

# Review Paper on “Development Strategy for High Specific Power Low Emission Diesel Engines”

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## Abstract

Considering the growing demand for emission reduction, diesel engines are becoming more and more popular. CO<sub>2</sub> can be further reduced by downsizing the engine. Engines in the range of 1.0 to 3.0 liter cubic capacity are being re-designed for high specific power in the range of 50 to 75 kW/l with peak firing pressure in the range of 160 to 200 bar, bsfc below 200 g/kWh and extremely low emissions to meet Euro V Norms and beyond.

This paper highlights development strategies employed to meet this enhanced dynamic performance for such compact diesel engines. Some of the areas highlighted are design considerations, high performance crank train, cylinder head and cylinder block to meet high mechanical and thermal loading, air induction with 4 valve technology and VNT/Dual turbochargers, fuel injection with piezo multi stage common rail fuel injection and emission control technology.

The use of diesel engine will continue with upward trend worldwide. With research efforts in material technology, induction, injection and combustion optimization and after- treatment devices, the future of diesel engines is looking bright and adaptable for wider range of applications.

## INTRODUCTION

A challenging project has been undertaken on design and development of advanced diesel engine with very high power output of 50 kW/l and 75 kW/l. Both these designs will meet Euro-IV emission norms and upgradable for Euro-V emission norms. The engine will have displacement of 1.5 liter with 3 cylinders and will incorporate very high injection pressures up to 1800 bar.

3 cylinder configuration will pose severe challenges in the NVH area. Specific power will also pose challenges in design of crank-train, cylinder block, cylinder head, combustion chamber, etc.

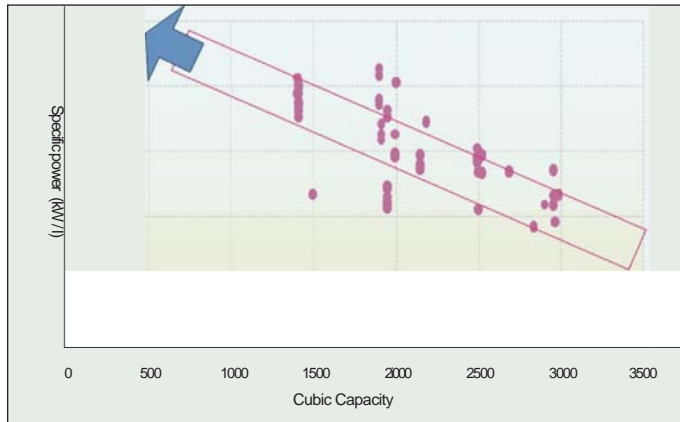
The paper will describe the evolution of technical specifications and targets through QFD, followed by concept design, DFMEA and design and development of various components/systems through systems approach.

Under Quality Function Deployment (QFD), the automotive industry leaders were contacted and their voice were captured and deployed to extract quality elements. Based on this, the major requirements/targets were finalized. Some of the major requirements were:

- 50 kW/l can be a contemporary design suitable for Asian market in 2010, whereas 75 kW/l may be for overseas market.
- The engine should have high torque backup.
- Fuel consumption should be below 200 g/kWh and above 20 km/liter for a passenger car application.
- Both these designs must meet Euro-IV emission norms and upgradable for Euro-V emission norms.
- It should be balanced and should have low noise and vibration.
- It should have low cost, low weight and high durability.
- Develop domestic competency in high performance engine design and development.
- Process engineering for new materials should be developed in the areas of prototype manufacturing, casting, machining, etc.
- Increasing tolerance level of engine/after-treatment devices for adulterated fuels.

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- The engine should have flexibility to be customized as per customer’s requirements for better acceptability in the market.
- The design should be of modular type and can be extended for 2, 3, 4 and 6 cylinder configuration.
- It should enhance the consumer’s experience when driving on the highways.



**Figure. 2: Fuel Consumption of Indian Diesel Vehicles**

The first step was to decide the total displacement of the

engine, number of cylinders and the displacement per cylinder. Fig. 2 shows Indian trend for the Diesel engine. It can be observed that if fuel consumption required is above 20 km/l, the engine total displacement has to be 1500 cc or below.

### DESIGN CONSIDERATIONS

Here bore to stroke ratio, peak combustion pressure, compression ratio, combustion chamber, etc. are discussed  
**BORE TO STROKE RATIO** : Initially, the Bore x Stroke were 84 x 90 mm for a ratio of 0.93. These were reviewed as given in Table- I and modified as 82 x 94 mm for a ratio of 0.87 [6].

A high bore to stroke ratio is not good for the K-factor evaluation [2]. This parameter is the ratio between the combustion bowl volume within the piston and the total volume of the combustion chamber at TDC. With low bore to stroke ratio, dead volumes are decreased and consequently K-factor is increased. This increases the mean air-fuel ratio within the combustion bowl, thus improving the combustion and giving lower particulate emissions.

**Table I: Review of Bore and Stroke**

CRITERIA	JUSTIFICATION	REQUIREMENTS		
		BORE	STROKE	BORE / STROKE RATIO
Surface to volume ratio	Lower ratio means low HC emission and low heat to cooling leading to fuel economy.	Lower	Higher	Lower
Piston speed	piston speed leads to higher friction, wear and inertia forces.		Higher, equivalent to 13m/s [1,2]	Lower
Pressure drop across valves	Low pressure drop requires higher bore, so that valves can be made larger and less restrictive, leading to higher power and higher thermal efficiency	Higher		Higher, but can be compensated by 4 valves.
Bench- mark	40 kW/l 44 kW/l 47 kW/l 54 kW/l 58 kW/l	83.0 69.6 79.5 75.0 85.0	92.0 82.0 95.5 84.5 96.0	0.90 0.85 0.83 0.88 0.88
Decision	Original 75 kW/l:12.6 m/s Revised 75 kW/l:13.2 m/s	84.0 82.0	90.0 94.0	0.93 0.87

**Table- II: Review of Crank Radius to Conrod Length**

CRITERIA	JUSTIFICATION	REQUIREMENTS		
		CRANK RADIUS	CON-ROD LENGTH	$\square = r/l$ RATIO
Rattling noise due to piston slap at low speed, load	Low noise requires short Rod length. 8% increase in length increases noise by 5 dB(A).	----	Shorter	Higher
Piston thrust, Bore wear & friction	Longer rod reduces , Max rod angle to cylindrical bore centerline. Less rod angle will reduce piston side loading, leading to lower friction & bore wear. But 8% increase in length reduces friction only by 1%.	----	Longer	Lower
Weight of Con Rod	Shorter Con Rod means low weight	----	Shorter	Higher
Engine height & weight	Lower engine height & weight requires shorter Con Rod	----	Shorter	Higher
Crankcase envelope	Shorter Con Rod will need lower crankcase envelope	----	Shorter	Higher
Piston skirt reduction for low friction & weight	Longer Con Rod & longer stroke will make shorter skirt compulsory	Longer	Longer	Neutral
Power	Decrease in Rod length by 22 % reduces power only by 0.6% (G.T.Power)	Longer	Longer	Neutral
Decision	Original 75 kW Revised 75 kW	47.0 47.0	159.0 146.0	0.29 0.32

## CRANK RADIUS TO CONNECTING ROD LENGTH RATIO

Initially, this ratio was 0.29. These were reviewed as given in table- II and modified as 0.32 mm leading to connecting rod length of 146 mm.

## COMBUSTION CHAMBER DESIGN:

In a common rail a DI diesel engine, the centrally located combustion chamber is usually characterized by a re-entrant bowl in a piston with upward protuberance in the centre of the chamber. This maximizes the volume in the outer region of the bowl. The four-valve configuration helps to place the injector vertically in the centre

The fundamental criteria for diesel combustion chamber design here are those of maximizing the contact area, improvements in air-fuel mixture formation, optimum distribution of mixture and reduction of fuel adhering to the cavity wall.

The fuel spray plumes angle into the piston bowl. As the piston approaches TDC, air is squished towards the spray plume by the piston rim. The combination of air motion and the spray velocity and direction create a vortex leading to air-fuel mixture improvements near the outer edge of the bowl [6].

A round lip and a spray impingement just on the lip corner produces larger spray volumes, improves the mixture formation and spray distribution. This helps to reduce HC and smoke to a great extent at high loads. This also

reduces thermal stresses on the lip edge [9, 10].

Various parameters to be optimized are bowl diameter, throat diameter, re-entrancy, bowl depth, spray included angle, distance from impinging wall to nozzle tip, bottom corner radius and lip squish, height and radius.

Euro V bowl should be shallower and should have large diameter than their predecessors [11]. The design trends are shown in Table- III. The most important parameter for emission control are bowl depth/bowl. diameter ratio and re-entrancy which is defined as the half the difference between bowl diameter and throat diameter.

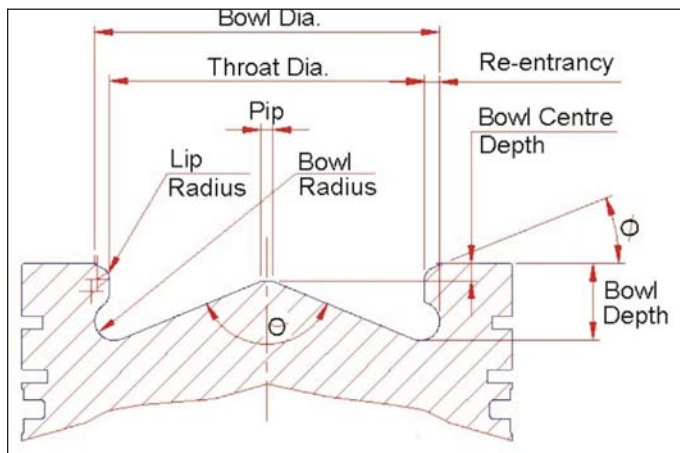


Figure 3: Piston bowl Nomenclature

Table III: Bowl Design Trends

	EURO III	EURO IV	EURO V
Bowl Dia.	-05 to -10%	100%	+05 to +10%
Throat Dia.	-08 to -12%	100%	+08 to +15%
Bowl depth	+10 to -15%	100%	-12 to -20%
Re-entrancy	2 to 4	1.5 to 3.5	1 TO 3
Bowl Dia./ Bowl Depth	0.3 to 0.5	0.25 to 0.4	0.2 to 0.3

## ROAD MAP

To meet the challenging targets of high specific power and low emissions, a roadmap is drawn with various selected technologies which will improve the power density and also reduce the PM emissions:

- Higher Boost Pressure with 2 Stage Turbo-charging
- Higher Intercooler Efficiency
- Higher Rail Pressure
- Higher Injection Pressure
- Higher Injection Rate Efficiency
- Higher Nozzle Hydraulic Flow

This will increase the specific power as well as NOx. To reduce NOx, the following technologies are planned:

- 4 Valves with Central Injector
- Lower Compression Ratio
- Optimized Combustion Chamber
- Nozzle Hole Optimization
- Multiple Injection Strategies
- Enhanced EGR System with Effective Cooling
- Coated DPF and DeNOx Catalyst Combination.

Table- IV thus shows the target specifications of 50 and 75 kW/I engines. Accordingly, System design specifications (SDS), Design Input sheets, functions and requirements of various systems were evolved and DFMEA done.

Table IV: Main Specifications of the Engines

Particulars	Stage 1	Stage 2
No. of Cylinders	3	3
Specific Displacement (liter/cylinder)	0.5	0.5
Engine Displacement (liter)	1.5	1.5
Bore x Stroke (mm x mm)	82 x 94	82 x 94
Rated Power (kW)	75@4000r/min	112@4200r/min
Power Density (kW/liter)	50	75
BMEP in bar (Rated/Max.)	15 / 20	21.5 / 26
Max. Torque (Nm)	235@2000r/min	307@2000r/min
Torque Back-up	— 30%	— 20%
Injection Pressure	>1600 bar	>1800 bar

Particulars	Stage 1	Stage 2
Minimum BSFC (g/kWh)	195	190
Rated BSFC (g/kWh)	235	235
Combustion pressure	160 bar Max.	200 bar Max.
Sound Power	< 100 dB(A)	< 95 dB(A)
Emission compliance	Euro IV	Euro V

Once the Specifications were frozen, MS-Project plan was made and was linked with a Project Tracking System (PTS).

#### HIGH PERFORMANCE CRANKTRAIN:

To meet high mechanical and thermal loading: high performance piston and rings, fractured and stepped connecting rod, micro alloy steel crankshaft, sputtered bearing, balancing solutions, etc. are planned.

#### PISTON :

Higher specific power increases piston temperature and large combustion bowl diameters (required to meet stringent emission norms) reduces the distance between the bowl and ring carrier. This increases the piston thermal loading as shown in Fig. 12 [11]. Hence, 5 mm thick rectangular Ni-resist insert is suggested with 1.5 mm thickness on either side after machining.

Above 50 kW, cooling gallery is must. For 75 kW/l, the bowl edge temperature may go above 400°C. To bring this down to a target of 385°C, variable cross section cooling gallery with a jet splitter is proposed using salt core technology. The target for top ring groove is 300°C and above bush is 235°C. The cooling effectiveness on fibre reinforced bowl edge with hard anodized crown is checked using FEA. These temperatures are then validated using the templug when the prototypes are made.

## CONCLUSION

The biggest challenge in Diesel technology for the future is development of high power density engines, which will meet future emission, noise, safety, durability and end-of-life requirements. A technology demonstrator project done at ARAI in this area will go a long way to set an example of excellence and future trend. A systems approach with good project management, benchmarking, concept design,

simulation strategy, mechanical design, tolerancing, vendor development, engine assembly and optimization is stressed here. The engine is expected to be ready by mid 2009.

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