Power System Technology
ISSN:1000-3673

Received: 06-06-2024 *Revised: 15-07-2024* *Accepted: 28-08-2024*

Root Cause Analysis of High Oil Consumption in 6.4L Heavy-Duty Engines Under Urban Driving Conditions

Vikrant Rayate,
Email: vikrant.rayate3086@gmail.com

Abstract

This paper discusses the high oil consumption in a 6.4L heavy-duty engine for urban driving cycle applications, which is currently in the range of 5,000 to 6,000 miles per quart. This is much worse than that of the highway cycles, which are nearly at 15,000–16,000 MPQ and way below the 26,000 MPQ benchmark that some competing brands have set for similar classes of engines. The research focuses on the specific identification of factors in the city driving cycle that are responsible for high oil consumption and explains these mechanisms. Its purpose is a comprehensive search for root causes that reveal problem areas, provide actionable insights, and solutions. The latter will not only improve oil efficiency but also close gaps in performance to the best in class, particularly across a myriad of challenging city-driving conditions.

Word count: 4,268

Keywords: High oil consumption, 6.4L heavy-duty engine, Urban driving, Miles per quart (MPQ), Highway cycles, Benchmark, Competing brands, City driving cycle, Increased oil consumption, Underlying mechanisms, Root cause analysis, Oil efficiency, Performance alignment, Challenging conditions.

1. Introduction

Optimizing the oil consumption in 6.4L heavy-duty engines for city cycle conditions is rated as one of the most difficult challenges on the road to engineering greatness. The objective of this paper is to solve the discrepancy in the oil consumption rates detected in city driving cycles that stay far behind benchmark performance set by competitive automobile manufacturers. The study benchmarked, did root cause analysis, and used other tools at one's disposal to find out exactly what drivers are behind high consumption of oil. It is our hope that this detailed investigation will shed some light into the ongoing discourse on oil consumption efficiency and environmental sustainability in regard to 6.4L heavy-duty engine design.

2. Literature Review

Karjalainen et al. [2] studied the formation processes of non-volatile exhaust particles during engine motoring, which appears to be dominated by lube oil consumption. Their results raise some serious environmental concerns but simultaneously point out a potential for mitigating particulate emissions and improvement in the overall efficiency of heavy-duty engines by better oil formulations. Kader et al. [3] assessed oil degradation regarding prolonged idling in heavy-duty vehicles and outlined that extended idle runs have no appreciably negative effects on oil quality, challenging perceptions about maintenance adjustments for high-idle vehicles. Kim et al. [4] examined the effects of additives in engine oils on diesel engine-emitted particulate matter. In this study, it was shown that additive formulation has huge effects on the formation of particles, showing that oil formulation is critical for mitigating environmental impact and enhancing emission characteristics. Gao et al. [5] have investigated energy distribution in turbocharged diesel engines to identify large losses in terms of energy through coolant and lubricating oil. The results of this study indicate that the potentials for improvement by optimizing thermal management systems may well offer very high benefits in improving fuel economy and reducing emissions, more so in heavy-duty applications. According to Tormos et al. [6], low viscosity engine oils gave quite considerable fuel consumption and friction reductions in heavy-duty vehicles. The study proposed that wider applications of the oils should be considered for improvement in fuel efficiency, which reduces operational cost and enhances engine performance. Macián et al. [7] assessed various low-viscosity engine oils for performance and degradation when exposed to a real-world fleet of heavy-duty vehicles. It was concluded that these said oils offer better performance with extended drain intervals, hence decreasing maintenance costs and increasing vehicle efficiency over time.

Honda and Ogano [8] studied diesel engine oils for their soot effects on friction reduction. They indicated that soot particles contribute to lowering friction in most engine oils, although they may also lead to elevated wear and oil viscosity, thus impacting engine performance and life expectancy. Padgurskas et al. [9] estimated the tribological properties of heavy-duty engine oils and found out that over some time, the acidity of the oil increases due to oxidation; thereafter, protection from surface wear is drastically reduced, particularly at high loads. The study therefore puts a premium on the need for control over oil quality as regards assuring reliability in engines. Wang et al. [10] conducted a study on how different viscosities of engine oils affected fuel consumption and the durability of engines in heavy-duty vehicles. Their results show that the use of low-viscosity oils decreases consumption while maintaining protection, so they are recommended for application to improve vehicle efficiency under real-world driving conditions. Knauder et al. [11] studied frictional losses in journal bearings for heavy-duty diesel engines. In the process, ultra-low viscosity oils could be shown to realize high friction reduction. According to the result of this study, possible frictional losses reductions of engines and fuel efficiency improvement relate to properly optimized formulation for lubricants. Tormos et al. [12] examined how a balance between lubricant and driving conditions ought to be reached to offer superior fuel economy. The results indicated that lower viscosity oils, with friction modifiers, can save much fuel; however, these are highly dependent

Power System Technology
ISSN:1000-3673

Received: 06-06-2024 *Revised: 15-07-2024* *Accepted: 28-08-2024*

upon driving conditions and vehicle design performance. Chen et al. [13] used modified sawdust as a lubricant oil filter in a diesel engine and found out its goodness in reducing wear and emissions while improving engine performance. Such filters, under these settlements, are here deduced to be an alternative solution to enhancing efficiency in an engine and bringing down environmental impacts.

3. Approach

3. 1 Root Cause Analysis

Good root cause analysis was done at the design and system levels to identify the factors that influence oil consumption. The oil consumption was found to be worst under city cycle conditions compared to the competitor vehicle. Moreover, it emerged that the value of oil consumption was higher than other HD engines belonging to the same family. The operating conditions for this 6.4L HD engine were more aggressive than those for other Same Family engines. This engine is used in various applications based on the end application. This includes both 8-speed and 6-speed transmissions. The balance between RPMs will be tighter in the 8-speed transmission as compared to the 6-speed, and that difference should be interesting to analyze in terms of its effect on oil consumption. The result for the MDS cylinder deactivation system analysis explained that as the MDS is higher, the worse is the oil consumption—the converse is true. DFSO can also be one of the factors that could cause high oil consumption; however, this is an appropriate volume for the engine and comparable to other engines. This engine has the worst bore distortion compared to other engines, and it runs at a higher degree when it is in V4 as opposed to other modes, wherein half of the cylinders will be on and half off. Part of this mode interacts with oil consumption, wherein high consumption was observed under V4, as found to be a trend both from the auto oiler system and CAE analysis as well.

Condition	**Level 1**	**Level 2**	**Level 3**
Vs. Competitor	Worse OC	~~No Difference~~	~~Better OC~~
HD 1 Vs. HD 2	Worse	~~No Difference~~	~~Better OC~~
Operating Conditions	~~Less Aggressive~~	~~No Difference~~	More Aggressive
6 Speed Vs. 8 Speed Trans	~~6 speed higher speed/load~~	Tighter RPM for 8 speed	~~8 speed higher speed/load~~
MDS On	~~More MDS = Better OC~~	~~No Difference~~	More MDS = Worse OC
DFSO	~~Less~~	Right	~~More~~
Bore Distortion	Worse	~~No Difference~~	~~Best~~
Auto oiler system	V4 Mode higher OC	~~No Difference~~	~~V4 Mode less OC~~
CAE Analysis	V4 Mode higher OC	~~No Difference~~	~~V4 Mode less OC~~

Table 1: Root Cause Analysis Table

Power System Technology
ISSN:1000-3673

Received: 06-06-2024 *Revised: 15-07-2024* *Accepted: 28-08-2024*

3. 2 Operating Condition

Good root cause analysis at the design and system levels was conducted to identify what are the influencing factors of oil consumption. It turned out that oil consumption was worst under city cycle conditions compared with the competitor vehicle, and furthermore, it had a higher value of oil consumption compared to other HD engines of the same family. The operating conditions for this 6.4L HD engine were more aggressive than those for other Same Family engines. This engine has many different end applications. This includes both an 8-speed and 6-speed transmissions. The balance between RPMs will be tighter in the 8-speed transmission compared to the 6-speed; that difference should be interesting to analyze in terms of its effect on oil consumption. The result for the MDS cylinder deactivation system analysis explained that the higher the MDS, the worse the oil consumption—the converse is true. DFSO can also be one of the factors that could cause high oil consumption; however, this is an appropriate volume for the engine and comparable to other engines. This engine has the worst bore distortion of all, and it does more running at a higher degree when it's in V4, which means that half of the cylinders are on and off compared to other modes. Offshoots from this mode interact with oil consumption, wherein under V4 it had high consumption, and the trend has been found to be so both from the auto-oiler system and CAE analysis.

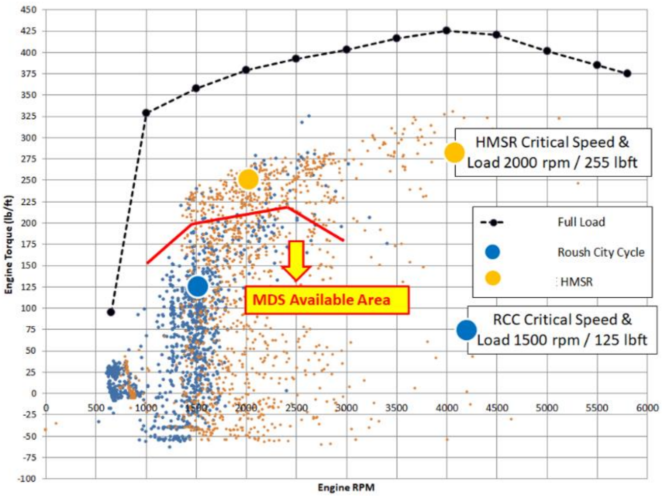


Figure 1: Engine Cycle Map

3.3 Transmission Effect on Oil Consumption

It was concluded that engines with 6-speed transmissions turn on the MDS more rarely compared with engines equipped with 8-speed transmissions, and that the oil consumption pattern in the case of engines equipped with 6-speed transmissions is more favorable compared to those fitted with 8 speed transmissions, all after an in-depth analysis of operational data

Received: 06-06-2024 *Revised: 15-07-2024* *Accepted: 28-08-2024*

studying interrelationship between transmission types versus engine modes or operational modes and oil consumption patterns. Although the 6-speed transmission engines do enjoy a relative advantage in efficiency, their current rate of oil consumption is not up to par with the very stringent targets set for it. There is an incongruence between performance and set goals, which demands technical revision and strategical reorientation to fine-tune and optimize with a view to achieving, if not surpassing, expectations related to oil consumption by these engines.

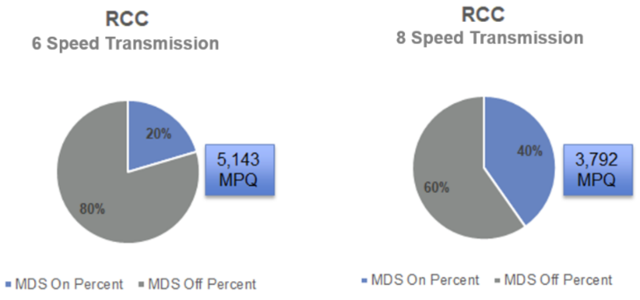


Figure 2: MDS On/Off Vs. Transmission

3.4 MDS Mode Comparison

An intriguing pattern emerged during the evaluation of vehicles powered by the same engine but equipped with different transmissions and configurations. The results revealed that when the Multiple Displacement System (MDS) was deactivated in one of the vehicles, it displayed the lowest oil consumption rates, exceeding the benchmark of 10,000 miles per quart (MPQ). This observation may mean that the deactivation of MDS could be a critical factor in oil efficiency and provide a gateway to achieving and exceeding the set targets in oil consumption.

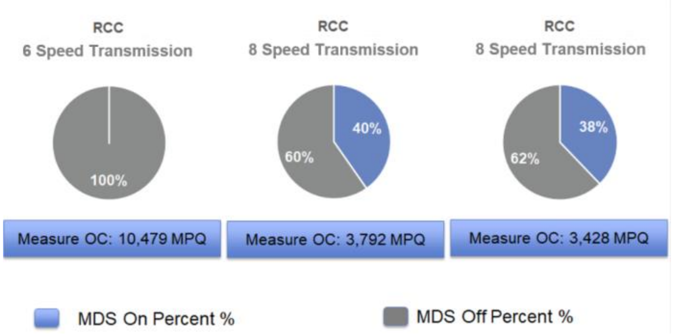


Figure 3: MDS On Vs. Off

Power System Technology
ISSN:1000-3673

Received: 06-06-2024 *Revised: 15-07-2024* *Accepted: 28-08-2024*

3.5 DFSO Comparison

In analyzing the Deceleration Fuel Shut-Off data across the engine lineup, a comprehensive comparison to a heavy-duty 5.7 L from the same family revealed that the latter, under transient and DFSO conditions, was on 5 percent more than the 6.4 L engine can ever be. This could be due to inherent variability within drive cycle parameters, proving there is an intricate link between engine behavior and different operational demands made upon it.

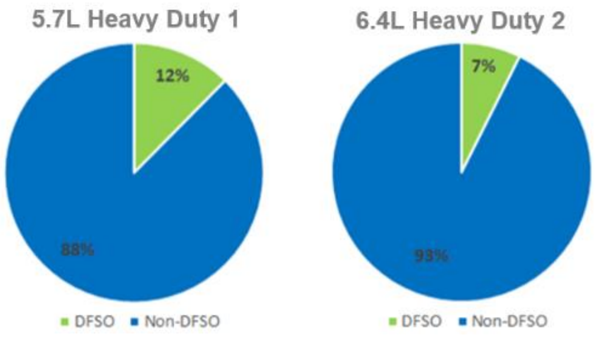
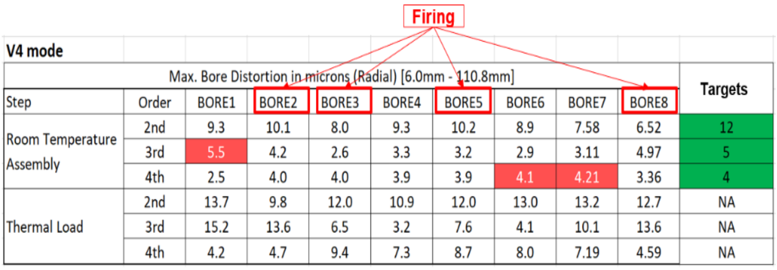


Figure 4: DFSO Heavy Duty Engine Comparison

3.6 Bore Distortion Results

Steered by sophisticated CAE software for bore distortion simulations, the assessment has revealed that target bore distortion levels were not reached for Bore 1 in respect to 3rd order harmonic distortion, nor for Bores 6 and 7 in respect to 4th order harmonic distortion. That's interesting, because cylinders #3 and #5 had the most 4th order bore distortion in V4 engine mode. And it was across cylinders #3 and #$6 that the highest level of 4th order distortion was revealed for V8 engine mode. This would seem to be indicative of where probable corrections to the design might be made for an engine.

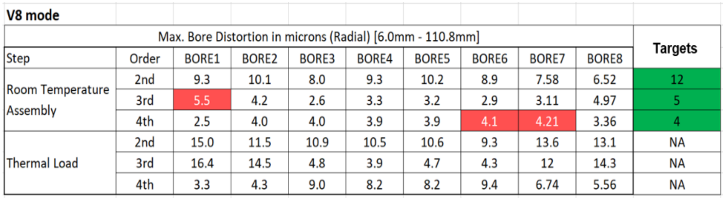


V4 mode

Max. Bore Distortion in microns (Radial) [6.0mm - 110.8mm]										Targets
Step	Order	BORE1	BORE2	BORE3	BORE4	BORE5	BORE6	BORE7	BORE8	
Room Temperature Assembly	2nd	9.3	10.1	8.0	9.3	10.2	8.9	7.58	6.52	12
	3rd	5.5	4.2	2.6	3.3	3.2	2.9	3.11	4.97	5
	4th	2.5	4.0	4.0	3.9	3.9	4.1	4.21	3.36	4
Thermal Load	2nd	13.7	9.8	12.0	10.9	12.0	13.0	13.2	12.7	NA
	3rd	15.2	13.6	6.5	3.2	7.6	4.1	10.1	13.6	NA
	4th	4.2	4.7	9.4	7.3	8.7	8.0	7.19	4.59	NA

Table 2: 6.4L Heavy Duty V4 Mode Bore Distortion

Received: 06-06-2024 *Revised: 15-07-2024* *Accepted: 28-08-2024*

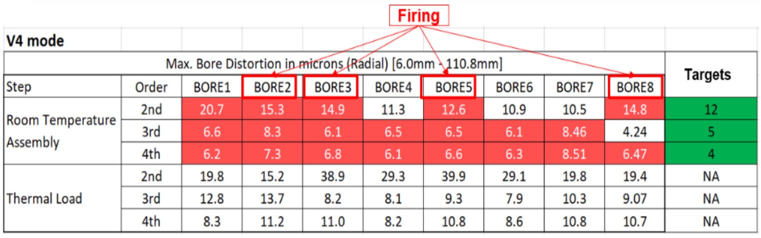


V8 mode

Step	Order	Max. Bore Distortion in microns (Radial) [6.0mm - 110.8mm]								Targets
		BORE1	BORE2	BORE3	BORE4	BORE5	BORE6	BORE7	BORE8	
Room Temperature Assembly	2nd	9.3	10.1	8.0	9.3	10.2	8.9	7.58	6.52	12
	3rd	5.5	4.2	2.6	3.3	3.2	2.9	3.11	4.97	5
	4th	2.5	4.0	4.0	3.9	3.9	4.1	4.21	3.36	4
Thermal Load	2nd	15.0	11.5	10.9	10.5	10.6	9.3	13.6	13.1	NA
	3rd	16.4	14.5	4.8	3.9	4.7	4.3	12	14.3	NA
	4th	3.3	4.3	9.0	8.2	8.2	9.4	6.74	5.56	NA

Table 3: 6.4L V8 Mode Bore Distortion

When evaluating the disparities between the 6.4 L engine and other 5.7 L heavy-duty engines that experienced oil consumption issues in urban driving conditions, it became apparent that the 6.4 L engine displayed superior performance. Consequently, this observation renders it highly unlikely that bore distortion is the primary cause of the engine's subpar performance.



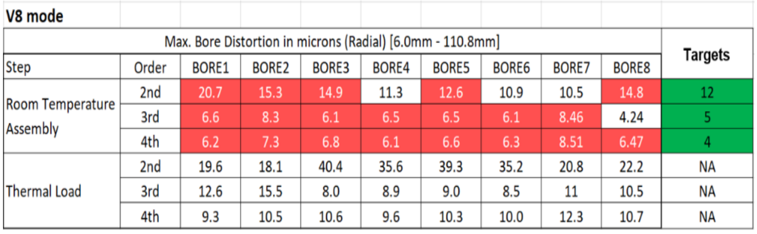
Firing

V4 mode

Step	Order	Max. Bore Distortion in microns (Radial) [6.0mm - 110.8mm]								Targets
		BORE1	BORE2	BORE3	BORE4	BORE5	BORE6	BORE7	BORE8	
Room Temperature Assembly	2nd	20.7	15.3	14.9	11.3	12.6	10.9	10.5	14.8	12
	3rd	6.6	8.3	6.1	6.5	6.5	6.1	8.46	4.24	5
	4th	6.2	7.3	6.8	6.1	6.6	6.3	8.51	6.47	4
Thermal Load	2nd	19.8	15.2	38.9	29.3	39.9	29.1	19.8	19.4	NA
	3rd	12.8	13.7	8.2	8.1	9.3	7.9	10.3	9.07	NA
	4th	8.3	11.2	11.0	8.2	10.8	8.6	10.8	10.7	NA

Table 4: 5.7L Heavy Duty V4 Mode Bore Distortion

The assessment of the room-temperature bore distortion demonstrated that the designated objectives were not realized for most of the bores, except for bores 4, 6, and 7, which achieved second-order distortion targets, and bore 8, which met third-order distortion targets. When subjected to thermal load conditions, cylinders #2 and #3 exhibited the most significant bore distortion in the V4 mode, whereas cylinders #7 and #8 exhibited the highest distortion levels in the V8 mode. This highlights specific areas that require special attention to satisfy distortion specifications.



V8 mode

Step	Order	Max. Bore Distortion in microns (Radial) [6.0mm - 110.8mm]								Targets
		BORE1	BORE2	BORE3	BORE4	BORE5	BORE6	BORE7	BORE8	
Room Temperature Assembly	2nd	20.7	15.3	14.9	11.3	12.6	10.9	10.5	14.8	12
	3rd	6.6	8.3	6.1	6.5	6.5	6.1	8.46	4.24	5
	4th	6.2	7.3	6.8	6.1	6.6	6.3	8.51	6.47	4
Thermal Load	2nd	19.6	18.1	40.4	35.6	39.3	35.2	20.8	22.2	NA
	3rd	12.6	15.5	8.0	8.9	9.0	8.5	11	10.5	NA
	4th	9.3	10.5	10.6	9.6	10.3	10.0	12.3	10.7	NA

Table 5: 5.7L V8 Mode Bore Distortion

Received: 06-06-2024 *Revised: 15-07-2024* *Accepted: 28-08-2024*

3.7 Auto Oil Steady State Results

An investigation for an auto oiler system was conducted on both highway cycles and city cycles. The results were quite interesting from this research. The two most prevalent focal points of attention for the high cycle and the city cycle ended up with different results. The high cycle ran primarily in the V8, whereas the city cycle was more in the V4 range but did switch to the V8 range periodically. In the city cycle, there was a huge difference in oil consumption between V8 and V4 modes at a common operating point of 2100 rpm and 190-Nm. The oil consumption at this point, in V4 as compared to V8 mode, increased sevenfold. This clearly shows that V4 operation at this speed and load point is especially objectionable.

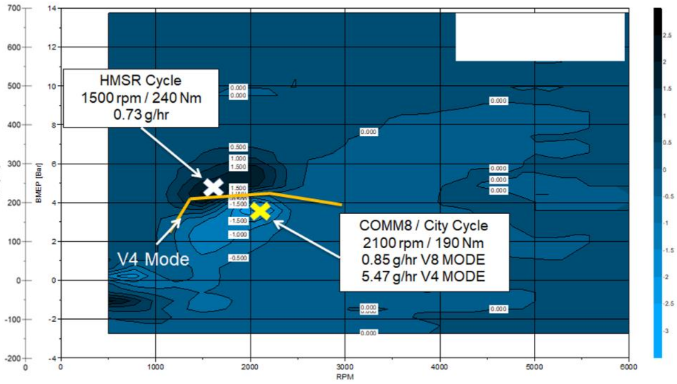


Figure 5: Auto Oil Measurement Map

3.8 CAE Analysis

Based on the results of the CAE analysis conducted to identify the high oil consumption in the V4 mode, a steady-state analysis was performed using the auto oil steady state measurement. This analysis examined the speed and load points that contribute to the observed high oil consumption. Additionally, a simulation was conducted in V8 mode to compare the results with those obtained in V4 mode. The aim of this comparison was to establish a correlation between the two conditions and to gain a better understanding of the underlying factors contributing to high oil consumption.

The results of the CAE examination conducted at a rotational speed of 2100 rpm and torque of 190 Nm (138 lb-ft) revealed that the consumption of oil was notably greater in the V4 mode than in the V8 mode, which aligns with the pattern observed in the auto oil study. Specifically,

Power System Technology
ISSN:1000-3673
Received: 06-06-2024 *Revised: 15-07-2024* *Accepted: 28-08-2024*

the oil consumption for bores 3 and 5 was appreciably higher; however, for bores 2 and 8, the oil consumption was within acceptable limits.

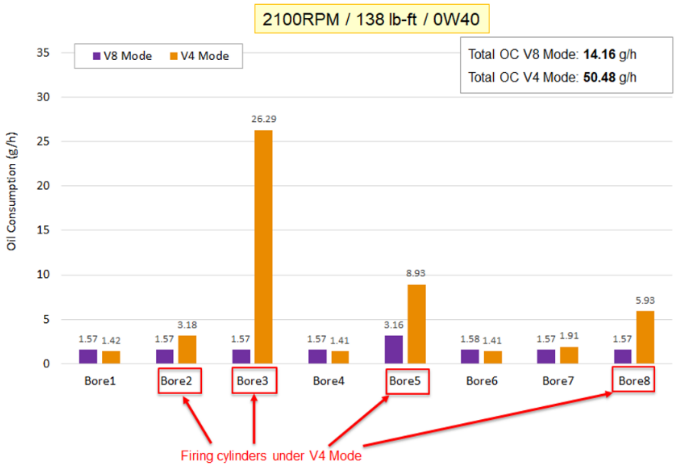
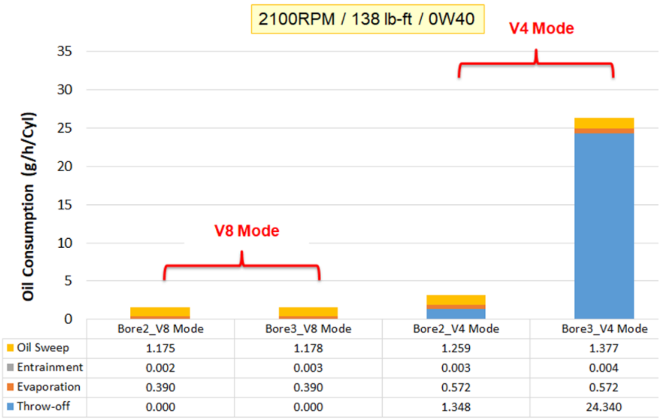


Figure 6: CAE Prediction For Oil Consumption

The analysis was refined to identify the mechanisms responsible for the high oil consumption observed in both the V4 and V8 engine operation modes. It was determined that oil throw-off is the primary factor contributing to oil consumption, followed closely by oil sweeps as the second major factor [14].



	Bore2_V8 Mode	Bore3_V8 Mode	Bore2_V4 Mode	Bore3_V4 Mode
Oil Sweep	1.175	1.178	1.259	1.377
Entrainment	0.002	0.003	0.003	0.004
Evaporation	0.390	0.390	0.572	0.572
Throw-off	0.000	0.000	1.348	24.340

Figure 7: CAE For Oil Consumption Mechanisms

In a concurrent investigation aimed at comprehending the sensitivity of bore distortion to oil consumption, a systematic examination was conducted. This examination entailed interchanging the bore distortions of the cylinders exhibiting the highest and lowest oil consumption rates, specifically between bores 2 and 3, to evaluate the resulting impact. The results demonstrated that oil consumption patterns were closely associated with bores

Power System Technology
ISSN:1000-3673

Received: 06-06-2024 *Revised: 15-07-2024* *Accepted: 28-08-2024*

displaying greater distortion [15], confirming that high oil consumption is primarily influenced by bore distortion. This discovery emphasizes the crucial role of bore integrity in optimizing the engine oil efficiency.

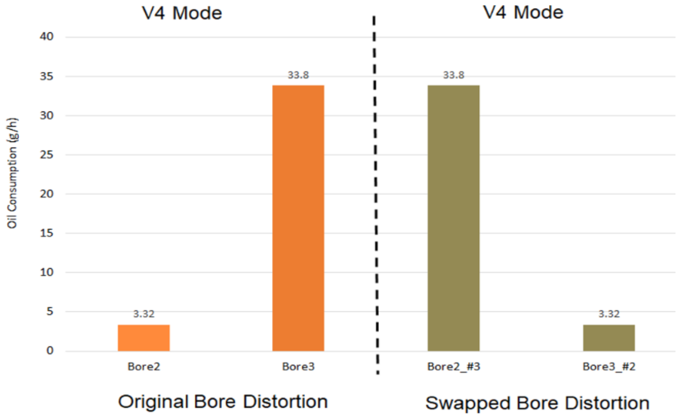


Figure 8: CAE Oil Consumption Prediction for Bore Distortion Sensitivity

Following the bore distortion sensitivity analysis, we conducted an in-depth examination of the bore distortion profiles. The shape of bore 3's profile was notably detrimental, exhibiting flaring at the top, which is likely to adversely affect oil consumption. Conversely, bore 2 maintained a straighter profile, narrowing at the top, which is potentially favorable for reducing oil consumption.

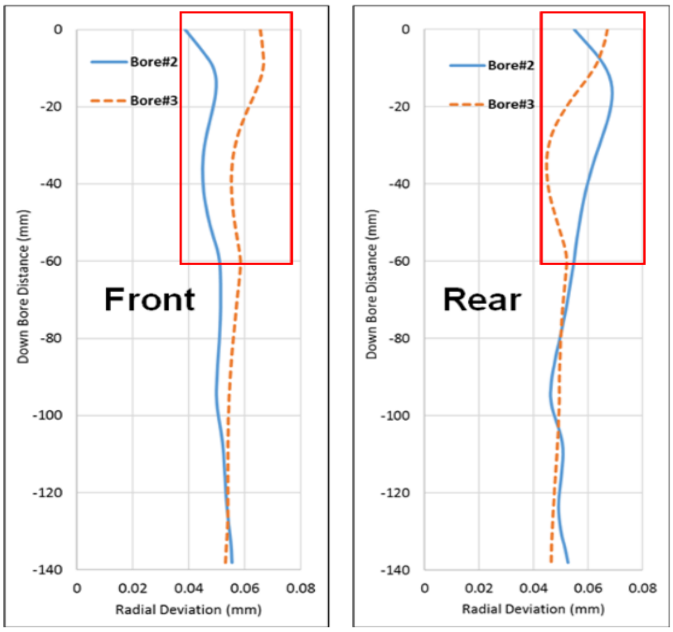


Figure 9: Bore Distortion Profile Comparison

Received: 06-06-2024 *Revised: 15-07-2024* *Accepted: 28-08-2024*

Given the detrimental consequences of bore distortion and profile on fuel consumption, it is imperative to understand the relationship between piston rings and the bore. To this end, CAE analysis was conducted to examine the ring's adaptability to the bore during V4 mode operation, with particular emphasis on the nuances of how piston rings conform to the distorted bore shape. This investigation aimed to capture the specific conditions prevalent in the V4 operating mode, thereby underscoring the vital role of synergy between the piston ring design and bore integrity in achieving optimal engine performance.

CAE analysis assessed the areas of bore conformity and non-conformity in relation to the piston rings, revealing that Ring 3 exhibited the poorest adaptation to the bore. Examination of both the top and second rings from cylinder 3 revealed the lowest levels of conformability, with gaps between the rings and bore observed in specific sections. These gaps are directly linked to increased oil consumption because they can lead to oil throw-off during operation, resulting in elevated oil consumption rates.

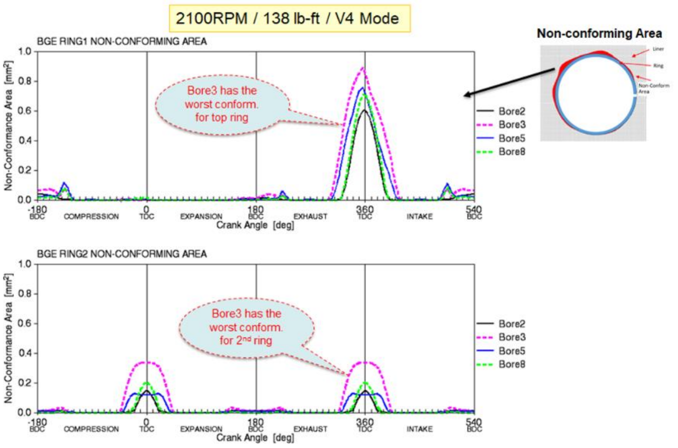


Figure 10: CAE Analysis for Ring Conformability

3.9 Possible Solution

A comprehensive series of CAE analyses was conducted to evaluate the impact of various ring design modifications on oil consumption, particularly in V4 mode operation. They found that altering the top ring from a symmetric to an asymmetric design resulted in a reduction in oil consumption. Additionally, increasing the tension of the second ring to 10N also led to a noticeable decrease in oil consumption. Remarkably, when these two adjustments were implemented simultaneously, the reduction in oil consumption was significantly greater than

Received: 06-06-2024 *Revised: 15-07-2024* *Accepted: 28-08-2024*

when each modification was applied independently, indicating a synergistic effect between the design changes.

Figure 11: CAE Analysis for Top Ring Shape, Second Ring Tension

A subsequent series of analyses focused on adjusting the top ring tension, modifying the oil rail face shape, and altering the oil expander tab angle. Despite efforts to increase the tension of the top ring, it did not result in any improvement in oil consumption and, in fact, worsened the issue for several cylinders. However, modifying the angle of the oil expander tab led to a modest reduction in oil consumption. Notably, reshaping the oil rail face to adopt a tapered design resulted in the most substantial decrease in oil consumption, underscoring the effectiveness of this adjustment.

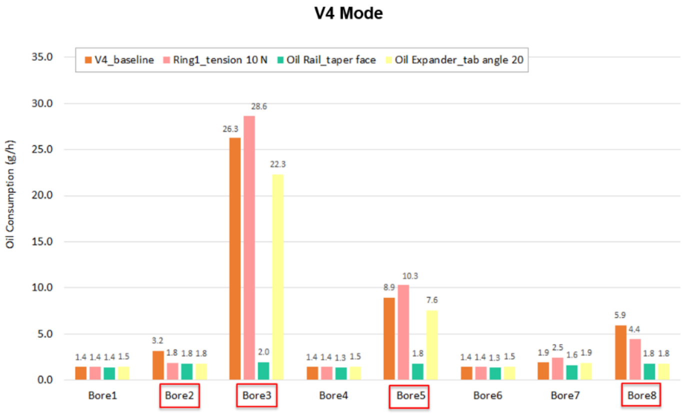


Figure 12: CAE Analysis for Top Ring Tension, Oil Rail Face, Tab Angle

The CAE analysis aimed to determine the impact of reducing the ring gap and increasing the oil ring tension on the oil consumption. Although the results were inconclusive, no significant improvement in the oil efficiency was observed. In some cases, oil consumption remained

Received: 06-06-2024 *Revised: 15-07-2024* *Accepted: 28-08-2024*

constant or even increased for certain cylinders, suggesting that these adjustments did not have a positive effect on overall oil consumption rates.

Figure 13: CAE Analysis for Second Ring Gap, Oil Ring Tension

The final CAE analysis was used to assess the various oils with varying viscosities. Substitution of different oils from the baseline resulted in higher oil consumption.

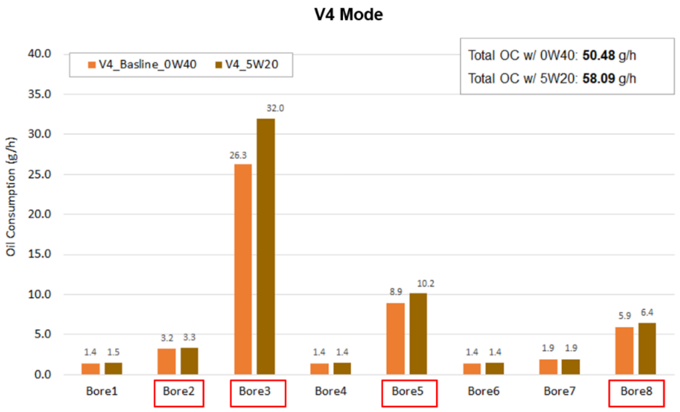


Figure 14: CAE Analysis for Different Oils

Through extensive CAE analyses, several crucial design parameters were identified as critical factors influencing oil consumption efficiency. These key elements encompass the profile shape of the top ring, tension of the second ring, face design of the oil rail, and the angle of the oil expander tab. Collectively, these factors have been recognized as significant contributors to

Received: 06-06-2024 *Revised: 15-07-2024* *Accepted: 28-08-2024*

improved oil consumption performance, underscoring their importance in the optimization of heavy-duty engine design.

4. Conclusions

The investigation into high oil consumption in heavy-duty engines during city driving revealed a complex issue. Various factors influence this, including engine operating modes, transmission types, bore distortion, and piston ring design. The study highlights a significant difference in oil consumption between engines with different transmission configurations. This finding underscores the need for further optimization to improve efficiency.

These critical findings of the study underline the deep impact of bore distortion and piston ring design on the consumption of oil. CAE simulation has identified specific bore distortions that increase the consumption of oil, thus showing how much correct modeling in an engine block and accurate configurations of piston rings may help to save oil. The design changes in the parameters of the piston ring, such as top ring profile, second ring tension, oil rail face shape, and expander tab angle, were found to be efficient ways to reduce oil consumption with a focus on city cycle driving.

Moreover, the test runs upon different viscosities of oil have revealed that there are difficulties in achieving optimal oil consumption by means of using a proper lubricant selection method, which calls for holistic approaches toward engine design and maintenance.

In conclusion, this study provides broad-ranging insight into the determinants of oil consumption in heavy-duty engines and thus opened avenues for further development. The identification of key design parameters for improving oil efficiency thus points to one giant step ahead toward developing more sustainable and efficient engines. These findings are of importance to the automotive industry, which is aimed at reducing the impact upon the environment while improving vehicle performance in this case, presenting a valuable resource for future innovation in the design and function of engines.

5. Future Work

Such effects of MDS V4 mode and bore distortion on oil consumption will be explored in future studies, building on the valuable insights learned from this study. Moreover, various design factors will be identified and integrated to further enhance oil efficiency. To meet these targets, we plan to work in a more structured and organized way by employing the Design for Six Sigma methodology, which can enable us in fine-tuning our techniques towards Oil Consumption reductions. The system modeling software used at Ricardo ringpack simulation

Received: 06-06-2024 *Revised: 15-07-2024* *Accepted: 28-08-2024*

forms a very key tool in estimating an exact measure for oil consumption. We executed a well-planned series of experiments in a Taguchi method to optimize the configuration of the piston ring pack and block system. Our primary objective is to significantly improve city cycle oil consumption rates, aiming for a benchmark of 10,000 miles per quart, without sacrificing highway cycle performance. This balanced approach to performance enhancement was rigorously validated through hundreds of hours of tests on engine dynamometer and in-service vehicles.

References

[1] Matope, S., Chirinda, G. P., & Sarema, B. (2022). Continuous Improvement for Cost Savings in the Automotive Industry. *Sustainability*, 14(22), 15319. https://doi.org/10.3390/su142215319

[2] Karjalainen, P., Ntziachristos, L., Murtonen, T., Wihersaari, H., Simonen, P., Mylläri, F., Nylund, N.-O., Keskinen, J., & Rönkkö, T. (2016). Heavy Duty Diesel Exhaust Particles during Engine Motoring Formed by Lube Oil Consumption. *Environmental Science & Technology*, 50(22), 12504–12511. https://doi.org/10.1021/acs.est.6b03284

[3] Kader, M. K., Ramani, T., & Jacobs, T. J. (2015). Effect of extended idle on oil degradation rates of heavy-duty vehicles. *International Journal of Heavy Vehicle Systems*, 22(3), 193. https://doi.org/10.1504/ijhvs.2015.071673

[4] Kim, K., Si, W., Jin, D., Kim, J.-H., Cho, J., Baek, S., Myung, C.-L., & Park, S. (2020). Characterization of engine oil additive packages on diesel particulate emissions. *Journal of Mechanical Science and Technology*, 34(2), 931–939. https://doi.org/10.1007/s12206-020-0142-3

[5] Gao, J., Chen, H., Tian, G., Ma, C., & Zhu, F. (2019). An analysis of energy flow in a turbocharged diesel engine of a heavy truck and potentials of improving fuel economy and reducing exhaust emissions. *Energy Conversion and Management*, 184, 456–465. https://doi.org/10.1016/j.enconman.2019.01.053

[6] Tormos, B., Ramírez, L., Johansson, J., Björling, M., & Larsson, R. (2017). Fuel consumption and friction benefits of low viscosity engine oils for heavy duty applications. *Tribology International*, 110, 23–34. https://doi.org/10.1016/j.triboint.2017.02.007

[7] Macián, V., Tormos, B., Miró, G., & Pérez, T. (2015). Assessment of low-viscosity oil performance and degradation in a heavy duty engine real-world fleet test. *Proceedings of the Institution of Mechanical Engineers. Part J Journal of Engineering Tribology*, 230(6), 729–743. https://doi.org/10.1177/1350650115619612

[8] Honda, T., & Ogano, S. (2015). Effect of Soot in Diesel Engine Oils on Lowering Friction. *SAE Technical Papers on CD-ROM/SAE Technical Paper Series*. https://doi.org/10.4271/2015-01-2033

Received: 06-06-2024 Revised: 15-07-2024 Accepted: 28-08-2024

[9] Padgurskas, J., Volskis, D., Rukuiža, R., Kupčinskas, A., Basheleishvili, N., & Tučkutė, S. (2023). Limitary State of Heavy-Duty Engine Oils and Their Evaluation According to the Change of Tribological Properties during Operation. *Lubricants*, 11(6), 236–236. https://doi.org/10.3390/lubricants11060236

[10] Wang, Z., Zhu, Y., Tao, C., Wang, Q., Zhao, M., & Chen, Z. (2018). Effect of Engine Oil on Fuel Consumption and Durability of Heavy-Duty Vehicle. *Lecture Notes in Electrical Engineering*, 477–495. https://doi.org/10.1007/978-981-10-8506-2_33

[11] Knauder, C., Allmaier, H., Sander, D., Salhofer, S., Reich, F., & Sams, T. (2015). Analysis of the Journal Bearing Friction Losses in a Heavy-Duty Diesel Engine. *Lubricants*, 3(2), 142–154. https://doi.org/10.3390/lubricants3020142

[12] Tormos, B., Pla, B., Bastidas, S., Ramírez, L., & Pérez, T. (2019). Fuel economy optimization from the interaction between engine oil and driving conditions. *Tribology International*, 138, 263–270. https://doi.org/10.1016/j.triboint.2019.05.042

[13] Chen, Z., Zhu, Y., Liu, X., & Zhao, M. (2019). Using modified sawdust as a lubricant oil filter in a diesel engine: Reducing wear and emissions while improving engine performance. *Journal of Mechanical Science and Technology*, 33(9), 4295–4301. https://doi.org/10.1007/s12206-019-0835-y

[14] Tornehed, P., & Olofsson, U. (2012). Modelling lubrication oil particle emissions from heavy-duty diesel engines. *International Journal of Engine Research*, 14(2), 180–190. https://doi.org/10.1177/1468087412452208

[15] George, T., Schille, V., McKinley, T., & Berardi, T. (2018). Real-time on-road oil consumption measurements for a commercial heavy-duty Diesel engine. *Proceedings*, 225–226. https://doi.org/10.1007/978-3-658-21015-1_144

Definitions/Abbreviations

MPQ: Miles per Quart
MDS: Multiple Displacement System
DFSO: Deceleration Fuel Shut Off
HD: Heavy Duty
CAE: Computer-Aided Engineering
RPM: Revolutions Per Minute
V4 mode: Engine operation mode with half the cylinders active
V8 mode: Engine operation mode with all cylinders active
DFSS: Design for Six Sigma