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Oil Consumption Optimization for Heavy Duty Engine Using Design for Six Sigma

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Abstract

This research examines the critical issue of high oil consumption during Multiple Displacement System (MDS) events in brake-specific fuel consumption (BSFC) engines. Currently, the oil consumption rates are 5,000–6,000 miles per quart (MPQ) in city driving conditions and 15,000–16,000 MPQ in highway cycles. However, the city cycle performance lags that of competitive automobile manufacturers, who report much lower consumption rates of approximately 26,000 MPQ. To address this problem, this study utilizes Ricardo ringpack simulation software to precisely measure oil consumption (g/h). The main objective is to conduct Design of Experiments (DOE) using the Taguchi method, focusing on the ideal function, control factors, and noise strategy to optimize the piston ring pack and block system. The goal is to improve the design for an efficient 10,000 MPQ oil consumption rate in city cycles without negatively impacting highway cycle performance. Both testing on the engine dynamometer and thorough vehicle tests verified that the design was optimized. This project is integrated with results from some prior research in "MDS impact on oil consumption" and "Bore distortion analysis" as noise factors, hence making the approach to the issue multidimensional. The results of this study provide insights and practical solutions for improving oil efficiency under different driving conditions in heavy-duty engines.

Word count: 4,122

Keywords: High oil consumption, Multiple Displacement System (MDS), brake-specific fuel consumption (BSFC), oil consumption rates, Ricardo ringpack simulation software, oil consumption (g/h), Design of Experiments (DOE), Taguchi method, ideal function, control factors, piston ring pack, block system, city cycles, highway cycle performance, engine dynamometer testing, vehicle tests, MDS impact on oil consumption, Bore distortion analysis, noise factors, heavy-duty engines.

1. Introduction

The last of these issues is quite challenging to the optimization of oil consumption in heavy-duty engines under dynamic conditions, such as in events of the Multiple Displacement System. The research seeks to discuss the discrepancy between measured oil consumption rates

across city driving cycles, which are far behind the competitive benchmarks set by world-class automobile manufacturers. Using advanced methodologies and making use of Ricardo ringpack simulation software, supplemented with a DOE approach founded upon the Taguchi method, seeks to unmistakably unravel the intricate interplay between piston ring pack dynamics and block system configurations and set targets for improvement. Built on these advanced methodologies, this research shall enhance the efficiency of oil consumption without compromising highway cycle performance and redefine benchmarks in city cycle performance. A stringent analytical framework underpins this study, fusing past insights into MDS impacts and bore distortion phenomena as two pivotal noise factors. This comprehensive investigation aims to add a different perspective to the nagging discourse on oil consumption efficiency and environmental sustainability in heavy-duty engine design.

2. Literature Review

Wang [1] applied the DFSS methodology to optimize intake and exhaust systems of heavy-duty diesel engines. This research showed that the application of DFSS effectively improved design robustness and minimized fuel consumption with special attention on some engine design variables related to turbocharger size and EGR efficiency. Jiao Li-wei [2] did an assessment of the consumption characteristics of the lube oil in heavy-duty diesel engines and established that the quantity of the lubricating oil consumed by the individual cylinders was very different. Oil consumption drastically increases when an engine operates above 75% of its full load, thus indicating there exists an optimization space in the design of the engines to avoid inefficiencies. Xu et al. [3] applied a multi-objective optimization technique in the combustion process of heavy-duty diesel engines for low-temperature combustion over an extremely broad range of loads. Their study showed how intake valve timing, start of injection timing, and EGR rate should be optimized to minimize simultaneously fuel consumption and emissions. Tormos et al. [4] assessed the benefits of low viscosity engine oils in friction and fuel consumption reduction under heavy-duty applications. Their findings indicated that LVEOs can drastically enhance fuel efficiency, particularly at urban driving conditions, since the rapid and efficient lubrication of the engine reduces friction. Zhao et al. [5] addressed real-time energy management in diesel-heavy duty hybrid electric vehicles by proposing a fuzzy-tuned equivalent consumption minimization strategy. The results had huge improvements in fuel economy through proper control of these hybrid systems, which is very instrumental in saving the total fuel consumption. Zhang et al. [6] focused on the problem of optimizing piston rings with a view to reducing oil consumption in diesel engines. During the analysis of the mechanism of oil consumption, using neural network predicting models helps in finding out many meaningful factors for decreasing oil consumption by better designing of piston rings.

Desantes et al. [7] examined the use of ANNs together with multi-objective optimization tools in the case of heavy-duty diesel engines at stationary operating conditions. Their study emphasizes the complications of reducing an engine's emission without either decreasing or at least keeping fuel consumption at a constant level using ANN models and optimizing the setting of an engine to comply with strict emission regulations. Shi and Reitz [8] performed an optimization study in 2008 on the effects of bowl geometry, spray targeting, and swirl ratio in a heavy-duty diesel engine operating at low and high loads. It has been noted that piston geometry should appropriately correspond to the characteristics of spray plumes for good fuel economy and low emissions in both low and high load conditions. Benajes et al. [9] combined a genetic algorithm with CFD to optimize the combustion system of a heavy-duty diesel engine operating on dimethyl ether. This investigation resulted in an optimum system that showed improved net indicated efficiency and significantly reduced NOx emission, which has already proven the potential for DME to become a sustainable fuel for heavy-duty applications. Sakthivel et al. [10] used the response surface methodology to predict and model the performance and emission characteristics of a diesel engine running with waste biomass pyrolysis oil. The results indicated that at optimal engine settings, there was increased break thermal efficiency with reduced emissions, thus proving applicability in diesel engines. Gao et al. [11] evaluated the energy flow in a turbocharged diesel engine and potential fuel economy and reductions in emissions. The research focused on correct thermal management and proper functioning of turbocharger performance for overall efficiency improvement, specifically at high-power-output operating conditions. Hiroyasu et al. [12] suggested a MOGA in company with phenomenological model-based optimization for heavy-duty diesel engine optimization. Pareto optimal solutions are identified, which balance reductions of specific fuel consumption and NOx and soot emissions in a very successful way, underpinning the efficacy of MOGAs in engine design optimization. In the case of Rayate's study [13], statistical optimization has improved the scuff resistance in the piston pin bores, which is an important factor in maintaining the efficiency and durability of the engine. This approach goes hand in hand with the optimization of oil consumption in heavy-duty engines through reliable component performance under operational stresses.

3. Approach

3.1 Function Description

The piston in an engine is essential for controlling oil consumption because it creates a tight seal within the cylinder and prevents excessive oil from entering the combustion chamber. To achieve this, piston rings, particularly oil control rings, play a crucial role in scraping and regulating oil on the cylinder walls. This ensures that the piston moves smoothly while minimizing the amount of oil burned during combustion, thereby maintaining sufficient lubrication.

For the engine, it is an important component in the running of the combustion chamber. Thus, this portion—known as the engine ring pack—accumulates three very different functions: sealing combustion chambers, managing oil consumption, and reducing friction [14]. It is a set of rings placed in the grooves of a piston's outer diameter. Normally, there are two types of rings in a ring pack: compression rings and oil rings. The compression rings sealed the combustion gases within the chamber for producing maximum power. In return, oil rings regulate the amount of oil existing on cylinder walls, hence preventing the excess of oil from entering into the combustion chamber and ensuring cylinders are well lubricated. For this engine, there exist two compression rings: an upper and a lower ring and one oil ring.

The cylinder in an engine is a critical component that plays a significant role in oil consumption. This provides a surface against which the piston and piston rings move, and the condition and smoothness of the cylinder walls are vital for maintaining an effective seal and controlling the oil film [15]. A well-maintained cylinder surface helps prevent excessive oil from bypassing the piston rings and burning in the combustion chamber, thereby optimizing oil consumption, and ensuring efficient operation of the engine. A proper cylinder function is essential for minimizing the oil consumption while maximizing the performance and longevity.

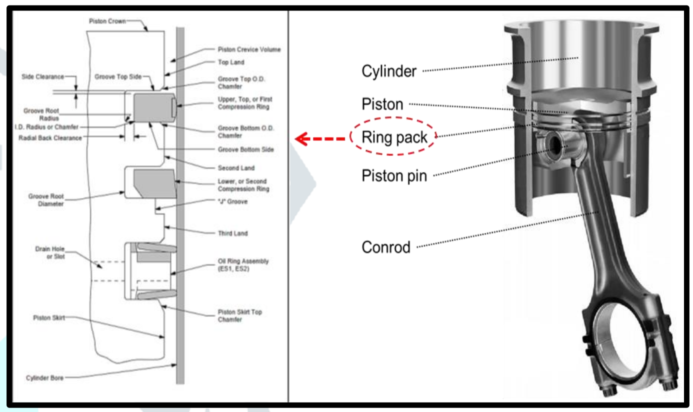

Figure 1: Piston Ringpack & Block System

3.2 Ideal Function

Metered lubrication of the cylinder bore is one of the functions of the piston, ringpack & block system. The symptoms of these systems can be oil consumption, friction, and emissions. As the goal was to optimize the oil consumption that was chosen as the ideal function. Its non-dynamic ideal function, smaller oil consumption the better.

System	Function	Symptoms	Input	Output Response	Response Type
Piston Ring Pack / Block System	Metered Lubrication to the Cylinder Bore	Oil Consumption, Friction, wear, emissions	M: Fy In Con Rod	y1: Fy Out Piston	Dynamic
		Friction, wear, emissions	NA	y2: Film Thickness	Non-Dynamic (NTB)
			NA	y3: Fit Dim Pstn/Cyl Actual / Fit Dim Pstn/Cyl Desired	Non-Dynamic (NTB)
			NA	y4: Friction	Non-Dynamic (STB)

			NA	y5: Temp	Non-Dynamic (NTB)
			NA	y6: Oil Consumption	Non-Dynamic (STB)

Table 1: Ideal Function

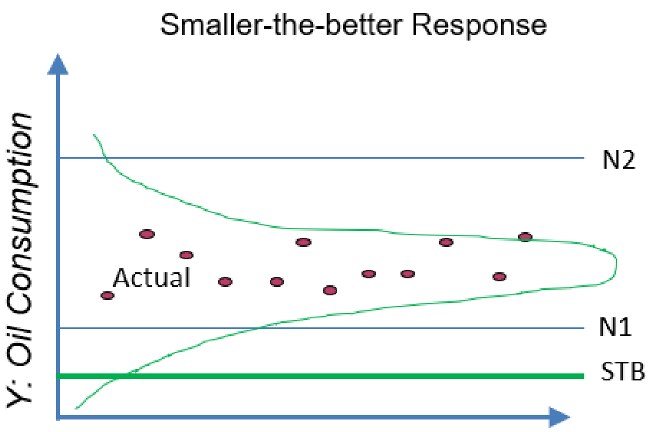

Figure 2: STB Graph for Oil Consumption

3.3 Factor Analysis

Factor analysis is a statistical technique commonly applied in Design for Six Sigma (DFSS) to examine the relationships between multiple factors that influence the outcomes of a process or product design. It is a useful tool for distilling a large set of variables into a smaller set of underlying factors by grouping variables that exhibit a strong correlation with one another [16]. In our study, we utilized factor analysis to identify the key design factors that can affect oil consumption in piston, ringpack, and block systems. initially listed around thirty-one characteristics that could potentially influence oil consumption, but conducting experiments for all these characteristics would have been impractical and would have resulted in a very large design of experiments (DOE) that would have been difficult to execute. Therefore, as a team, we focused on the top eight characteristics that could be realistically studied, with three design levels that were deemed manufacturable.

	Factor Analysis							
	Factor Name (Brief Nickname)	Definition	Influence	Factor Type	Level 1	Level 2	Level 3	Notes / Comments (why not including factor)
1	UCR : OD Profile	Upper Compression Ring	---	Control	Sym BF	Asym BF		
2	UCR Twist (Profile)	Upper Compression Ring	---	Control	Twist # 1 (Even)	No Twist		Current design - Twist # 1. Limited by simulation software
3	UCR : Axial Height	Upper Compression Ring	---	Control	1	1.2	1.5	Not significant based on "Hercules" based design
4	UCR : Radial Thickness	Upper Compression Ring	---	Control	3.1	3.5 (BGE/Ford)	4	Run confirmation/benchmarking study to keep or remove factor
5	UCR: Gap	Upper Compression Ring	---	Control	0.25	0.37	0.47	No improvement seen in sensitivity study
6	UCR : Tension	Upper Compression Ring	---	Control	4.2 (5.7L)	8.3 (BGE)	10.9	Analyze friction in addition to oil consumption
7	LCR Twist (Profile)	Lower Compression Ring	---	Control	Neutral-cast	Positive Twist-steel		Limited by simulation software
8	LCR : Axial Height	Lower Compression Ring	---	Control	1	1.2	1.5 (Ford)	Run confirmation/benchmarking study to keep or remove factor
9	LCR : Radial Thickness	Lower Compression Ring	---	Control	4.15 (BGE)	4.37 (Ford)	4.60	Manufacturing range 3.7 – 4.7 mm BGE – Min 4, Max 4.3 Ford – Min 4.15, Max 4.44
10	LCR Ring : Gap	Lower Compression Ring	---	Control	0.375	0.6		Initial sensitivity study did not show improvement

Table 2: Factor Analysis Design Factors

	Factor Analysis							
	Factor Name (Brief Nickname)	Definition	Influence	Factor Type	Level 1	Level 2	Level 3	Notes / Comments (why not including factor)
11	UCR & LCR: Gap Ratio	Upper & lower compression ring gap Ratio	---	Control	0.8 (5.7L)	1.11 (Ford)	1.62 (BGE)	Second ring gap did not show significant improvement
12	LCR: Tension	Lower Compression Ring	---	Control	8.1 (BGE)	10.6	14.25 (Ford)	BGE – Min 5.65, Max 10.55 Ford – Min 11.4, Max 17.1
13	Oil Rail : OD profile (Actual profile)	NA	---	Control	Reg Barrel (BGE)	High Barrel	Taper face	
14	Oil Rail : Rail size h1 x a1	NA	---	Control	2 x 0.4	1.9 x 0.4		Limited by manufacturing and assembly
15	Oil Ring : Gap	NA	---	Control	0.3 (BGE)	0.4 (Ford/5.7L)		BGE – Min 0.15, Max 0.45 Ford – Min 0.15, Max 0.65
16	Oil Ring : Tension	NA	---	Control	32	35	40	No improvement seen in sensitivity study
17	Oil Expander : Tab Angle	NA	---	Control	10 (BGE)	15	20 (Ford)	
18	Piston Land & Profile	NA	---	Control	Current BGE	New BGE	Ford	Piston design includes changes to land designs, profile and ring groove
19	Cylinder Bore Distortion	NA	---	Control	BGE with (Deck plate)	BGE (Non deck plate)		
20	Cylinder Bore Surface Profile	NA	---	Control	5.7L/BGE	Apache		

Table 3: Factor Analysis Design Factors

	Factor Analysis							
	Factor Name (Brief Nickname)	Definition	Influence	Factor Type	Level 1	Level 2	Level 3	Notes / Comments (why not including factor)
21	Number of piston drain holes	NA		Control	4	6	8	Run confirmation/benchmarking study to keep or remove factor
22	Size of the piston drain holes	NA		Control	2	2.5	3	Run confirmation/benchmarking study to keep or remove factor
23	Location of the drain holes	NA		Control	Ford	BGE	5.7L	Analyzed via bore distortion
24	Counterbore depth (Head bolt position)	NA		Control	35.6	37.3		Analyzed via bore distortion
25	Head bolt load – M12	NA		Control	55.2kN	59.2kN	69.2kN	Analyzed via bore distortion
26	Head bolt load – M8	NA		Control	13.7kN	18.7kN	23.7kN	Analyzed via bore distortion
27	Deckface Thickness (For water jackets)	NA		Control		10.8	12.9	Analyzed via bore distortion
28	Siamese Width (Refer backup slide)	NA		Control		45.8	53.2	Analyzed via bore distortion
29	End cylinders rib width (Refer backup slide)	NA		Control	26	28.2		Analyzed via bore distortion
30	Head Gasket	NA		Control	Apache	BGE	5.7L	Analyzed via bore distortion
31	Piston to bore clearance	NA		Control		0.055 mm		Not possible to simulate this with Ringpak software. Important for high speed-load condition

Table 4: Factor Analysis Design Factors

The Drawing from our previous work on identifying the root cause of high oil consumption, we discovered that MDS cylinder activation and deactivation had a substantial influence on oil consumption. MDS mode changes the engine operation from V8 mode, where all cylinders are fired, to V4 mode, where only half of the engine is fired, and the other half is not. During our investigation, we found that two specific speed load points, 2100 rpm/158 lb-ft and 1500 rpm/44.25 lb-ft, were high oil consumption areas on the engine running map. As a result, the mode of operation in the MDS and the speed-load points were deemed noise factors. To ensure that our solution to improve oil consumption at low-speed load levels did not worsen the situation at high-speed and high-load levels, we used another speed level of 5600 rpm/384.5 lb-ft.

	Factor Analysis							
	Factor Name (Brief Nickname)	Definition	Influence	Factor Type	Level 1	Level 2	Level 3	Notes / Comments
34	Engine Speed-Torque	Engine crankshaft rotations (RPM) & Torque	Lower speed-torque causes higher oil consumption	Noise	2100 rpm 138 lb-ft	1500 rpm 44.25 lb-ft	5600 rpm 384.5 lb-ft	
35	Engine Mode	Combustion Mode	V4 mode increases oil consumption.	Noise	V4 Mode	V8 Mode		Simulate 1 cylinder bore for each level

Table 5: Factor Analysis Noise Factors

Ricardo Ringpack simulation software was used to precisely determine the estimated oil consumption in these specific circumstances. This advanced software offers a comprehensive analysis of the ring dynamics and precise oil consumption prediction. The necessary input for the cylinder pressure and temperature predictions is derived from one-dimensional simulations.

3.4 Noise Strategy

A modified compound strategy will be use to focus on V4 mode conditions (N1) and (N2), and V8 mode conditions (N3) and (N4)

Noise Factor Levels for N			
Noise Factor	**Level**		
Engine Speed-Torque (S)	2100 rpm 138 lb-ft	1500 rpm 44.25 lb-ft	5600 rpm 384.5 lb-ft
Engine Mode (L)	V4 Mode		V8 Mode

Table 6: Noise Strategy

N1: V4, 2100rpm, 138 lbft

N2: V4, 1500rpm, 44.25 lbft

N3: V4, 2100rpm, 138 lbft

N4: V8, 5600rpm, 384.5 lbft

3.5 Data Collection Plan

A Taguchi L18 array is established to incorporate various design and noise factors. It is important to note that the CAE tool was utilized in this study. The primary objective of this study is to predict oil consumption and present the findings in a clear and concise manner.

									A	B	C	D	E	F	G	H	N1	N2	N3	N4
	A	B	C	D	E	F	G	H	UCR : OD Profile	UCR : Tension	LCR : Radial Thickness	LCR: Tension	Oil Rail : OD profile	Oil Expander : Tab Angle	Piston Land & Profile	Cylinder Bore Distortion	2100 rpm 138 lb-ft V4 Mode	1500 rpm 44.25 lb-ft V4 Mode	2100 rpm 138 lb-ft V8 Mode	5600 rpm 384.5 lb-ft V8 Mode
1	1	1	1	1	1	1	1	1	Sym BF	4.2	4.15	8.1	Reg Barrel	10	KS	BGE Deck Plate				
2	1	1	2	2	2	2	2	2	Sym BF	4.2	4.37	10.6	High Barrel	15	KS New	BGE Non-Deck Plate				
3	1	1	3	3	3	3	3	3	Sym BF	4.2	4.6	14.25	Taper Face	20	Ford	BGE Deck Plate				
4	1	2	1	1	2	2	3	3	Sym BF	8.3	4.15	8.1	High Barrel	15	Ford	BGE Deck Plate				
5	1	2	2	2	3	3	1	1	Sym BF	8.3	4.37	10.6	Taper Face	20	KS	BGE Deck Plate				
6	1	2	3	3	1	1	2	2	Sym BF	8.3	4.6	14.25	Reg Barrel	10	KS New	BGE Non-Deck Plate				
7	1	3	1	2	1	3	2	3	Sym BF	10.9	4.15	10.6	Reg Barrel	20	KS New	BGE Deck Plate				
8	1	3	2	3	2	1	3	1	Sym BF	10.9	4.37	14.25	High Barrel	10	Ford	BGE Deck Plate				
9	1	3	3	1	3	2	1	2	Sym BF	10.9	4.6	8.1	Taper Face	15	KS	BGE Non-Deck Plate				
10	2	1	1	3	3	2	2	1	Asym BF	4.2	4.15	14.25	Taper Face	15	KS New	BGE Deck Plate				
11	2	1	2	1	1	3	3	2	Asym BF	4.2	4.37	8.1	Reg Barrel	20	Ford	BGE Non-Deck Plate				
12	2	1	3	2	2	1	1	3	Asym BF	4.2	4.6	10.6	High Barrel	10	KS	BGE Deck Plate				
13	2	2	1	2	3	1	3	2	Asym BF	8.3	4.15	10.6	Taper Face	10	Ford	BGE Non-Deck Plate				
14	2	2	2	3	1	2	1	3	Asym BF	8.3	4.37	14.25	Reg Barrel	15	KS	BGE Deck Plate				
15	2	2	3	1	2	3	2	1	Asym BF	8.3	4.6	8.1	High Barrel	20	KS New	BGE Deck Plate				
16	2	3	1	3	2	3	1	2	Asym BF	10.9	4.15	14.25	High Barrel	20	KS	BGE Non-Deck Plate				
17	2	3	2	1	3	1	2	3	Asym BF	10.9	4.37	8.1	Taper Face	10	KS New	BGE Deck Plate				
18	2	3	3	2	1	2	3	1	Asym BF	10.9	4.6	10.6	Reg Barrel	15	Ford	BGE Deck Plate				

Table 7: Data Collection Plan

3.6 Data Analysis Non-Dynamic (STB) – Oil Consumption

The analysis revealed that Experiment #3 demonstrated exceptional performance with an S/N ratio of -6.14, significantly influenced by Level 3 control factors, which significantly enhanced the S/N ratio. The adjustments made to factors E, F, G, and H in this experiment contribute significantly more to its success than the other variables. Conversely, Experiment #6 underperformed, with the lowest S/N ratio of -14.75. The selection of different levels for factors B, E, F, G, and H in this case appears to detrimentally affect the outcome, in contrast to the configurations that led to the optimal results in Experiment #3.

	A	B	C	D	E	F	G	H	N1	N2	N3	N4	Mean	S/N
1.	1	1	1	1	1	1	1	1	7.728	1.468	1.354	4.026	3.64	-13.01
2.	1	1	2	2	2	2	2	2	5.296	1.418	1.596	3.229	2.88	-10.32
3.	1	1	3	3	3	3	3	3	1.732	1.446	1.309	3.104	1.90	-6.14
4.	1	2	1	1	2	2	3	3	9.259	1.477	2.933	3.189	4.21	-14.26
5.	1	2	2	2	3	3	1	1	1.717	1.435	1.346	3.178	1.92	-6.26
6.	1	2	3	3	1	1	2	2	10.03	1.408	2.185	3.466	4.27	-14.75
7.	1	3	1	2	1	3	2	3	1.68	1.353	2.199	3.265	2.12	-7.02
8.	1	3	2	3	2	1	3	1	1.889	1.453	1.377	3.176	1.97	-6.45
9.	1	3	3	1	3	2	1	2	1.731	1.462	1.604	3.174	1.99	-6.48
10.	2	1	1	3	3	2	2	1	1.654	1.367	1.671	3.137	1.96	-6.34
11.	2	1	2	1	1	3	3	2	6.48	1.443	2.405	3.747	3.52	-12.03
12.	2	1	3	2	2	1	1	3	4.3	1.466	1.397	3.292	2.61	-9.22
13.	2	2	1	2	3	1	3	2	2.67	1.487	1.584	3.105	2.21	-7.30
14.	2	2	2	3	1	2	1	3	1.856	1.451	1.509	3.848	2.17	-7.53
15.	2	2	3	1	2	3	2	1	3.496	1.371	1.831	3.248	2.49	-8.45
16.	2	3	1	3	2	3	1	2	1.768	1.446	1.641	3.284	2.03	-6.70
17.	2	3	2	1	3	1	2	3	1.705	1.428	3.555	3.14	2.46	-8.36
18.	2	3	3	2	1	2	3	1	2.35	3.775	3.589	3.75	3.37	-10.67

Table 8: Oil Consumption & S/N Prediction

3.7 Noise Separation

The separation between the V4 mode conditions N1 and N2 was pronounced, with N1 yielding higher and variable results across various control factors. A noticeable distinction exists between the N1 conditions and the remaining conditions N2, N3, and N4. As anticipated, the N1 condition demonstrates the cause of concern in terms of oil consumption performance, and the baseline control factors have not been optimized for this condition. The N1 condition represents a developmental stage that has not yet been optimized for oil consumption. The experimental factors contributing to the outliers are the symmetric barrel face top ring, lower second ring tension, lower tab angle, regular barrel face oil rail, and non-deck plate block. Many of these factors are currently in use, and the increased oil consumption for certain combinations appears to be logical. Conditions N2/N3 exhibited the best performance, with both the baseline and various control levels already optimized for this condition. The L6 run under the N1 condition revealed elevated oil consumption. This run included numerous baseline control factors, indicating that the baseline design was not optimized for this specific condition.

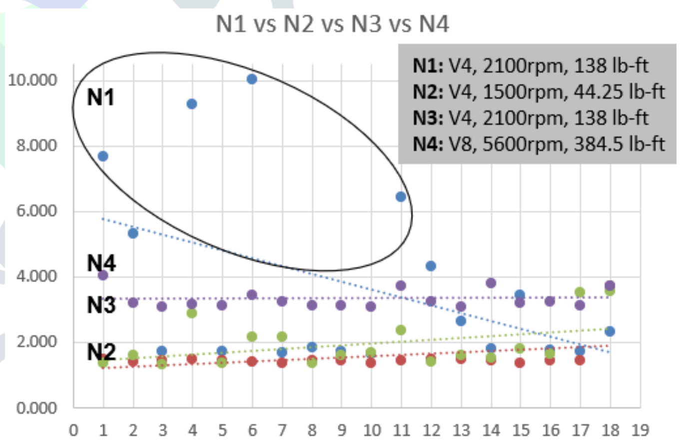

Figure 3: Noise Separation Graph

Figure 4: Best Vs. Worst Run

3.8 Response Plots & Selecting Optimal Design Factors

Selecting Optimal Design Factors

Factor A: Optimal Design Profile
The Asym Barrel Face (A2) profile was selected for its overall better performance compared that with of the Symmetric Barrel Face. The Asym Barrel Face demonstrated superior results in the V4 mode, whereas the Symmetric Barrel Face was found to be more effective in the V8 mode.

Factor B: Top Ring Tension
B3 was chosen as the optimal option for top-ring tension. In general, a higher top-ring tension was found to be better for reducing oil consumption. Analyzing both the V4 and V8 modes, it was observed that higher tension performed well in the V4 mode, while lower tension was more suitable for the V8 mode.

Factor C: Second Ring Radial Thickness
The C2 option was selected for the second ring radial thickness, although its impact was deemed relatively small.

Factor D: Second Ring Tension
D3 was chosen as the optimal option for second-ring tension. It was found that a higher tension had a significant impact, with the second ring tension performing better in both the V4 and V8 modes.

Factor E: Oil Rail Profile
A tapered face oil rail design (E3) was selected as the optimal option. This design was found to be more effective than both high- and regular-barrel designs, performing well in both V4 and V8 modes.

Factor F: Oil Expander Tab Angle
F3 was selected as the optimal option for the oil expander tab angle. It was determined that a higher tab angle was more advantageous, with this option performing better in both the V4 and V8 modes.

Factor G: Piston Land and Ring Groove
The current design (G1) was selected as the optimal option for the piston land and ring groove. This design was found to be the best in both the V4 and V8 modes.

Factor H: Bore Distortion
Deck-plate bore distortion (H1) was selected as the optimal option for bore distortion. The deck plate performed well in V4 mode, whereas the non-deck plate option was more suitable for V8 mode.

V4, V8 MODE & WOT (V8 MODE)

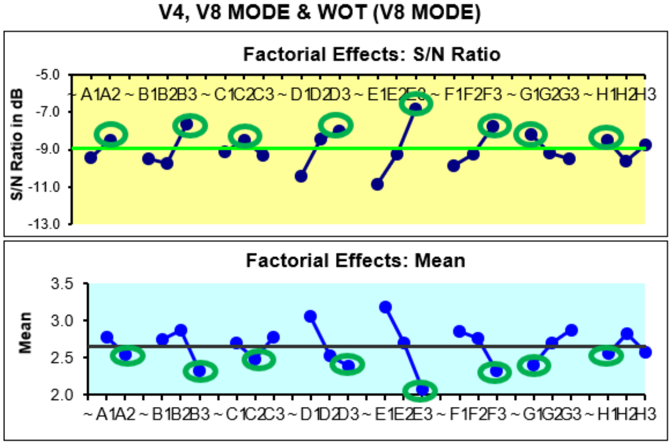

Figure 5 : V4, V8 Mode Response Plot

V4 MODE

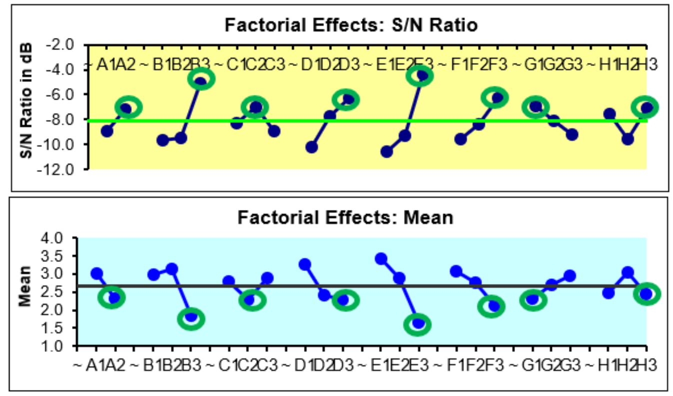

Figure 6 : V4 Mode Response Plot

3.9 Prediction & Confirmation

The control factors oil rail profile, LCR, UCR tension, and oil expander angle are critical in the design process and have resulted in a substantial improvement in the signal-to-noise ratio from the initial design to the optimal design.

	Control Factor	Initial Level	Optimal Level	S/N Gain	Rank	Mean Gain	Rank	Reason for Level Selection
A	UCR OD Profile	Sym BF	Asym BF	0.9	6	0.23	8	Maximize S/N
B	UCR Tension	8.3	10.9	2.14	3	0.55	3	Maximize S/N
C	LCR : Radial Thickness	4.15	4.37	0.61	7	0.21	6	Maximize S/N
D	LCR: Tension	8.1	14.25	2.45	2	0.67	2	Maximize S/N
E	Oil Rail : OD profile	Reg Barrel	Taper Face	4.02	1	1.11	1	Maximize S/N
F	Oil Expander : Tab Angle	10	20	2.08	4	0.53	4	Maximize S/N
G	Piston Land & Profile	KS	KS	0	8	0.47	5	Maximize S/N
H	Cylinder Bore Distortion	Non-Deck Plate	Non-Deck Plate	1.06	5	0.26	7	Maximize S/N

Table 9: S/N Gain Control Factors

The optimization process resulted in a significant improvement in both prediction and confirmation, with 57% and 73% increases, respectively. This indicates that the designed model is reliable and effective. The S/N response table also demonstrated a substantial 73% gain and 99.7% confirmation, further supporting the reliability of the designed model.

Example		Predicted S/N	Confirmed S/N	Predicted Mean	Confirmed Mean
A2, B3, C2, D3, E3, F3, G1, H2	Optimal Design	-6.29	-6.27	2.8	1.92
A1, B2, C1, D1, E1, F1, G1, H2	Initial Design	-14.48	-23.24	2.39	10.49
	Gain	8.19	16.97	0.41	-8.57
	% Gain	57%	73%	17%	82%
	% Confirmation		99.7%		68.6%

Table 10: Prediction & Confirmation Summary

3.10 Verification Plan

The subsequent stage in the process involved verifying the validity of the design through practical field testing. The optimized design was subsequently installed on the engine, and the engine was operated on a vehicle under city cycle conditions for 10,000 miles to assess the MPQ performance. The optimized solution performed exceptionally well, achieving an oil consumption rate of 9563 MPQ after 10,000 mi.

This performance is nearly 50% higher than that of a vehicle equipped with an initial or baseline design.

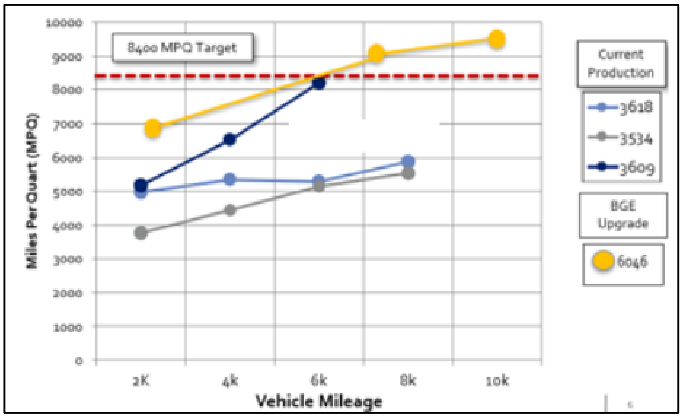

Figure 7: City Cycle Oil Consumption Performance

4. Implementation Plan

An addition to the part design guide document updated the design factors that had been identified as major oil consumption drivers so that it could be a good reference for future programs and help implement reduced designs. One of the key points for the future program is an optimized design feature that shall already be taken into operation under an engine upgrade plan scheduled in the near future.

5. Conclusions

The paper has shown a significant amount of improvement in oil consumption rates for heavy-duty engines through efficient Design for Six Sigma methodologies. This paper optimizes the piston ring pack and block system, along with a comprehensive design of experiments to observe improvements in oil consumption, especially during city driving cycles. Clearly, the findings enhance the understanding of the factors that influence oil consumption and hence open scope for more fuel-efficient and environment-friendly designs of engines. This study lays the groundwork for further technological advances in engines by providing a roadmap to achieve peak performance but considering its critical problem of oil consumption.

6. Future Work

This will form the basis of future work when this solution is implemented in new programs and its overall durability, scuff, and other performance cycles of importance to engine durability are validated. Friction is not included within the scope of this project; therefore, CAE ring friction analysis and dyno friction equivalency for this optimized design will be an area of future work. This should be done to ensure that oil consumption improvements aren't made at the expense of engine friction.

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Definitions/Abbreviations

Multiple Displacement System (MDS): A technology in engines that allows the deactivation of half of the cylinders to improve fuel efficiency.

Brake-Specific Fuel Consumption (BSFC): A measure of the fuel efficiency of an engine design.

Miles per Quart (MPQ): A metric used to measure oil consumption, indicating how many miles can be driven per quart of oil.

Ricardo ringpack simulation software: A tool used for precise measurement and prediction of oil consumption in engines.

Design of Experiments (DOE): A systematic method to determine the relationship between factors affecting a process and the output of that process.

Taguchi method: A statistical method developed by Genichi Taguchi to improve the quality of manufactured goods.

MDS impact on oil consumption: Refers to how the activation and deactivation of cylinders in MDS mode affect oil consumption.

Bore distortion analysis: The study of deformations in the cylinder bore and their impact on engine performance.

Piston ring pack: A set of rings installed on a piston, essential for sealing the combustion chamber and managing oil consumption.

Cylinder: The central working part of an engine where the piston moves.

Compression rings: Rings that seal the combustion gases within the combustion chamber.

Oil rings: Rings that manage oil on the cylinder walls to prevent excessive oil from entering the combustion chamber.

Design for Six Sigma (DFSS): A business process management method related to traditional Six Sigma. DFSS focuses on design and process development to achieve six sigma quality.

Factor analysis: A statistical technique used to identify the underlying relationships between variables.

Noise factors: Variables that cause variability in a process but are not of primary interest to the researcher.

Control factors: Variables that are controlled during an experiment to test their effects on the outcome.

Ideal function: The optimal performance characteristics of a system.

Signal-to-noise ratio (S/N): A measure used in experiments to compare the level of a desired signal to the level of background noise.

Deck-plate bore distortion: Deformation of the cylinder bore when a deck plate is used during engine assembly.

L18 array: A specific orthogonal array used in Taguchi methods for design of experiments.
Asymmetric (Asym) Barrel Face: A profile design of the piston ring with different shapes on either side.

Symmetric (Sym) Barrel Face: A profile design of the piston ring with identical shapes on both sides.

V4 mode: Engine operation mode where only half the cylinders are active.

V8 mode: Engine operation mode where all cylinders are active.

Oil Expander Tab Angle: The angle of the tabs on the oil expander ring, affecting its tension and performance.

Control Factors Oil Rail Profile, LCR, UCR Tension, and Oil Expander Angle: Key design parameters affecting oil consumption efficiency.

MPQ Performance: Measurement of miles per quart, indicating the efficiency of oil consumption.