Comparative Analysis of Full-Synthetic and Semi-Synthetic Oil Performance in a 250cc 4-Stroke Motorcycle Engine: An Experimental Study Using Analysis of Variance

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Abstract. Selecting the right engine oil determines the performance and service life of a motorcycle engine. However, empirical evidence on the performance differences between full-synthetic and semi-synthetic oils under real-world operating conditions is still limited. This study comprehensively analyzes the performance differences between the two oil types in a 250cc 4-stroke motorcycle engine using an experimental approach with rigorous statistical methods. The experiment was conducted on a Kawasaki Ninja 250 RR Mono by measuring four critical parameters: engine vibration, oil temperature, torque, and power at various engine speeds. The results showed highly statistically significant differences in all tested parameters ($p < 0.05$). Full-synthetic oil demonstrated superior performance with a vibration reduction of up to 30%, a reduction in operating temperature of almost 2°C, and an increase in torque and power of approximately 2-3% compared to semi-synthetic oil. Further analysis revealed that oil type had the greatest influence on engine mechanical stability, followed by thermal management and power efficiency. These findings provide empirical justification for oil selection based on usage profile and performance priorities. This research contributes to the development of evidence-based engine maintenance strategies and provides practical guidance for users in optimizing motor vehicle performance.

1 Introduction

The development of modern automotive technology has driven significant evolution in the field of tribology and engine lubrication [1]. Engine oil has transformed from a simple lubricant into a multifunctional fluid that plays a critical role in determining performance, efficiency, and service life of motor vehicle engines [2]. In internal combustion engines, engine oil performs five main functions: reducing friction between

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moving components, transferring heat from critical zones, preventing corrosion and oxidation, cleaning deposits and contaminants, and damping mechanical vibrations [3]. The complexity of these functions demands increasingly sophisticated oil formulations to meet the operational demands of modern engines operating under high pressure, extreme temperatures, and varied engine speeds [4].

1.1 Practical Problem

Motorcycle users, particularly in Southeast Asian markets, face a recurring decision between full-synthetic and semi-synthetic oils. Full-synthetic oils, produced predominantly from Group IV polyalphaolefin (PAO) and/or Group V esters, offer superior molecular uniformity and thermal-oxidative stability. Semi-synthetic oils, blended from Group II/III and a small proportion of Group IV/V base stocks, provide a compromise between performance and economy [2]. Despite the price premium of full-synthetic oils (typically 30–50% higher), consumers lack clear, quantitative evidence to justify this investment for motorcycle applications.

1.2 Scientific Gap

Although laboratory studies have documented differences in physicochemical properties between these oil types, empirical research quantifying their impact on engine performance under real-world operating conditions remains limited. Polingala et al. [5] identified differences in dielectric breakdown voltage at various temperatures but did not explore implications for operational parameters. Vibrational characteristics of mechanical systems using Empirical Wavelet Transforms but did not specifically compare lubricant types. Critically, the majority of existing comparative studies rely on simple descriptive analysis without rigorous statistical validation, making it impossible to establish the significance of observed differences objectively.

1.3 Consequences of the Gap

Without statistically validated performance data, oil selection remains guided by manufacturer marketing claims, anecdotal evidence, or price-driven decisions rather than evidence-based reasoning. This leads to suboptimal maintenance practices that may compromise engine longevity, fuel efficiency, and rider comfort.

1.4 Research Gap and Novelty

No published study has simultaneously evaluated the effect of oil type on vibration, temperature, torque, and power in a single motorcycle engine platform using ANOVA with effect size quantification. Prior research typically examined one or two parameters in isolation without statistical hypothesis testing. This study fills the gap by providing a multi-parameter, statistically rigorous comparison that ranks the practical importance of oil type using eta-squared (η^2) effect sizes. The resulting hierarchy (vibration >

temperature > torque > power) represents a novel contribution not previously documented in the literature.

This study aims to analyze the influence of engine oil type (full-synthetic vs. semi-synthetic) on a 250cc 4-stroke motorcycle engine by: (1) measuring and comparing vibration, temperature, torque, and power across 2000–9000 RPM; (2) testing statistical significance using ANOVA at 95% confidence; (3) calculating effect sizes; (4) identifying the most responsive parameters; and (5) providing evidence-based oil selection recommendations.

2 Method

2.1 Research Design

This research employs a comparative experimental design with a within-subjects (repeated-measures) structure: the same motorcycle was tested with oil A (semi-synthetic) and oil B (full-synthetic) in separate sessions. Between sessions, a washout procedure was conducted consisting of a 10-minute engine flush with oil flush additive, complete drainage, and a 50 km break-in run with the new oil to eliminate carry-over effects. The experiment was conducted in the Automotive Engineering Laboratory of Universitas Negeri Padang from August to October 2024 under controlled conditions: ambient temperature 28 ± 2 °C, relative humidity 65 ± 5%, and atmospheric pressure 101.3 ± 0.5 kPa.

2.2 Research Object and Specification

The test vehicle was a 2014 Kawasaki Ninja 250 RR Mono with a 249cc 4-stroke DOHC parallel twin-cylinder engine (bore × stroke: 62.0 × 41.2 mm), compression ratio 11.6:1, maximum power 39 PS @ 12,500 RPM, maximum torque 21.5 N.m @ 10,000 RPM, EFI, liquid-cooled, and 6-speed manual transmission. The vehicle was selected due to its 25,000 km mileage (mid-life condition), complete service history, no modifications, and verified mechanical condition through compression test (11.2 kg/cm^2), leak-down test (<8% leakage), valve clearance check (inlet 0.19 mm, exhaust 0.27 mm), and ignition timing verification.

2.3 Research Variables

The independent variable was engine oil type: (1) semi-synthetic oil (SAE 10W-40, API SL, JASO MA2, brand X) and (2) full-synthetic oil (SAE 10W-40, API SN, JASO MA2, brand Y). Identical viscosity grade was selected to isolate the effect of base stock chemistry. The dependent variables were engine vibration (mm/s), oil temperature (°C), engine torque (N.m), and engine power (HP). Control variables included fuel octane rating (RON 92), tire pressure, chain tension, rider weight simulation (70 kg), and cooling system condition.

2.4 Instruments and Calibration

Vibration was measured using a Digital Vibration Meter Model VM-6360 (range 0.1–200 mm/s RMS, frequency 10–1000 Hz, accuracy ±3%). Temperature was measured using a Type K Thermocouple (range –40 °C to 375 °C, accuracy ±1.5 °C). Torque and power were measured using a Dynojet 250i Chassis Dynamometer (maximum 250 HP, torque accuracy ±0.5%, RPM accuracy ±10 RPM, sampling rate 100 Hz). All instruments were calibrated by BPFK (Calibration Testing and Facilitation Center) with valid certificates traceable to national standards.

2.5 Data Collection Procedure

Preparation included oil change, engine flushing, valve clearance adjustment, spark plug inspection, air filter cleaning, chain and tire checks, and fuel top-up (RON 92), followed by a 50 km break-in run. Vibration and temperature were measured at five RPM points (2000–3600 RPM) in steady-state neutral-gear operation, held for 60 seconds with data recorded in the final 30 seconds, replicated three times with 5-minute cooling intervals. Torque and power were measured on a chassis dynamometer at 4000–9000 RPM (4th gear, wide-open throttle), with three dyno pulls, 10-minute cooling intervals, SAE J1349 correction, and 15% drivetrain loss estimation.

2.6 Data Analysis Methods

One-way ANOVA was used to test the null hypothesis H_0: $\mu_{\text{full-synthetic}} = \mu_{\text{semi-synthetic}}$ at $\alpha = 0.05$. Before conducting ANOVA, its key assumptions were checked: normality of residuals was assessed using the Shapiro-Wilk test (all $p > 0.05$), and homogeneity of variances was verified using Levene's test (all $p > 0.05$), confirming that the assumptions were adequately met for all parameters. Effect size was calculated using eta-squared (η^2):

$$\eta^2 = \frac{SSB}{(SSB + SSW)} \tag{1}$$

Interpreted per Cohen's convention: $\eta^2 < 0.01$ (negligible), 0.01–0.06 (small), 0.06–0.14 (medium), > 0.14 (large). Pearson correlation analysis was conducted to examine interrelationships among parameters using:

$$r = \frac{\sum[(xi - \bar{x})\,(yi - \bar{y})]}{\sqrt{\sum(xi - \bar{x})^2 . \sum(yi - \bar{y})^2}} \tag{2}$$

Statistical significance of correlations was tested with a two-tailed t-test at $\alpha = 0.05$. Analysis was performed using Python (NumPy, SciPy, Pandas) and cross-validated with SPSS Statistics version 26.

3 Results and Discussion

3.1 Engine Vibration

Table 1 presents the vibration data measured at five RPM levels.

Table 1. Complete data on engine vibration measurement at various RPM levels

RPM	Semi-synthetic (mm/s)	Full-synthetic (mm/s)	Difference (%)
2000	8.03	4.67	41.8%
2400	8.10	5.17	36.2%
2800	8.67	6.13	29.3%
3200	9.43	6.87	27.1%
3600	10.20	8.27	18.9%
Mean±SD	8.87±0.89	6.22±1.39	30.7%

Full-synthetic oil consistently produced lower vibrations across all RPM levels, with the greatest percentage reduction at 2000 RPM (41.8%) and the smallest at 3600 RPM (18.9%). This pattern indicates that the advantage of full-synthetic oil is most pronounced at low RPM, where boundary and mixed lubrication regimes dominate and base stock chemistry is most critical [6], [7].

Table 2. ANOVA table for machine vibration parameters

Source of Variation	df	Sum of Squares	Mean Square	F-ratio	p-value
Between Groups	1	70.5625	70.5625	87.42	<0.001***
Within Groups	28	22.6080	0.8074	-	-
Total	29	93.1705	-	-	-

*Note: *** p < 0.001; F-table (df1=1, ff2=28, α=0.05) = 4.20*

F = 87.42 ($p < 0.001$) decisively rejects H_0, with $\eta^2 = 0.757$ (very large effect), indicating oil type explains 75.7% of total vibration variance. This is attributed to three mechanisms: (i) molecular uniformity of PAO producing superior film strength that minimizes asperity contact [5]; ((ii) viscosity stability maintaining optimal film thickness; and (iii) better damping characteristics of synthetic base stock [8]. Practically, this vibration reduction can extend component fatigue life by 20–30% and improve rider comfort (**Table 2**).

3.2 Oil Temperature

Table 3 presents the oil temperature data recorded at steady-state operation for each RPM point. Full-synthetic oil maintained consistently lower operating temperatures, with the largest difference at 2800 RPM (2.44°C) and smallest at 3600 RPM (1.23°C). The mid-range RPM advantage reflects limited cooling airflow combined with moderate-to-high friction heat, maximizing the thermal benefit of full-synthetic oil's higher thermal conductivity [2], [9]. **Table 4** presents the ANOVA results for oil temperature.

Table 3. Complete data on oil temperature measurement at various RPM levels

RPM	**Semi-synthetic (°C)**	**Full-synthetic (°C)**	**Difference (°C / %)**
2000	64.53	62.47	2.06 / 3.2%
2400	64.87	62.70	2.17 / 3.3%
2800	65.77	63.33	2.44 / 3.7%
3200	66.63	64.93	1.70 / 2.6%
3600	66.90	65.67	1.23 / 1.8%
Mean±SD	65.74±1.04	63.82±1.34	1.92 / 2.9%

Table 4. ANOVA table for oil temperature parameters

Source of Variation	**df**	**Sum of Squares**	**Mean Square**	**F-ratio**	**p-value**
Between Groups	1	36.864	36.864	12.56	0.008**
Within Groups	28	82.208	2.936	-	-
Total	29	119.072	-	-	-

F = 12.56 (p = 0.008) confirms a significant temperature difference, with $\eta^2 = 0.309$ (large effect). Although the absolute difference is modest (1.92 °C), based on the Arrhenius relationship, a 2 °C reduction can lower oil oxidation rate by approximately 25%, extending drain intervals and reducing deposit formation [10].

3.3 Engine Torque Analysis

Table 5 presents complete data on engine torque.

Table 5. Complete data on engine torque measurement at various RPM levels

RPM	**Semi-synthetic (N.m)**	**Full-synthetic (N.m)**	**Difference (N.m / %)**
4000	11.21	14.80	3.59 / 32.0%
4500	17.24	18.28	1.04 / 6.0%
5000	18.48	18.64	0.16 / 0.9%
5500	18.94	18.98	0.04 / 0.2%
6000	19.48	19.46	-0.02 / -0.1%
6500	19.87	20.01	0.14 / 0.7%
7000	20.26	20.49	0.23 / 1.1%
7500	20.09	20.30	0.21 / 1.0%
8000	19.72	19.89	0.17 / 0.9%
8500	19.38	19.63	0.25 / 1.3%
9000	18.60	18.84	0.24 / 1.3%
Mean±SD	18.70±2.83	19.17±1.88	0.47 / 2.5%

Full-synthetic oil showed higher torque at most RPM levels. The 32.0% difference at 4000 RPM reflects superior boundary lubrication at low speed, where film strength and additive chemistry are critical [3], [6]. In the mid-range (5000–6000 RPM), minimal differences (<1%) suggest combustion efficiency masks lubrication effects. At high RPM (7000–9000), a consistent 0.9–1.3% advantage reflects the shear stability of synthetic base stock [11]. The negative difference at 6000 RPM (–0.1%) falls within dynamometer measurement uncertainty (±0.5%) and does not indicate a systematic semi-synthetic advantage.

To test the statistical significance of the observed torque difference between the two types of oil, an analysis of variance was carried out with the results presented in **Table 6**.

Table 6. ANOVA table for engine torque parameters

Source of Variation	df	Sum of Squares	Mean Square	F-ratio	p-value
Between Groups	1	6.4827	6.4827	8.73	0.015*
Within Groups	64	47.552	0.7430	-	-
Total	65	54.0347	-	-	-

Note: * $p < 0.05$; F-table ($df_1=1$, $df_2=64$, $\alpha=0.05$) = 3.99

F = 8.73 (p = 0.015) is significant, with $\eta^2 = 0.120$ (medium effect), indicating oil type explains 12.0% of torque variance. The observed 2.5% torque improvement aligns with Zhmud et al. [7], who estimated a 20% friction reduction yields approximately 2–3% power gain. For high-mileage users (~15,000 km/year), a 2% efficiency improvement could save approximately 12 L of fuel annually, potentially offsetting the 20–30% price premium of full-synthetic oil [12].

3.4 Engine Power

Engine power is the final manifestation of the energy conversion efficiency in the propulsion system and is greatly affected by mechanical losses including friction [13], [14], [15]. **Table 7** presents comprehensive data on engine power measurements at the same operational range as torque measurements to evaluate the power delivery characteristics of both types of oil.

Table 7. Engine power at various RPM levels

RPM	Semi-synthetic (HP)	Full-synthetic (HP)	Difference (HP / %)
4000	7.65	8.45	0.80 / 10.5%
4500	10.99	11.61	0.62 / 5.6%
5000	13.01	13.13	0.12 / 0.9%
5500	14.69	14.72	0.03 / 0.2%
6000	16.47	16.48	0.01 / 0.1%
6500	18.20	18.36	0.16 / 0.9%
7000	19.98	20.23	0.25 / 1.3%
7500	21.22	21.42	0.20 / 0.9%
8000	22.21	22.42	0.21 / 0.9%
8500	23.19	23.51	0.32 / 1.4%
9000	23.56	23.86	0.30 / 1.3%
Mean±SD	17.89±5.24	18.41±5.01	0.52 / 2.9%

The power pattern mirrors the torque findings: full-synthetic is superior at low RPM (10.5% at 4000), shows minimal difference at the peak power zone (0.1–0.2% at 5500–6000), and maintains a consistent advantage at high RPM (0.9–1.4%).

Table 8. ANOVA for engine power

Source of Variation	df	Sum of Squares	Mean Square	F-ratio	p-value
Between Groups	1	8.1120	8.1120	6.89	0.023*
Within Groups	64	75.392	1.1780	-	-
Total	65	83.504	-	-	-

Note: * $p < 0.05$

F = 6.89 (p = 0.023) is significant. $\eta^2 = 0.097$ (medium effect), with oil type explaining 9.7% of power variance. Whitby [6] reported 2–3% fuel economy improvements with synthetic oils in commercial applications, providing independent corroboration (**Table 8**).

3.5 Summary of ANOVA Results

Table 9 presents a consolidated summary of all ANOVA analysis results to facilitate comparative evaluation across parameters.

Table 9. Comprehensive ANOVA summary

Parameter	F-hitung	F-tabel	p-value	η^2	Effect Size	Decision
Vibration	87.42	4.20	<0.001***	0.757	Very Large	Reject H_0
Temperature	12.56	4.20	0.008**	0.309	Large	Reject H_0
Torque	8.73	3.99	0.015*	0.120	Medium	Reject H_0
Power	6.89	3.99	0.023*	0.097	Medium	Reject H_0

Note: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$

All parameters showed significant differences. The effect size hierarchy vibration (75.7%) > temperature (30.9%) > torque (12.0%) > power (9.7%) indicates that oil type most strongly affects mechanical stability, followed by thermal management, with moderate effects on power delivery. This hierarchy has not been explicitly documented in prior research and represents a novel contribution, suggesting that oil selection criteria should prioritize vibration control and thermal management rather than peak power output alone.

3.6 Correlation Analysis between Performance Parameters

Table 10 presents a correlation matrix that quantifies the strength and direction of the relationship between each pair of measured parameters. The very strong positive correlation between vibration and temperature ($r = 0.834$, $p < 0.001$) empirically validates the friction-heat generation mechanism described in classical tribological theory [3], [8]: increased friction produces both higher vibration and elevated heat. Significant negative correlations between vibration and torque ($r = -0.267$) and power ($r = -0.289$) indicate that lower vibration corresponds to improved mechanical efficiency. The near-perfect correlation between torque and power (r = 0.987) is expected given their mathematical relationship. These patterns confirm that full-synthetic oil provides system-level improvement rather than isolated parameter benefits.

Table 10. Pearson correlation matrix

Parameter	Vibration	Temperature	Torque	Power
Vibration	1.000	0.834***	-0.267*	-0.289*
Temperature	0.834***	1.000	-0.312*	-0.328**
Torque	-0.267*	-0.312*	1.000	0.987***
Power	-0.289*	-0.328**	0.987***	1.000

Note: ***$p < 0.001$; ** $p < 0.01$; * $p < 0.05$

3.7 Comparison with Previous Studies

The 30.7% vibration reduction aligns with findings by Pawar et al. [3], who reported 18–24% friction coefficient reduction for synthetic PAO versus Group II minerals. The slightly higher reduction in this study reflects the comprehensive measurement approach capturing cumulative effects across the engine system. The 1.92°C temperature reduction is consistent with the theoretical predictions of Rudnick [2] but is smaller than the 4–6°C differentials observed by Tirmizi et al. [10] in heavy-duty diesel applications—a discrepancy explained by differences in engine size, cooling system configuration, and operational severity. The 2.5–2.9% torque and power improvements closely match predictions by Zhmud et al. [7]. However, the 32% torque improvement at 4000 RPM exceeds typical reported values, suggesting that boundary lubrication at low RPM may offer greater potential for differentiation than previously recognized.

3.8 Limitations

This study tested a single motorcycle unit (2014 Kawasaki Ninja 250 RR Mono), ensuring internal consistency but limiting generalizability to other engine configurations and wear conditions. All measurements were conducted under steady-state laboratory conditions over short durations, which may not fully represent real-world scenarios including extreme temperatures or long-term oil degradation. The RPM range tested (2000–9000) excluded idle and maximum engine speed. Only one brand of each oil type was evaluated, preventing distinction between base stock effects and proprietary additive formulations. The study focused on technical performance without comprehensive economic cost-benefit or environmental impact analysis.

4 Conclusion

This experimental study demonstrated statistically significant differences ($p < 0.05$) across all four parameters when comparing full-synthetic and semi-synthetic oils in a 250cc 4-stroke motorcycle engine. Full-synthetic oil reduced engine vibration by 30.7% ($F = 87.42$, $p < 0.001$, $\eta^2 = 0.757$, very large effect), lowered operating temperature by 1.92°C ($F = 12.56$, $p = 0.008$, $\eta^2 = 0.309$, large effect), increased torque by 2.5% ($F = 8.73$, $p =$

0.015, $\eta^2 = 0.120$, medium effect), and increased power by 2.9% ($F = 6.89$, $p = 0.023$, $\eta^2 = 0.097$, medium effect). The effect size hierarchy vibration > temperature > torque > power—indicates that oil selection criteria should be prioritized according to application needs.

For practical recommendations, high-mileage riders (> 15,000 km/year) or those operating under demanding conditions should consider full-synthetic oil for its documented benefits in vibration reduction, thermal management, and efficiency gains. Budget-conscious users with lower mileage under normal conditions may find semi-synthetic oil provides acceptable performance. Future research should pursue longitudinal studies over extended drain intervals, multi-engine comparative studies, comprehensive economic analyses, and field validation under diverse real-world conditions to broaden the applicability of these findings.

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