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Improvement of Valve Timings in Camless Heavy-Duty Diesel Engine

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Abstract - *The existing design of the Internal Combustion Engine is at risk of obsolescence due to its high emissions and depletion of fossil fuels. Despite the measures taken to control emissions by introducing various norms, the environment is still impacted. The "Camless Technology" concept, also known as fully variable valve actuation, offers the unique ability to have independent control of the intake and exhaust valves in an Internal Combustion Engine. In an Internal Combustion Engine, the timing, duration, and lift of the valve have a significant impact on engine performance. An engine equipped with a variable valve timing actuation system has different valve timings for different engine speeds and conditions, improving the performance of the engine. To optimize engine performance across the entire operating range, a camless electronically controlled pneumatic/hydraulic valve actuator system is being explored which permits variation in valve lift, duration, and timing. The current technologies which attempted to achieve Variable Valve Timing are still directly or indirectly dependent on the rotation of CAM. Hence, by simulating "Camless Technology" the benefits of having such type of system are demonstrated. Simulation of "Camless Technology" is done using 1-D thermodynamic simulation software. As this technology is operational in passenger vehicles, this project focuses on the Heavy-Duty Diesel Engine which is used in transportation mainly due to their good thermal efficiency. The simulations were initiated with the study of a single-cylinder diesel engine. In a single cylinder CI engine, the valve lift profile is generated and optimized by varying the lift, time of actuation, duration of opening for both inlet and exhaust valves. The goal is to improve engine performance by maximizing the volumetric efficiency and brake power and minimizing the pumping losses. The optimization was done by using the "Genetic Algorithm". Further, similar simulations and optimizations are done for a six-cylinder turbocharged diesel engine by considering, RGF (Residual Gas Fraction). Thus, the A/F ratio is controlled effectively in transient zones which ensures lower NOx which can be handled with minimum support from after-treatment.*

***Key Words*: Camless, GT – SUITE, 6 – Cylinder Turbocharged Diesel Engine, Emissions, Residual Gas Fraction, RGF**

1. INTRODUCTION

Improvements of the performance of engines are continually investigated, so that it consumes less fuel while its impact on the greenhouse emissions is reduced. The variable valve timing (VVT) that was first proposed in 1880 has been proved to be a very effective method in improving engine performance until today. In an Internal Combustion Engine, the timing, duration, and lift of the valve have a significant impact on engine performance. An engine equipped with a variable valve timing actuation system has different valve timings for different engine speeds and conditions, improving the performance of the engine.

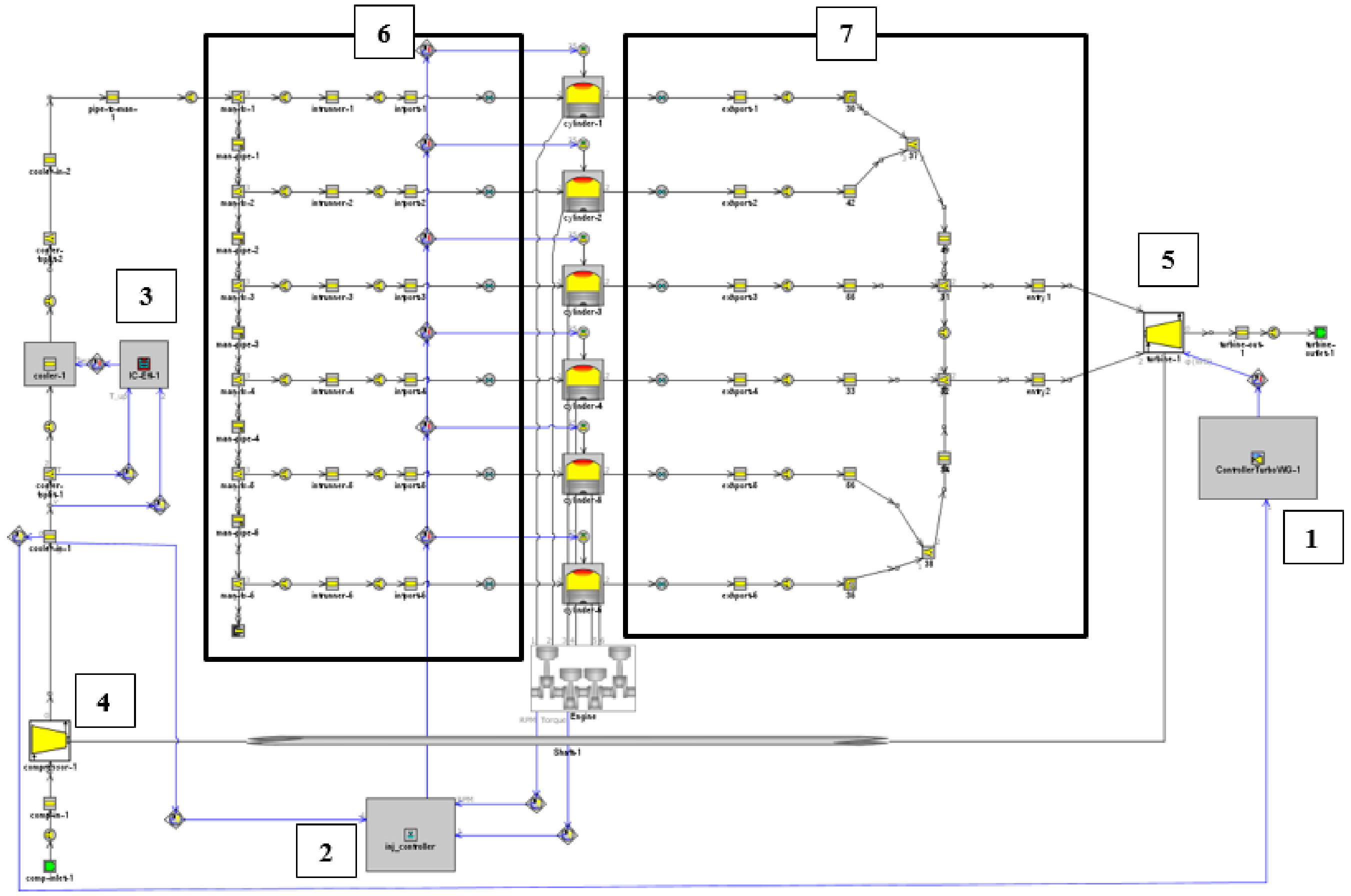

Figure -1: GT Suite Model for 6-Cylinder Turbocharged Diesel Engine

1. ControllerTurboWG-1:

This template is used to target various engine performance parameters in single-stage turbocharged applications. It has also been found to be effective in controlling the high-pressure turbocharger in two-stage applications. Its purpose is to eliminate the need for tuning the turbocharger.

2. Inj_Controller:

This template is used to target various engine performance parameters at part-load operation by adjusting the injected fuel quantity.

3. IC-Eff-1:

This template is used to model a control system that actuates the intercooler outlet gas temperature based on intercooler effectiveness data

4. Compressor:

This template represents a compressor in a turbocharged or supercharged engine.

5. Turbine:

This object is used to represent a turbine of a turbocharger and/or a power turbine. It can model a fixed geometry turbine, a turbine with a wastegate, or a variable-geometry turbine (VGT). It will predict the output power, mass flow rate, and outlet temperature using map data describing the turbine performance.

6. Intake Manifold:

The intake manifold is the part of an engine that supplies the fuel/air mixture to the cylinders.

7. Exhaust Manifold:

An exhaust manifold collects the exhaust gases from multiple cylinders into one pipe and passes it to the after-treatment system of the engine.

2. METHODOLOGY

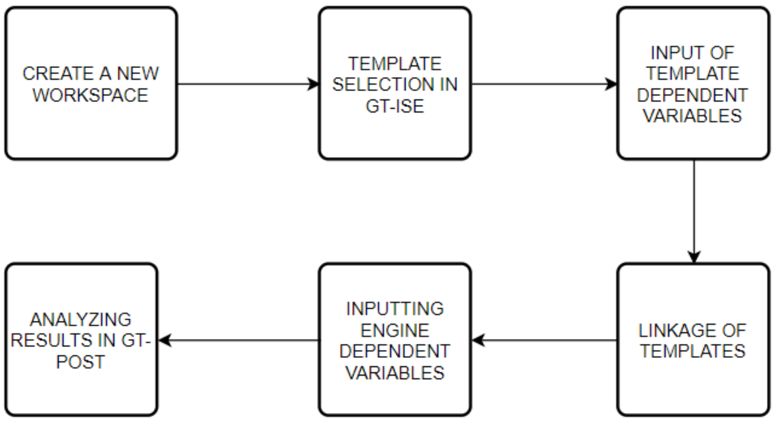

Figure -2: Methodology

3. BOUNDARY CONDITIONS

VARIABLE	VALUE
Inlet Crank Timing Angle	360
Outlet Crank Timing Angle	180
Angle Multiplier for Inlet	1.2694
Angle Multiplier for Exhaust	1.1437
Lift Multiplier for Inlet	1
Lift Multiplier for Exhaust	1

Table - 2: Initialization of Dependent Variables

The valve timings followed for the further simulations are as follows:

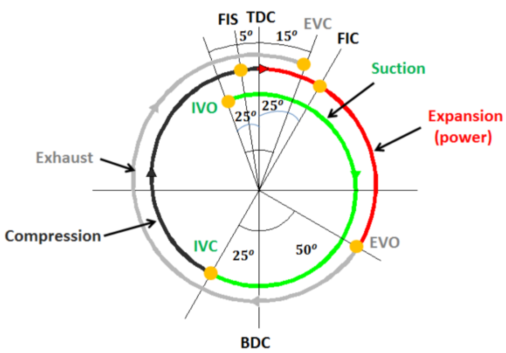

Figure -3: Valve Timings

Simulations were carried out at four different cases – 2200, 1800, 1200, 800 RPMs at Full Load.

Engine Geometry is as follows:

<table>
<tr><td>Bore (mm) :</td><td colspan="2">100</td></tr>
<tr><td>Stroke (mm) :</td><td colspan="2">130</td></tr>
<tr><td>Connecting Rod Length (mm) :</td><td colspan="2">220</td></tr>
<tr><td>Compression Ratio</td><td colspan="2">16.5</td></tr>
<tr><td>TDC Clearance Height (mm) :</td><td colspan="2">0.5</td></tr>
<tr><td>Number of Cylinders :</td><td colspan="2">6</td></tr>
<tr><td>Total Displacement (L) :</td><td colspan="2">6.126</td></tr>
<tr><td>Cylinder Number and Arrangement:</td><td colspan="2">6 Cylinder Inline Turbocharged</td></tr>
<tr><td>Peak Torque (Nm) :</td><td colspan="2">1000 Nm @1200 RPM</td></tr>
<tr><td>Engine Power (kW) :</td><td colspan="2">196 kW @2200 RPM</td></tr>
<tr><td>Firing Order :</td><td colspan="2">1-5-3-6-2-4</td></tr>
<tr><td>Valves / Cylinder:</td><td colspan="2">2</td></tr>
<tr><td rowspan="2">Valve Reference Diameter (mm) :</td><td>Inlet</td><td>Exhaust</td></tr>
<tr><td>45.5</td><td>37.5</td></tr>
</table>

Table - 3: Engine Specifications

The full load condition values are targeted by the injection controller which would vary the fuel intake such that the Brake Torque reaches the targeted value. The values of Brake Torque are maintained at the full load conditions for all the RPMs.

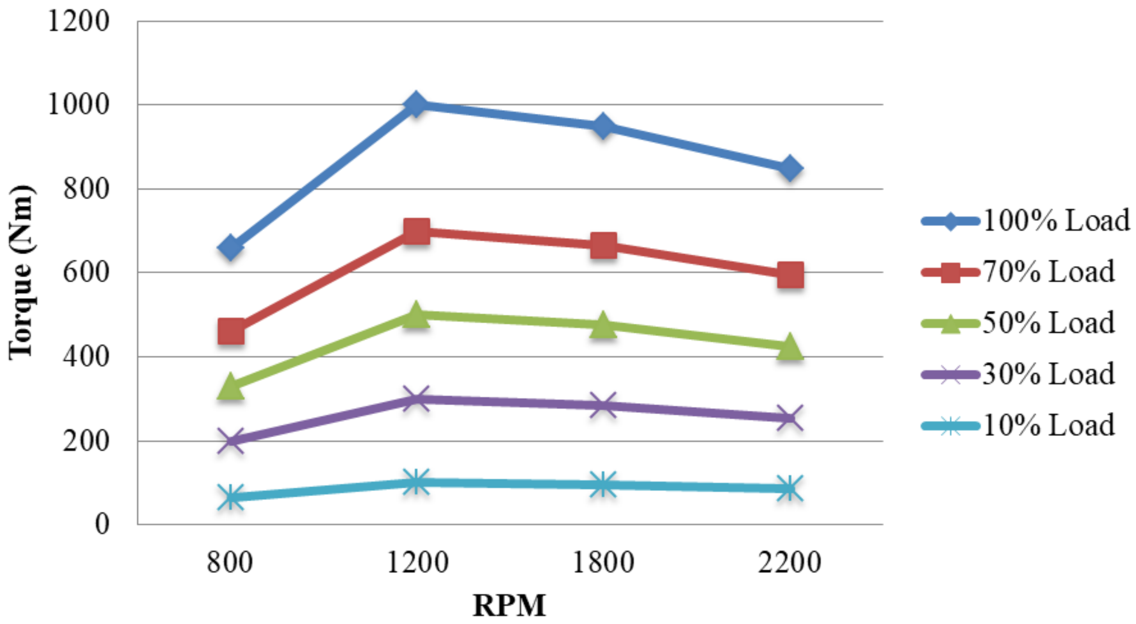

Chart – 1: Torque (Nm) vs RPM at various loads

4. RESULTS

The mass flow rate curves show the negative direction of mass flow, hence indicating pumping losses. VVT has lower pumping losses and compared to Non-VVT.

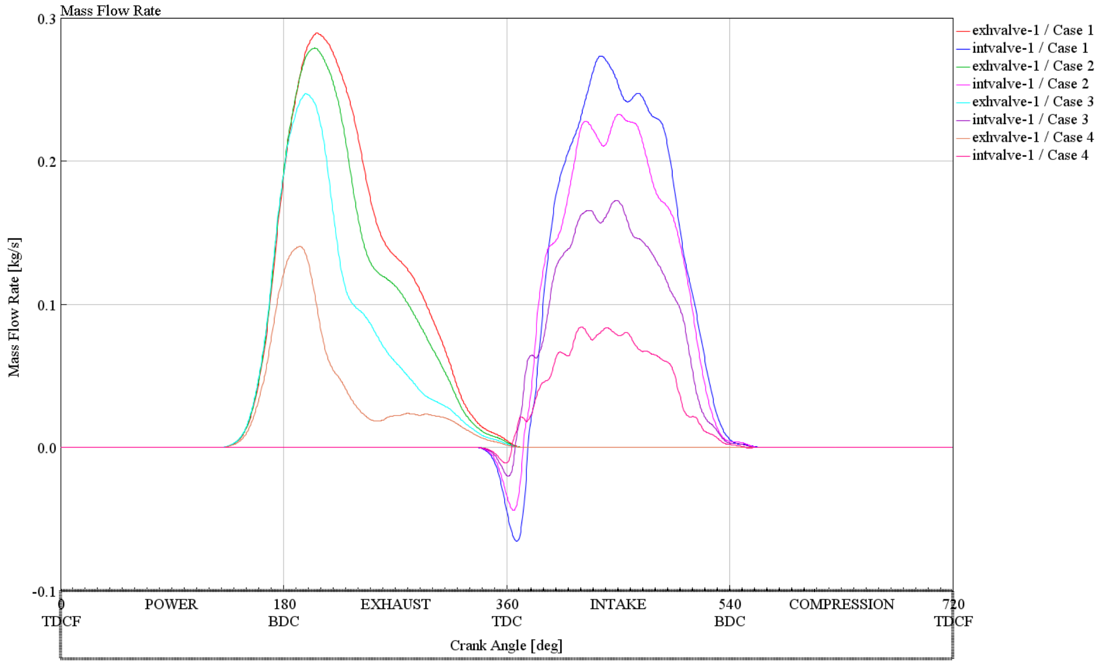

Chart – 2: Mass FR vs Crank Angle (Non-VVT)

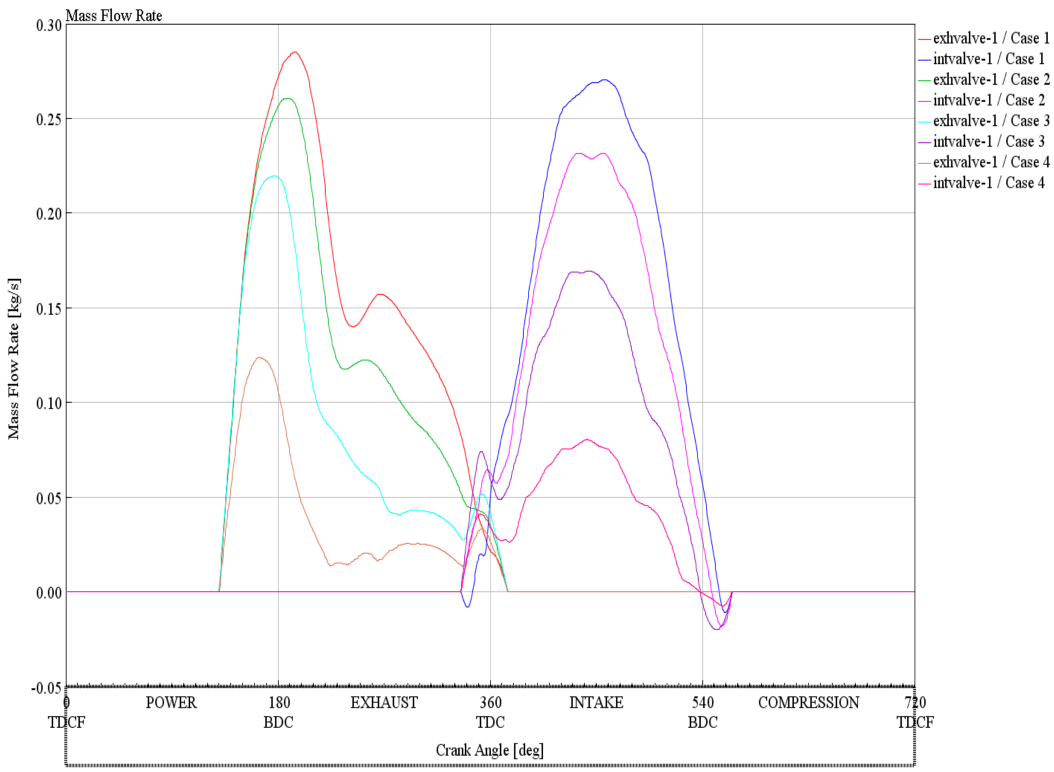

Chart – 3: Mass FR vs Crank Angle (VVT)

	1	2	3	4
Brake Power [kW]	195.8	179.2	125.8	55.3
Brake Power [HP]	262.5	240.4	168.7	74.2
Brake Torque [N-m]	849.7	950.9	1000.9	660.5
IMEP [bar]	16.34	17.91	18.43	12.34
FMEP [bar]	1.94	1.79	1.46	1.14
PMEP [bar]	-1.27	-0.67	0.21	0.20
Air Flow Rate [kg/h]	802.6	719.2	534.7	260.5
BSAC [g/kW-h]	4100	4012	4251	4707
Fuel Flow Rate [kg/h]	52.2	43.3	28.2	12.1
BSFC [g/kW-h]	266.7	241.6	224.5	218.2
Volumetric Efficiency [%]	141.6	155.0	172.9	126.3
Volumetric Efficiency (M) [%]	70.8	78.2	85.8	86.2
Trapping Ratio	1.000	0.999	1.000	1.000
A/F Ratio	15.37	16.61	18.94	21.57
Brake Efficiency [%]	31.4	34.7	37.3	38.4

Table - 4: Engine Performance (VVT)

	1	2	3	4
Brake Power [kW]	196.2	179.9	125.9	55.3
Brake Power [HP]	263.1	241.3	168.8	74.1
Brake Torque [N-m]	851.5	954.5	1001.9	659.6
IMEP [bar]	16.48	18.04	18.48	12.32
FMEP [bar]	2.04	1.86	1.49	1.14
PMEP [bar]	-0.90	-0.27	0.54	0.29
Air Flow Rate [kg/h]	1057.6	882.6	618.4	282.6
BSAC [g/kW-h]	5391	4906	4912	5113
Fuel Flow Rate [kg/h]	45.5	39.4	26.5	11.8
BSFC [g/kW-h]	231.8	218.8	210.8	214.0
Volumetric Efficiency [%]	186.5	190.3	200.0	137.1
Volumetric Efficiency (M) [%]	93.1	96.0	98.7	98.0
Trapping Ratio	0.997	0.984	0.962	0.943
A/F Ratio	23.26	22.42	23.30	23.90
Brake Efficiency [%]	36.1	38.3	39.7	39.1

Table - 5: Engine Performance (NON - VVT)

As more air is passed through the opening of the intake valve, this results in higher volumetric efficiency.

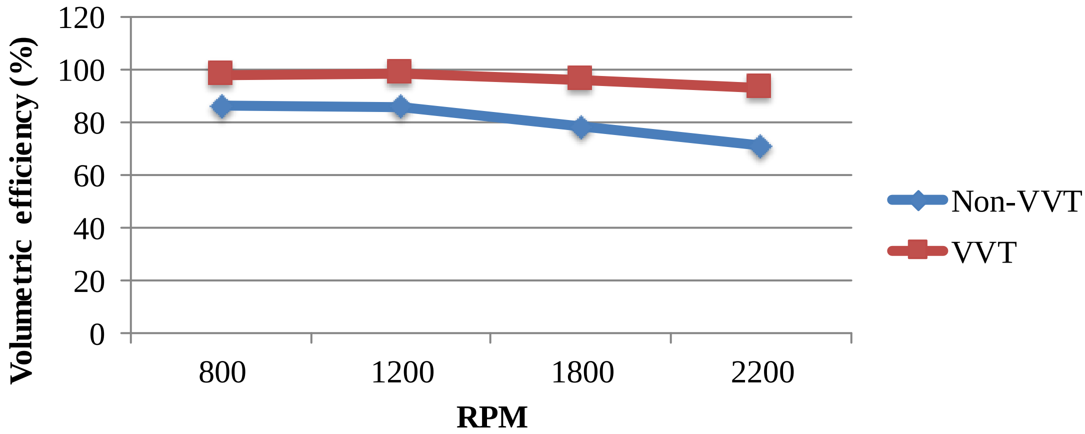

Chart – 4: Volumetric efficiency vs RPM

Pumping loss in engines is the difference in work done to pump out the exhaust gas and the work done to induce the fresh charge (fuel+air mixture) into the intake manifold. Since the exhaust gases must be pumped out against the atmospheric pressure, the higher the intake pressure, the lesser will be the pressure difference between intake and exhaust ports. Since the IMEP has increased, the pumping losses reduce in VVT.

The positive PMEP indicate that at low speeds, exhaust gas velocity is less which results in low-pressure drop and less reverse flows this happens since the engine is turbocharged, the exhaust pressure is lesser than the intake pressure.

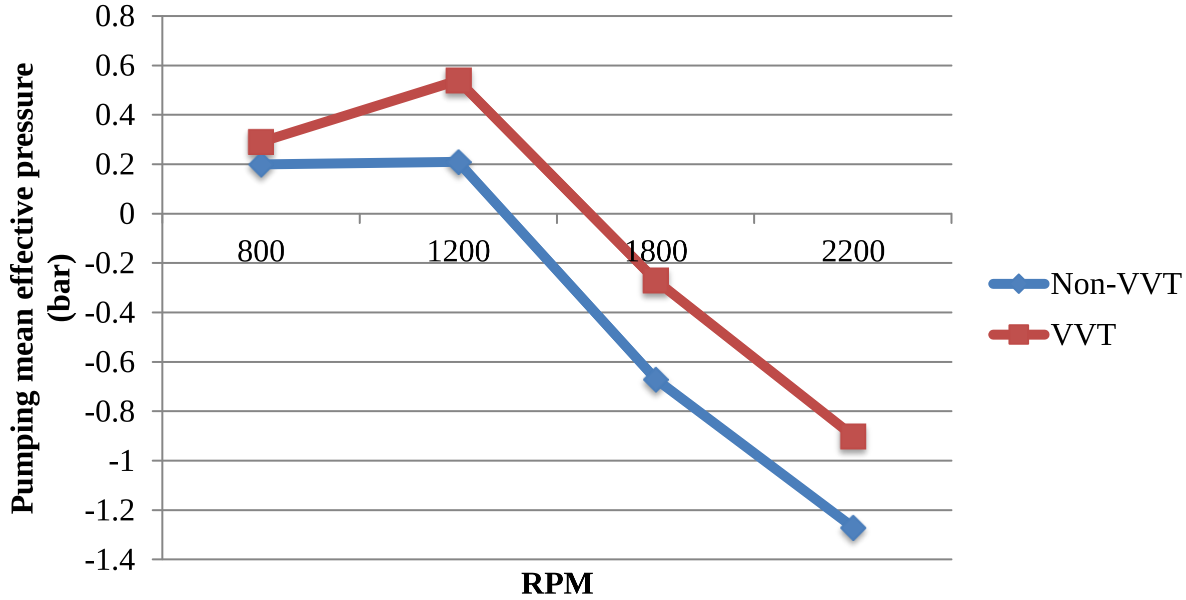

Chart – 5: Pumping Mean Effective Pressure(bar) vs RPM

With the increase in BMEP, there is an improvement in Brake efficiency in the case of VVT.

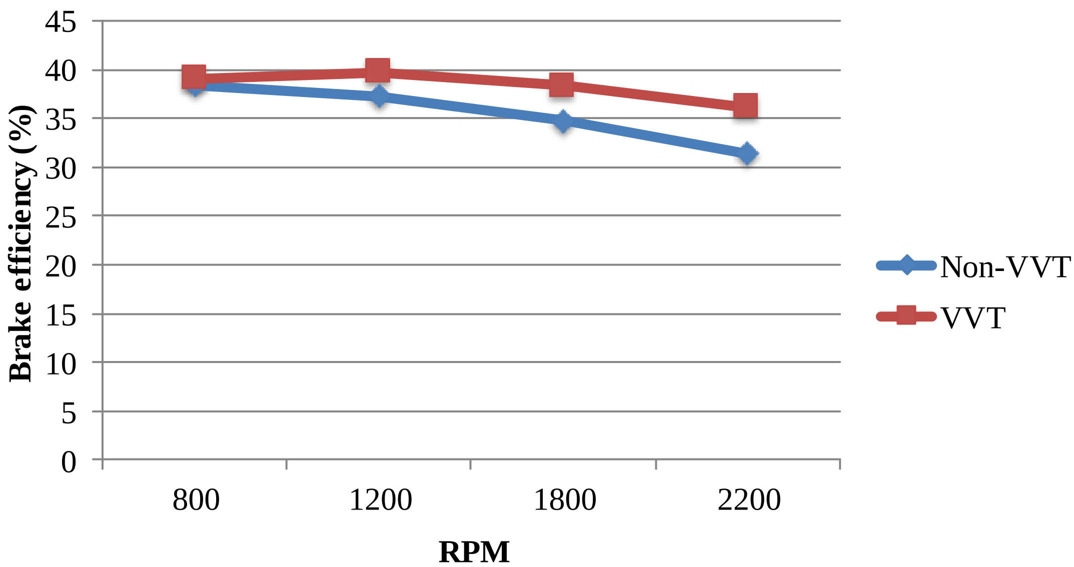

Chart – 6: Brake efficiency (%) vs RPM

With the increased airflow rate, the air density is higher in the cylinder. This resulted in a more efficient combustion of the charge, hence improving BSFC and decreasing fuel consumption.

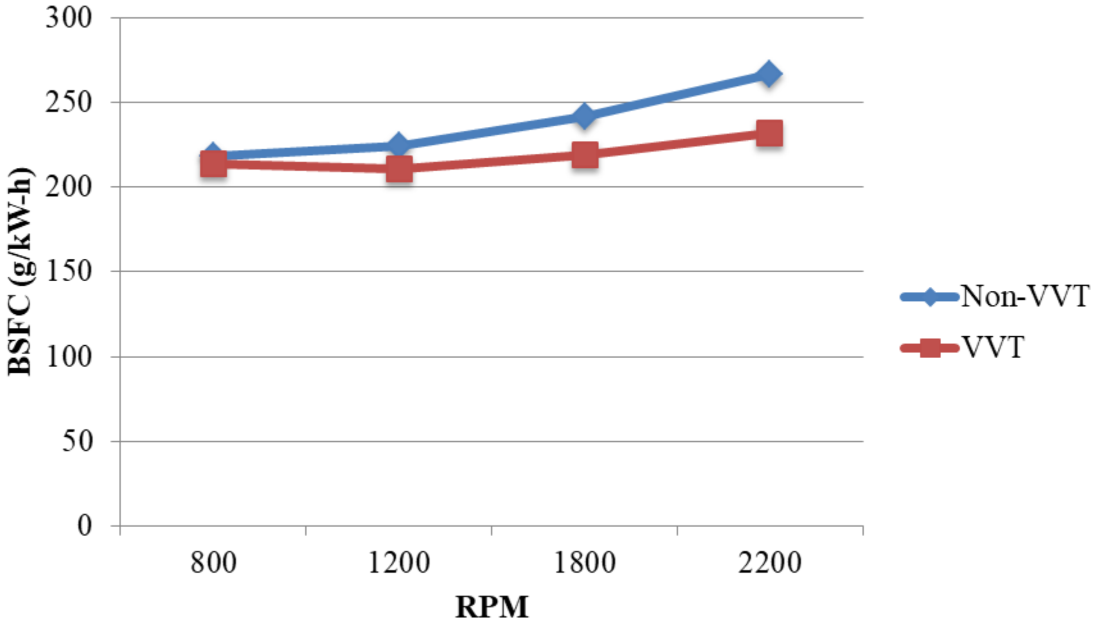

Chart – 7: BSFC (g/kW-h) vs RPM

RPM	NOx (Non-VVT) (in PPM)	NOx (VVT) (in PPM)
2200	2093	2891
1800	2595	3209
1200	2566	2720
800	2820	3055

Table - 6: NOx (PPM)

With the increase in the airflow rate leaving the cylinder, the NOx emissions have increased. Thus, indicating that the valve timings must be optimized such that NOx emissions are decreased with the factor of lower BSFC.

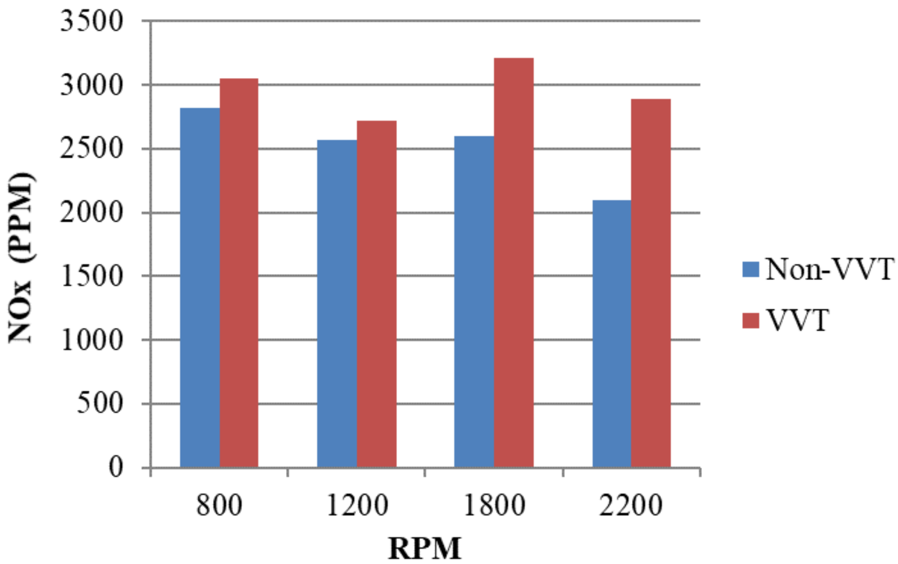

Chart – 8: NOx (PPM) at various RPM

5. CONCLUSION

1. The valve timings are not perfect, hence need optimization.
2. The values of NOx are not effectively controlled in the Trapezoidal Lift Profile.
3. The percentage change in the performance criteria for different RPM is as follows:

	800 RPM	1200 RPM	1800 RPM	2200 RPM
Pumping losses (bar)	↓ by 0.09 bar	↓ by 0.33 bar	↓ by 0.4 bar	↓ by 0.37 bar
BSFC (g/kW-h)	1.92% ↓	6.1 % ↓	9.43 % ↓	13.08 % ↓
Volumetric efficiency (%)	13.68% ↑	15.03 % ↑	22.67% ↑	31.49 % ↑
Brake efficiency (%)	1.82% ↑	6.43% ↑	10.37% ↑	14.97 % ↑
NOx (PPM)	8.34 % ↑	6.01 % ↑	23.66 % ↑	38.12 % ↑

Table - 7: Engine Parameter Comparison

6. OPTIMIZATION OF VALVE TIMINGS FOR 6-CYLINDER DIESEL ENGINE

To optimize the valve timings, a method termed as "Genetic Algorithm" is used.

7. METHODOLOGY

The independent variables i.e valve duration and the timing are varied in a certain range such that the objectives are satisfied.

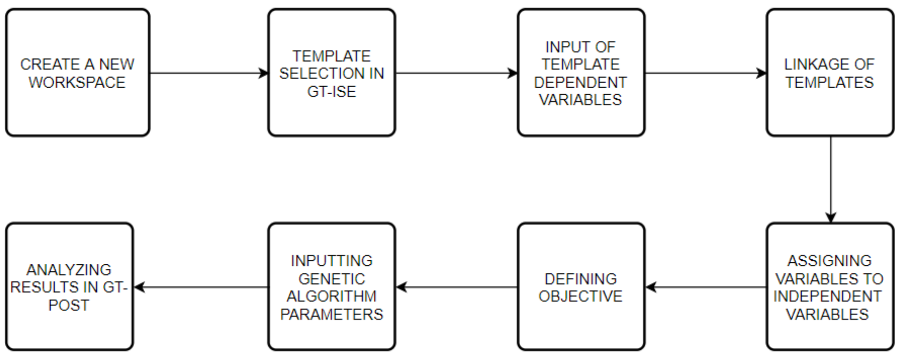

Figure -4: Methodology

8. BOUNDARY CONDITIONS

I. **Objectives:**

a. Maximum Volumetric Efficiency

b. Minimum Pumping Losses

c. Minimum BSFC

II. **Variables varied:**

a. Cam timing angle for both inlet and exhaust valves.

b. Angle Multiplier for both inlet and exhaust valves.

III. **Cases:**

a. 2200 RPM

b. 1800 RPM

c. 1200 RPM

d. 800 RPM

Population Size :	64
Number of Generations :	10
Crossover Rate :	1
Crossover Rate Distribution Index :	15
Mutation Rate Distribution Index :	20

Table - 8: Genetic Algorithm Properties

9. RESULT

Results obtained from the Non-VVT simulation are compared with the optimized valve timing values. Engine performance is significantly improved with the optimized valve timings. By the optimization, we inferred that NOx emissions are not controlled by varying the valve timing.

The optimized values are as follows:

VARIABLE	**2200 RPM**	**1800 RPM**	**1200 RPM**	**800 RPM**
Inlet Crank Timing Angle	351.26303	363.9506	369.6297	361.9092
Exhaust Crank Timing Angle	173.93082	175.38991	184.29062	189.60878
Angle Multiplier for Inlet	0.9049653	0.9231095	0.90140027	1.0326452
Angle Multiplier for Exhaust	1.0962038	1.0928614	0.96053356	1.0529289
Inlet Lift Multiplier	1.2694	1.2694	1.2694	1.2694
Exhaust Lift Multiplier	1.1437	1.1437	1.1437	1.1437

Table - 9: Optimized Initial Values of Dependent Variables

The new valve timings are as follows with reference to TDC

RPM	2200	1800	1200	800
IVC	-170	-167	-166	-146
EVO	119	121	136	137
IVO	329	341	347	336
EVC	388	388	372	395

Default Valve Timing

	All RPMs
IVC	-155
EVO	130
IVO	335
EVC	375

Table - 10: Optimized Valve timings

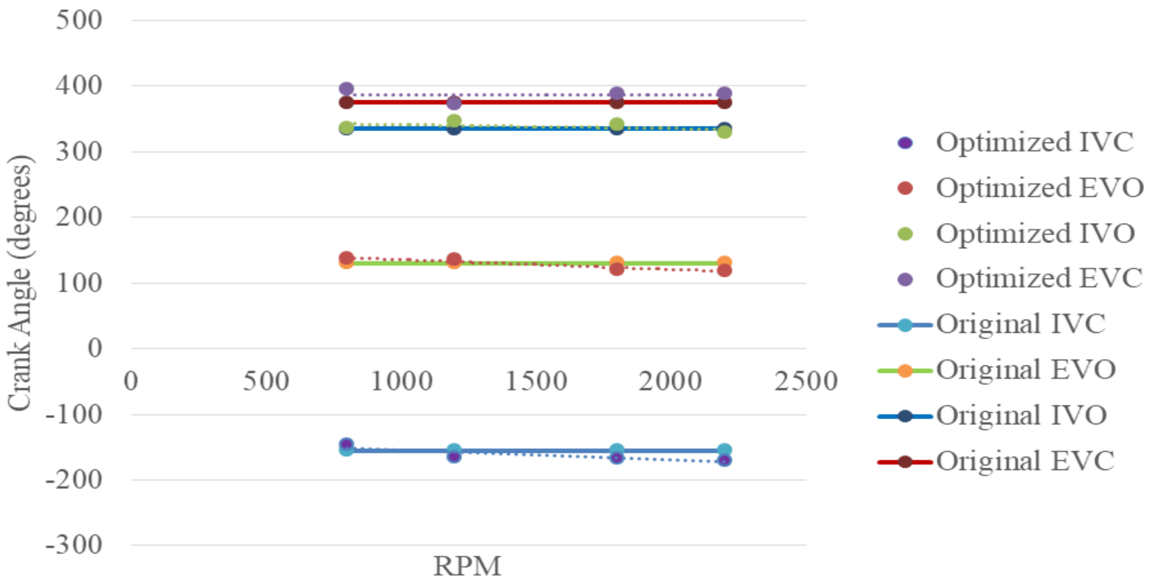

Chart – 9: Valve timing Optimization

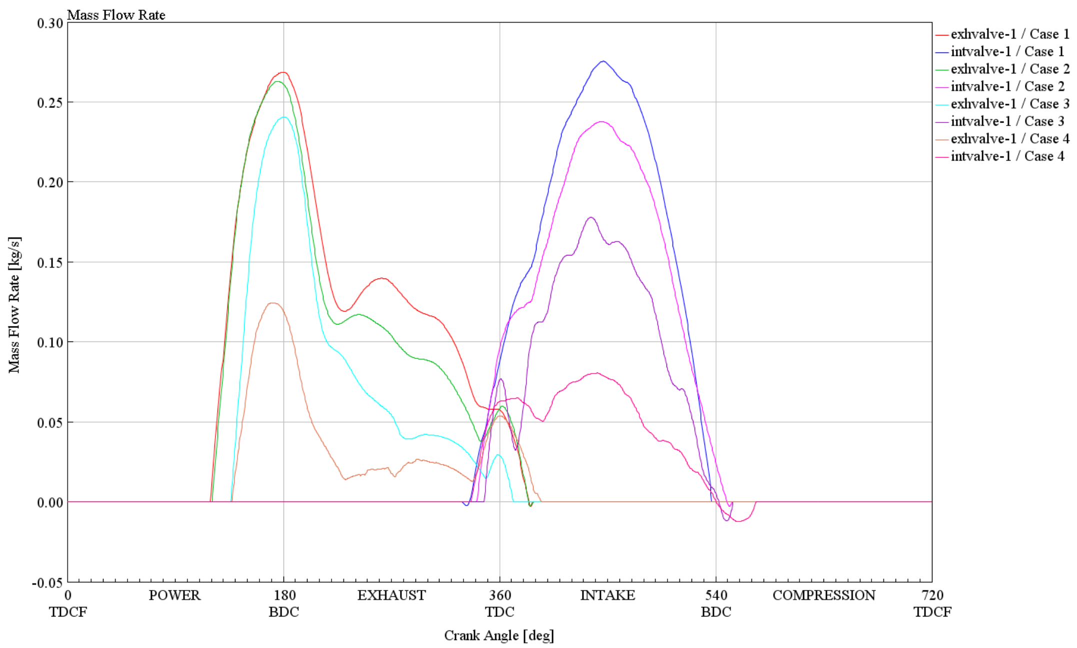

Chart – 10: Mass FR vs Crank Angle

	1	2	3	4
Brake Power [kW]	195.8	179.2	125.8	55.3
Brake Power [HP]	262.5	240.4	168.7	74.2
Brake Torque [N-m]	849.7	950.9	1000.9	660.5
IMEP [bar]	16.34	17.91	18.43	12.34
FMEP [bar]	1.94	1.79	1.46	1.14
PMEP [bar]	-1.27	-0.67	0.21	0.20
Air Flow Rate [kg/h]	802.6	719.2	534.7	260.5
BSAC [g/kW-h]	4100	4012	4251	4707
Fuel Flow Rate [kg/h]	52.2	43.3	28.2	12.1
BSFC [g/kW-h]	266.7	241.6	224.5	218.2
Volumetric Efficiency [%]	141.6	155.0	172.9	126.3
Volumetric Efficiency (M) [%]	70.8	78.2	85.8	86.2
Trapping Ratio	1.000	0.999	1.000	1.000
A/F Ratio	15.37	16.61	18.94	21.57
Brake Efficiency [%]	31.4	34.7	37.3	38.4

Table - 11: Engine Performance (NON - VVT)

	1	2	3	4
Brake Power [kW]	196.3	179.5	126.4	55.3
Brake Power [HP]	263.2	240.7	169.5	74.1
Brake Torque [N-m]	852.1	952.3	1006.0	659.9
IMEP [bar]	16.45	18.01	18.56	12.32
FMEP [bar]	2.01	1.87	1.50	1.14
PMEP [bar]	-0.51	-0.09	0.57	0.27
Air Flow Rate [kg/h]	1037.0	919.7	608.9	311.9
BSAC [g/kW-h]	5282	5124	4817	5643
Fuel Flow Rate [kg/h]	44.5	38.7	26.5	11.8
BSFC [g/kW-h]	226.6	215.5	209.5	213.1
Volumetric Efficiency [%]	182.9	198.3	196.9	151.3
Volumetric Efficiency (M) [%]	91.8	99.8	96.5	109.6
Trapping Ratio	0.973	0.966	0.988	0.852
A/F Ratio	23.32	23.78	22.99	26.48
Brake Efficiency [%]	37.0	38.8	40.0	39.3

Table - 12: Engine Performance (Optimized VVT)

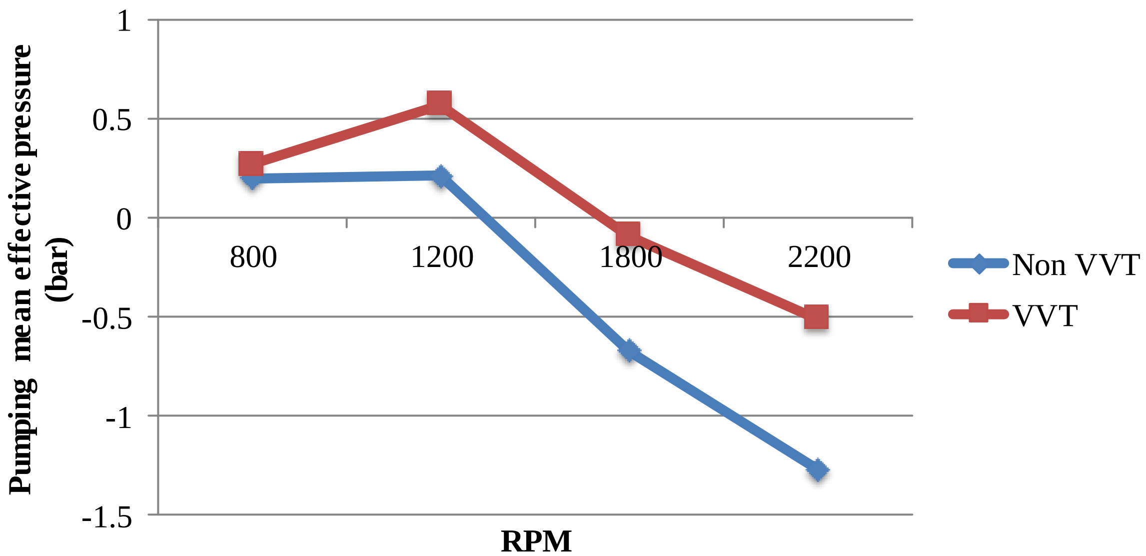

Chart – 11: PMEP vs RPM

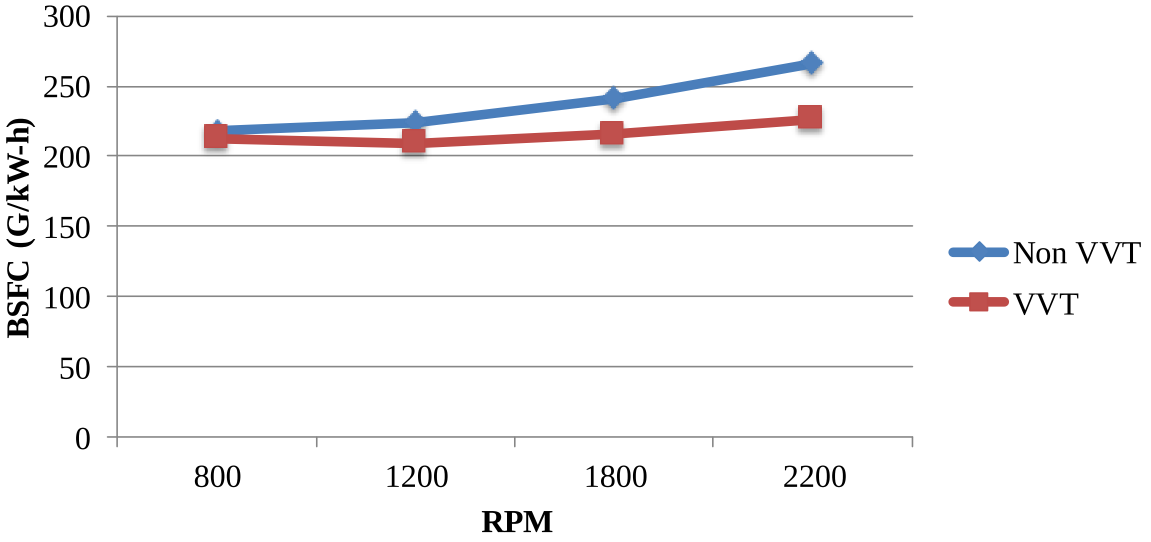

Chart – 12: BSFC vs RPM

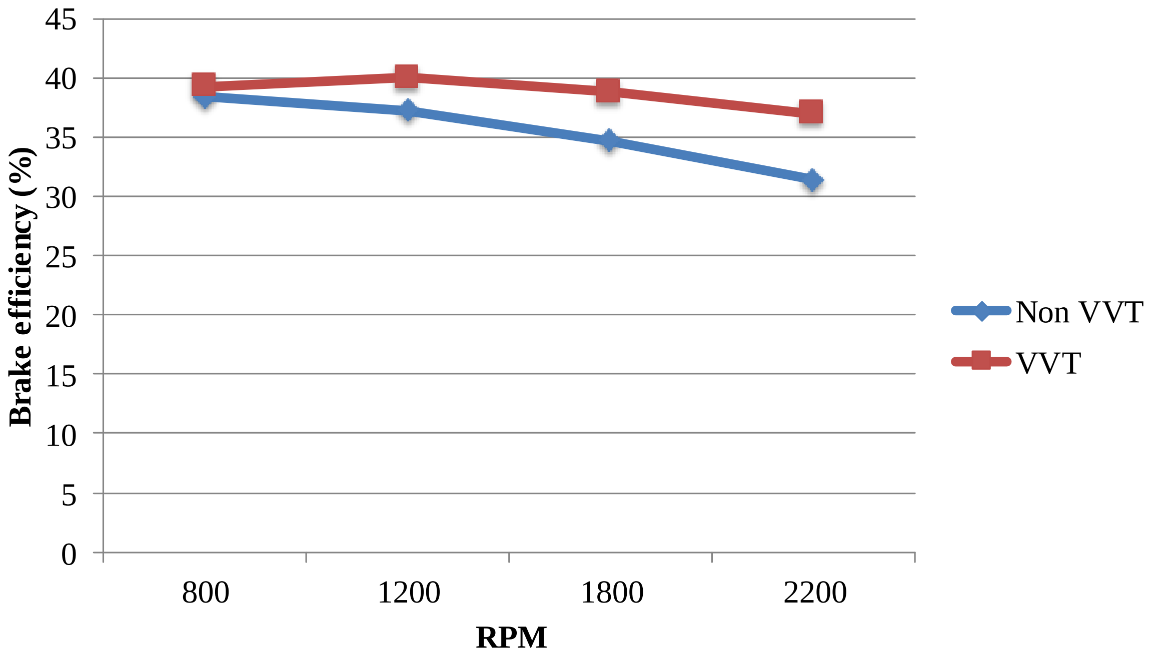

Chart – 13: Brake Efficiency vs RPM

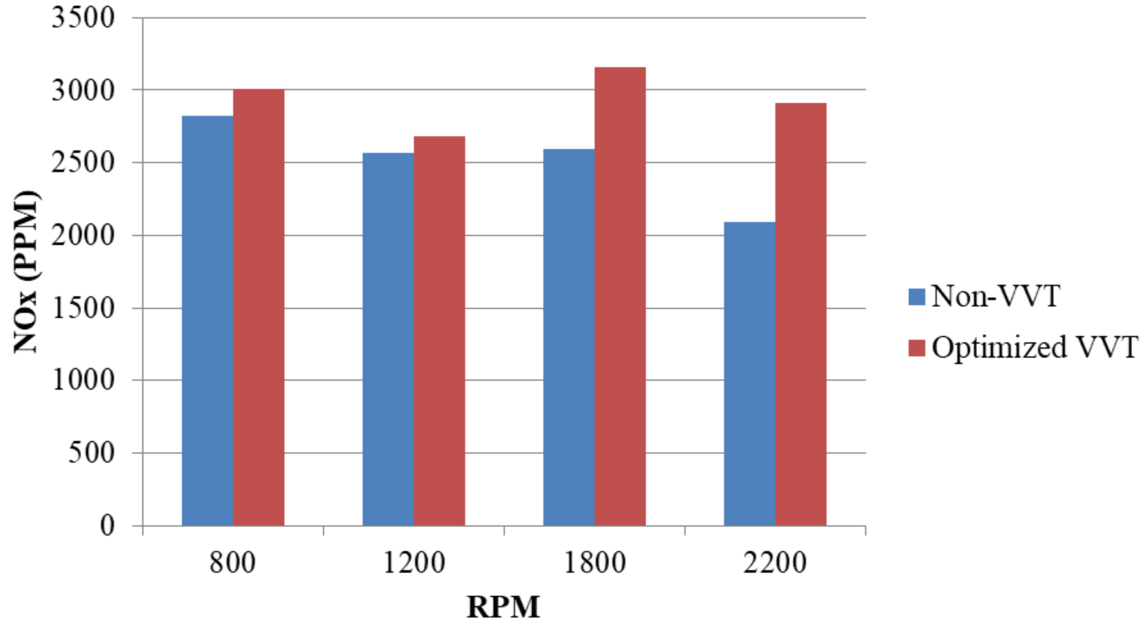

Chart – 14: NOx (PPM) for various RPM

RPM	NOx (Non-VVT) (PPM)	NOx (Optimized VVT) (PPM)
2200	2093	2911
1800	2595	3159
1200	2566	2687
800	2820	3010

Table - 13: NOx (PPM) for Various RPM and Conditions

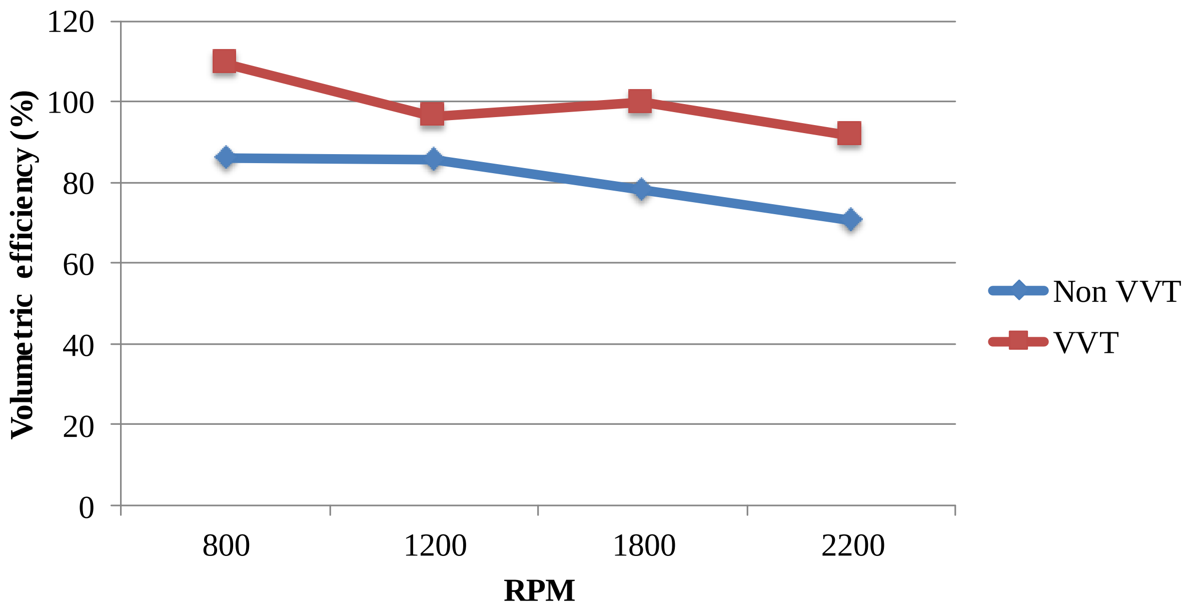

Chart - 15: Volumetric Efficiency vs RPM

10. CONCLUSION

1. The engine performance is enhanced by the optimization of valve timing. Lesser fuel is used to produce the same amount of power or torque.
2. The NOx values or emissions are not controlled by the optimization of valve timing. Emissions cause various environmental problems, which need to be solved. In further simulations, a way of emission control is done by adjusting the valve timing.
3. The percentage change in the performance criteria for different RPM is as follows:

	800 RPM	1200 RPM	1800 RPM	2200 RPM
Pumping losses (bar)	↓ by 0.07 bar	↓ by 0.36 bar	↓ by 0.58 bar	↓ by 0.76 bar
BSFC (g/kW-h)	2.33% ↓	6.68% ↓	10.8% ↓	15.03% ↓
Volumetric efficiency (%)	27.14% ↑	12.47 % ↑	27.62% ↑	29.66% ↑
Brake efficiency (%)	2.34% ↑	7.23% ↑	11.81% ↑	17.83% ↑
NOx (PPM)	6.73 % ↑	4.71 % ↑	21.73 % ↑	39.08 % ↑

Table - 15: Engine Parameter Comparison

11. EMISSION CONTROL BY THE INCREASE OF RESIDUAL GAS FRACTION

RESIDUAL GAS FRACTION

For all RPMs, an optimized value has been achieved. The issue of knocking and emission reduction is not considered in these results, hence the further simulations add another objective to maximize the RGF inside the cylinder. Residual gas is already burned gas from previous engine cycles that are left in the cylinder. The main reason to use residual gas is to lower the amount of NOx that is formed. The temperature in the cylinder is so high that the nitrogen and oxygen in the air react and form NOx. By using residual gas, the total mass in the cylinder is increased which means that also the heat capacity of the charge is increased. This results in lower maximum temperature and the end that less NOx is formed. There are two ways to increase the amount of residual gas in the cylinder. Either through Exhaust Gas Recycling, EGR, which is to lead back the exhaust gases to the cylinder, or to close the exhaust valve before all exhaust gas has left the cylinder. When residual gas stays in the cylinder, it is sometimes called internal EGR. The amount of residual gas is often measured as a fraction of the total mass and the definition of the residual gas fraction is the ratio between the mass of residual gas and the total mass:

$$x_{rg} = \frac{m_{rg}}{m_{tot}}$$

12. METHODOLOGY

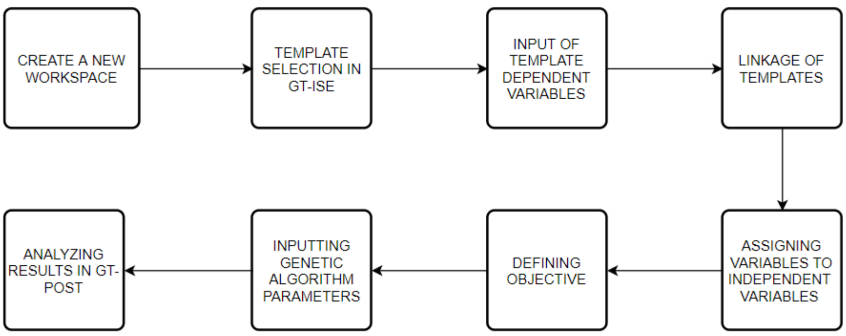

Figure -5: Methodology

The valve duration, valve timing, and valve lift are optimized such that the engine cylinder has a higher percentage of residual gases at the end of a cycle.

13. BOUNDARY CONDITIONS

For all RPMs, an optimized value has been achieved. The issue of knocking and emission reduction is not considered in these results, hence the further simulations add another objective to maximize the RGF inside the cylinder.

- The residual gas fraction must be maximum because,
  - To minimize knocking.
  - To decrease NOx (ppm).
  - To increase heat capacity at part load conditions.

I. Variables varied:

a. Cam timing angle for both inlet and exhaust valves.

b. Angle Multiplier for both inlet and exhaust valves.

c. Lift Multiplier for both inlet and exhaust valves

II. Objectives:

a. Maximize Volumetric Efficiency

b. Minimize Pumping Losses

c. Maximize Residual Gas Fraction

d. Minimize BSFC

III. Cases:

a. 2200 RPM

b. 1800 RPM

c. 1200 RPM

d. 800 RPM

By the independent control of valves, the valve timing can be adjusted such that the exhaust gases are kept inside the cylinder for a longer duration of time. This reduces NOx but decreases volumetric efficiency which in turn affects the brake efficiency. So a perfect trade-off must be maintained such that an intermediate value is determined by altering the valve timings. A-F ratio was constrained to have an ideal trade-off.

14. RESULTS

	1	2	3	4
Brake Power [kW]	195.8	179.2	125.8	55.3
Brake Power [HP]	262.5	240.4	168.7	74.2
Brake Torque [N-m]	849.7	950.9	1000.9	660.5
IMEP [bar]	16.34	17.91	18.43	12.34
FMEP [bar]	1.94	1.79	1.46	1.14
PMEP [bar]	-1.27	-0.67	0.21	0.20
Air Flow Rate [kg/h]	802.6	719.2	534.7	260.5
BSAC [g/kW-h]	4100	4012	4251	4707
Fuel Flow Rate [kg/h]	52.2	43.3	28.2	12.1
BSFC [g/kW-h]	266.7	241.6	224.5	218.2
Volumetric Efficiency [%]	141.6	155.0	172.9	126.3
Volumetric Efficiency (M) [%]	70.8	78.2	85.8	86.2
Trapping Ratio	1.000	0.999	1.000	1.000
A/F Ratio	15.37	16.61	18.94	21.57
Brake Efficiency [%]	31.4	34.7	37.3	38.4

Table - 16: Engine Performance (NON - VVT)

	1	2	3	4
Brake Power [kW]	196.8	179.2	125.7	55.3
Brake Power [HP]	263.9	240.4	168.6	74.1
Brake Torque [N-m]	854.3	950.8	1000.5	659.5
IMEP [bar]	16.50	17.94	18.43	12.32
FMEP [bar]	2.01	1.82	1.47	1.14
PMEP [bar]	-0.89	-0.23	0.56	0.30
Air Flow Rate [kg/h]	919.1	768.7	537.3	253.9
BSAC [g/kW-h]	4670	4289	4274	4596
Fuel Flow Rate [kg/h]	48.9	41.4	27.7	12.1
BSFC [g/kW-h]	248.4	230.8	220.4	218.9
Volumetric Efficiency [%]	162.1	165.7	173.8	123.2
Volumetric Efficiency (M) [%]	79.7	84.1	85.7	85.0
Trapping Ratio	1.000	0.999	1.000	0.999
A/F Ratio	18.80	18.59	19.39	21.00
Brake Efficiency [%]	33.7	36.3	38.0	38.3

Table - 17: Engine Performance (RGF VVT)

The control over the timing of the closing of exhaust valves increased the total trapped mass and burned residual gas percentage in the engine cylinder after the end of a cycle. This allowed in a decrease of NOx emissions.

VARIABLE	2200 RPM	1800 RPM	1200 RPM	800 RPM
Inlet Crank Timing Angle	358.54828	354.06567	357.24036	360.84772
Outlet Crank Timing Angle	170.13966	170.01965	170.09232	170.12965
Angle Multiplier for Inlet	1.0765269	1.0417707	1.0783402	1.042012
Angle Multiplier for Exhaust	0.9012413	0.90279853	0.9003899	0.9009436
Lift Multiplier for Inlet	1.1036676	1.1781933	0.97360855	0.91504544
Lift Multiplier for Exhaust	0.9154268	0.9050106	0.9211583	0.9194507

Table - 18: Optimized Initial Values of Dependent Variables

Comparing the mass flow rate curve with Non-VVT depicts that by optimizing the valve timing and constraining the A-F ratio, we can limit the exhaust air leaving the cylinder hence increasing the residual gases inside the cylinder

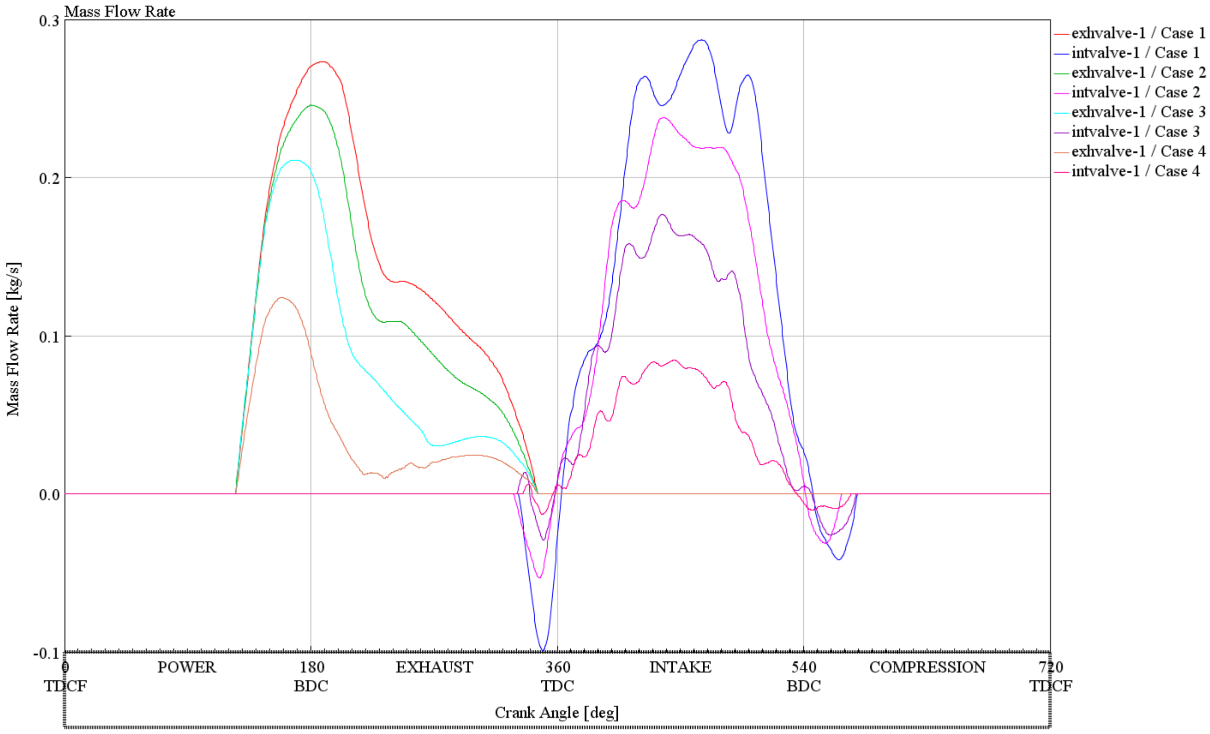

Chart - 16: Mass FR vs Crank Angle

Mass Flow Rate (Exhaust – Non VVT) :	0.15 kg/s
Mass Flow Rate (Exhaust –VVT - RGF) :	0.11 kg/s

Table - 19: Mass Flow Rate Comparison of Exhaust Valve at 800 RPM

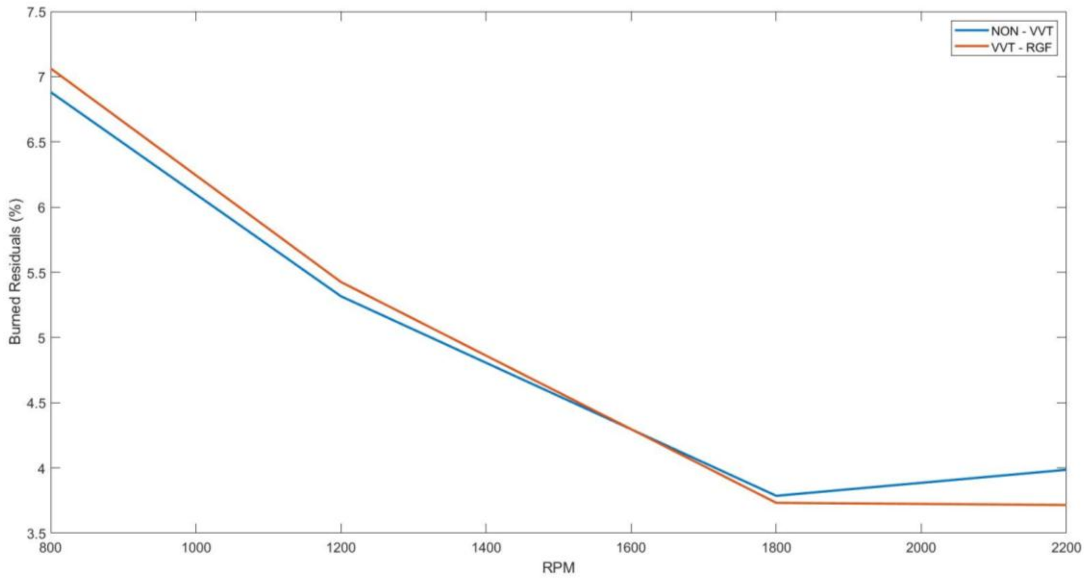

Chart - 17: Burned Residuals vs RPM

The higher trapped mass or burned residuals gas % the more reduction in the NOx emission in the cycle.

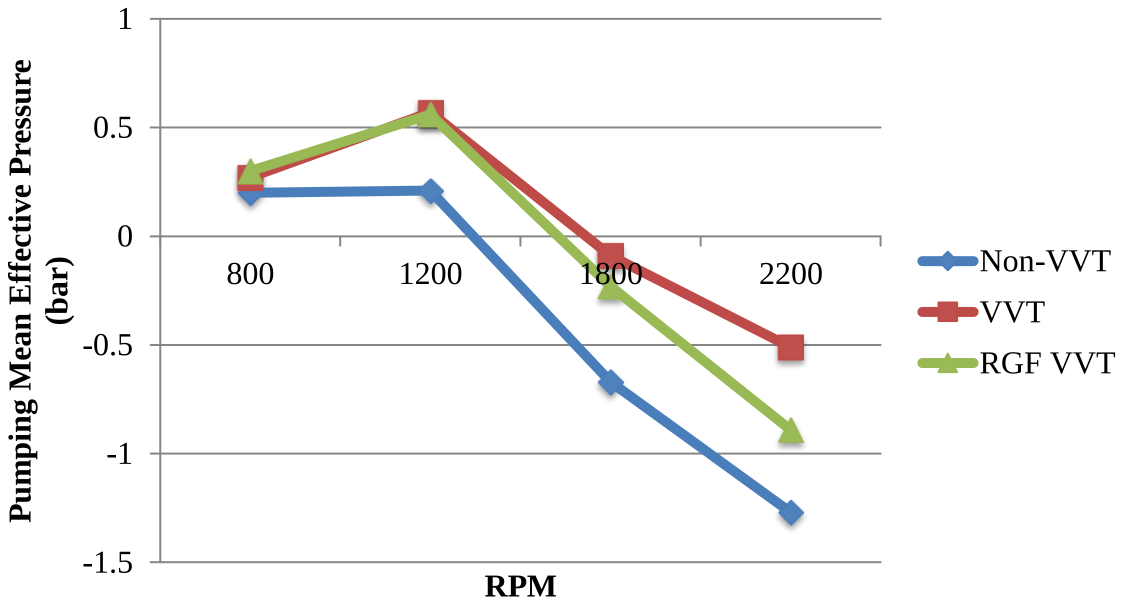

Chart - 18: PMEP (bar) vs RPM

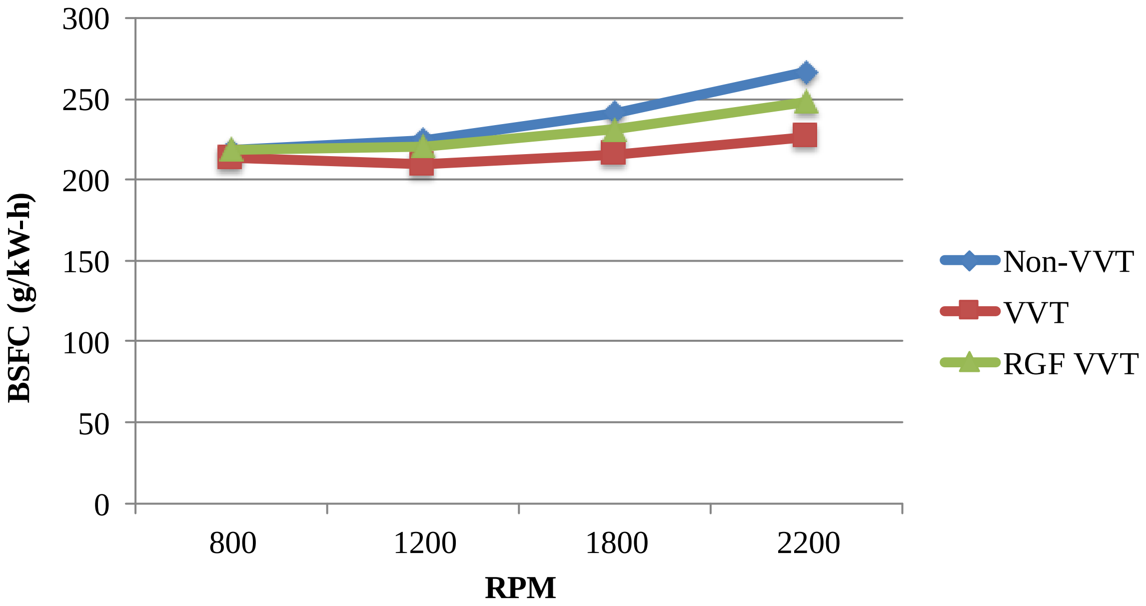

Chart - 19: BSFC (g/kW-h) vs RPM

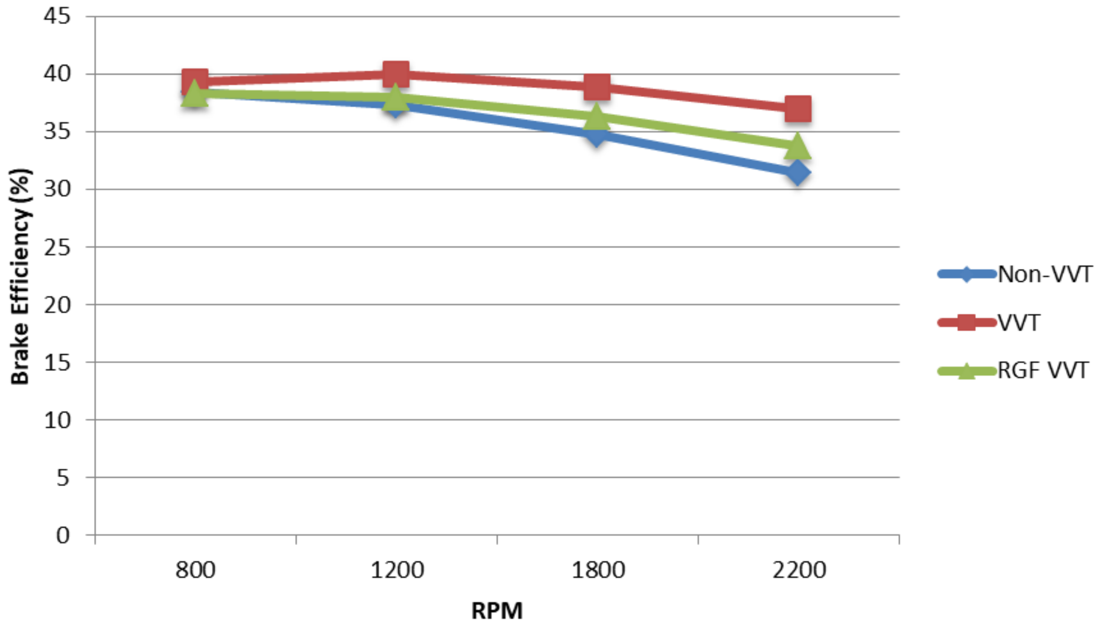

Chart - 20: Brake efficiency (%) vs RPM

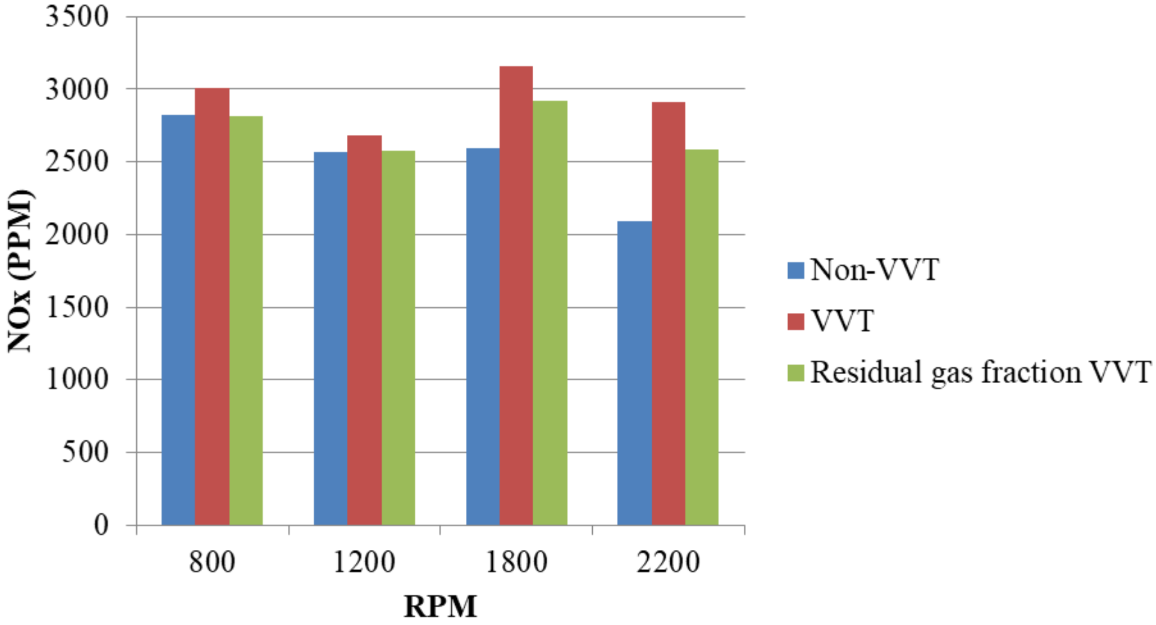

Chart - 21: NOx (PPM) vs RPM

RPM	NOx (Non-VVT)	NOx (RGF VVT)
2200	2093	2584
1800	2595	2918
1200	2566	2581
800	2820	2811

Table - 20: NOx emissions in ppm

RPM	2200	1800	1200	800
IVC	-141	-152	-142	-146
EVO	125	125	125	125
IVO	332	328	330	335
EVC	346	346	346	346

Table - 21: Change in Valve Timings

15. CONCLUSIONS

1. A perfect tradeoff between BSFC and Residual Gas Fraction was obtained such that the required brake power was produced by significant low emissions.
2. By the trend shown in valve timing, it clearly shows that the exhaust valve is opened for a short duration of time which resulted in trapping of exhaust gas inside the engine cylinder.

NON – VVT Exhaust Open Duration = 245 Degrees
VVT – RGF Exhaust Open Duration = 221 Degrees

3. The percentage change in the performance criteria for different RPM is as follows:

	800 RPM		1200 RPM		1800 RPM		2200 RPM	
Pumping losses (bar)	↓ by 0.07 bar	↓ by 0.1 bar	↓ by 0.36 bar	↓ by 0.35 bar	↓ by 0.58 bar	↓ by 0.44 bar	↓ by 0.76 bar	↓ by 0.38 bar
BSFC (g/kW-h)	2.33% ↓	0.32% ↑	6.68% ↓	1.83% ↓	10.8% ↓	4.47% ↓	15.03% ↓	6.86% ↓
Volumetric efficiency (%)	27.14% ↑	1.39% ↓	12.47 % ↑	0.11% ↓	27.62% ↑	7.55% ↑	29.66% ↑	12.57% ↑
Brake efficiency (%)	2.34% ↑	0.26% ↓	7.23% ↑	1.87% ↑	11.81% ↑	4.61% ↑	17.83% ↑	7.32% ↑
NOx (PPM)	6.73% ↑	0.32% ↑	4.71% ↑	0.58% ↑	21.73%	12.45% ↑	39.08% ↑	23.46% ↑

Table - 22: *Engine Parameters Comparison*

Percentage change from non-VVT to VVT (blue)

Percentage change from non-VVT to VVT - RGF (pink)

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