	71	71

Table A2— Average emission responses from L 18 experiment

Parameters	40% W_{max}			80% W_{max}		
	CO (%)	HC(PPM)	Smoke (HSU)	CO (%)	HC(PPM)	Smoke (HSU)
A. No. of holes						
1. One	30.46	7.86	5.18	23.32	4.99	3.45
2. Two	26.89	7.23	3.74	24.07	5.81	2.57
B. Piston-to-head clearance (mm)						
1. 1.25	29.12	7.65	3.73	24.02	3.42	2.78
2. 1.35	28.48	8.75	5.73	24.69	7.58	4.23
3. 1.50	28.44	6.40	3.92	25.37	5.21	2.01
C. Nozzle protrusion (mm)						
1. 0.95	28.89	6.72	5.46	25.12	5.13	4.20
2. 1.35	28.95	8.46	4.73	25.21	5.93	3.12
3. 2.30	28.19	7.61	3.2	23.75	5.14	1.71
D. Start of injection timing (Deg)						
1. 15.8 before TDC	25.71	10.01	4.61	22.73	6.28	2.84
2. 18.8 before TDC	29.30	6.12	4.78	25.82	4.94	3.66
3. 21.8 before TDC	31.03	6.66	3.98	25.53	4.98	2.52
E. Inj. control pressure (atm)						
1. 130	31.31	8.49	4.12	25.44	5.45	2.57
2. 140	25.84	5.18	4.34	23.51	4.02	3.00
3. 150	28.89	9.13	4.92	25.13	6.74	3.47
F. Swirl Level						
1. Low	26.94	6.72	4.17	21.93	4.40	1.65
2. Medium	31.39	5.18	5.28	28.82	6.50	4.24
3. High	27.71	9.13	3.94	23.34	5.31	3.14

Table A3— SN ratios for CO, HC, smoke data at 40% W_{max}

Run No.	CO (%)	HC(ppm)		SMOKE (HSU)	
	SN ratio (dB)	SN ratio (dB)	SN ratio+43 (dB)	SN ratio (dB)	SN ratio+40 (dB)
1	30.0	–35.563	7.437	–35.987	4.013
2	33.979	–34.843	8.157	–35.848	4.152
3	33.979	–33.118	9.882	–36.839	3.160
4	27.959	–33.979	9.021	–29.248	10.752
5	30.0	–35.682	7.318	–32.041	7.959
6	33.979	–33.118	9.882	–35.563	4.437
7	33.979	–38.603	4.397	–36.192	3.808
8	25.850	–40.437	2.566	–35.918	4.082
9	24.437	–30.0	13.0	–35.708	4.292
10	33.979	–38.129	4.871	–35.778	4.222
11	21.938	–28.129	14.871	–35.780	4.219
12	20.862	–42.305	0.696	–37.385	2.615
13	23.010	–32.305	10.696	–33.804	6.196
14	33.979	–34.149	8.850	–35.707	4.293
15	21.938	–36.284	6.716	–39.276	0.724
16	24.437	–39.085	3.915	–36.258	3.741
17	27.959	–33.979	9.021	–36.325	3.675
18	33.979	–37.521	5.479	–36.056	3.944

Table A4—SN ratios for CO, HC, smoke data at 80% W_{max}

Run No	CO (%)	HC (ppm)		SMOKE (HSU)	
	SN ratio (dB)	SN ratio (dB)	SN ratio+44 (dB)	SN ratio (dB)	SN ratio+40 (dB)
1	21.938	–40.828	3.172	–37.729	2.270
2	27.959	–40.0	4.0	–36.650	3.349
3	27.959	–39.567	4.434	–37.502	2.498
4	30.0	–37.521	6.479	–31.005	8.995
5	25.850	–36.902	7.098	–32.568	7.432
6	20.862	–39.138	4.862	–39.181	0.819
7	25.850	–40.0	4.0	–37.385	2.615
8	24.437	–42.279	1.721	–39.134	0.866
9	23.010	–34.843	9.157	–37.788	2.212
10	27.959	–40.434	3.566	–35.848	4.152
11	20.0	–39.138	4.862	–37.026	2.974
12	18.297	–43.541	0.459	–38.537	1.463
13	23.010	–34.843	9.157	–35.848	4.152
14	30.0	–33.118	10.882	–36.258	3.742
15	18.416	–36.989	7.010	–39.736	0.264
16	21.938	–39.567	4.434	–36.964	3.036
17	23.010	–36.989	7.010	–36.646	0.354
18	33.979	–39.085	4.915	–37.025	2.975

ppm – parts per million HSU – Hatridge Smoke Unit

$$\text{SN Ratio(dB)} = -10\log\left[1/n\sum_{i=1}^{i=n} Y_i^2\right]$$

$$= -10\log\left[\frac{1}{3}\left\{0.02^2+0.02^2+0.02^2\right\}\right]$$

$$= 33.98\text{ dB}$$

The SN Ratio value is contained within the 99.995% confidence interval obtained. So the optimum condition is confirmed by a confirmation test.

Similar calculations were made for other emissions in 40% and 80% of maximum load using the following strong effects:

40% Maximum load

Strong effects for hydrocarbon (HC) : $B_2 D_3 F_1$
Strong effects for smoke : $A_1 B_2 C_1 G_2$

80% Maximum load

Strong effects for carbon monoxide (CO) : $D_1 F_3 G_2$
Strong effects for hydrocarbon (HC) : $B_2 D_1 F_3 G_2$
Strong effects for smoke : $B_2 C_1 D_1 G_2$

The predicted ranges of S/N ratio for CO, HC and smoke for 40% W_{max} and 80% W_{max} are given in Tables 10 and 11 respectively.