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Extended drain interval performance of SAE 15W40 CI-4 diesel engine oil under plain and inclined terrain operations

Kim Michael Angelo R. Miraflores

College of Engineering, Xavier University - Ateneo de Cagayan, **Philippines**

Email address: kimmichaelangelomiraflores@gmail.com

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Abstract: Engine oil plays a critical role in ensuring efficient engine operation and prolonging service life by reducing friction, dissipating heat, and protecting components from wear. This study evaluates the performance of SAE 15W40 mineral multigrade diesel engine oil operated beyond the original equipment manufacturer's recommended drain interval under varying terrain conditions. Four passenger buses powered by Yuchai, Weichai, and Cummins engines were subjected to a 20,000-kilometer road test covering inclined and plain terrain without oil or filter replacement. Oil condition was assessed using standardized ASTM methods for kinematic viscosity and Total Base Number (TBN). Viscosity values at both 40°C and 100°C remained within acceptable limits throughout the extended interval. TBN values remained above 50% of the fresh oil baseline, indicating retention of alkalinity reserve and additive effectiveness. These results demonstrate that SAE 15W40 diesel engine oil can maintain functional integrity up to 20,000 km under mixed terrain conditions.

Keywords : diesel engine oil; extended drain interval; oil condition monitoring; viscosity; TBN

1. Introduction

Heavy-duty diesel engines in public transportation fleets operate under demanding and variable thermo-mechanical conditions. Sustained torque, cyclic loading, elevated combustion temperatures, and long duty cycles expose engine components to combined frictional and thermal stresses [1]. These effects are intensified in routes with alternating inclined and flat terrain, where continuous elevation gain increases Brake Mean Effective Pressure (BMEP), lubricant shear stress, and sump temperature [2]. Under these conditions, engine oil is required to maintain film integrity and protect components under fluctuating load and temperature regimes [3].

Engine oil provides lubrication through hydrodynamic and boundary film formation while also contributing to heat dissipation and contaminant control [4], [5]. It further functions to neutralize acidic by-products and suspend soot and wear particles during operation [6], [7], [8]. The effectiveness of these functions is governed by the stability of the base oil and additive system during operation [9]. In service, lubricant degradation is driven by thermal oxidation, additive depletion, soot accumulation, fuel dilution, and mechanical shear, which progressively alter physicochemical properties and reduce lubrication effectiveness if not monitored [10], [11], [12].

Oil Condition Monitoring (OCM) is widely applied to evaluate lubricant condition and support condition-based maintenance strategies [13], [14]. Used oil analysis (UOA) parameters, including kinematic viscosity and Total Base Number (TBN), provide measurable indicators of lubricant condition and machine health [1]. Recent studies have incorporated regression-based trend analysis and predictive modeling to estimate degradation rates and remaining useful life under controlled and industrial operating conditions [15], [16], [17].

Most published studies on extended drain intervals rely on laboratory simulations or controlled experimental conditions. While these approaches provide insight into degradation mechanisms, they do not fully capture the variability of real-world fleet operations. Empirical evidence on extended drain performance in operational public transport systems, particularly under terrain-dependent duty cycles, remains limited [18]. Increased engine load and operating temperature under severe duty cycles have been associated with accelerated oxidation and wear processes [11]. However, the extent to which terrain-induced load variation influences degradation rates during extended service intervals has not been sufficiently quantified, particularly using statistically validated trend analysis.

This study addresses this limitation by evaluating the performance of SAE 15W40 API CI-4 mineral diesel engine oil under extended drain conditions up to 20,000 km in operational public transport buses. The investigation was conducted under actual service conditions, including routes with inclined and plain terrain profiles, without oil or filter replacement during the monitoring period. Lubricant condition was assessed using standardized ASTM methods for viscosity and Total Base Number (TBN). Degradation behavior was evaluated using regression-based trend analysis and statistical comparison to examine the influence of terrain on lubricant performance and wear characteristics. The results provide field-based evidence for assessing the feasibility of extended drain intervals under mixed operating conditions.

2. Material and methods

2.1 Research design and experimental framework

This study employed a longitudinal field-based experimental design to evaluate the performance of SAE 15W40 API CI-4 mineral multigrade diesel engine oil under extended drain interval conditions up to 20,000 km. The investigation focused on real-world public transport fleet operations under two terrain classifications:

a) Inclined terrain (mountainous duty cycle)
b) Plain terrain (low-elevation duty cycle)

Field validation was selected instead of laboratory simulation to capture realistic thermo-mechanical loading conditions, combustion variability, soot generation, and cyclic stress profiles. Previous studies [18], [19] have shown that laboratory-based aging may underestimate oxidation kinetics and additive depletion compared to field operation. Therefore, operational validation is necessary when assessing extended drain interval performance under real service conditions. Oil Condition Monitoring (OCM) was conducted at fixed mileage intervals of 5,000 km (5k, 10k, 15k, and 20k km). This sampling strategy follows condition-based maintenance practices that emphasize periodic monitoring to establish degradation trends rather than relying on single-point measurements [18].

2.2 Test vehicles and operational conditions

Four operational passenger buses powered by heavy-duty diesel engines were monitored under commercial service conditions. The units were selected based on continuous route deployment and the availability of route classification data to enable comparison across terrain-dependent operating conditions. Table 1 summarizes the engine specifications, including rated power and oil capacity. These parameters influence engine thermal loading and lubricant residence time, which are relevant to degradation behavior during extended service.

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Table 1. The selected engines represent heavy-duty compression ignition systems commonly used in Southeast Asian transport fleets

Bus ID	Engine Brand	Model	Power (kW)	Oil Capacity (L)	Route Type
88815	Yuchai	YC6L	234	25	Inclined
8188	Weichai	WP7	199	25	Inclined
818	Cummins	ISDe140	103	13	Mixed
8840	Weichai	WP6220E50	158	23	Plain

The influence of duty cycle variability on lubricant degradation has been recognized in oil condition monitoring (OCM) studies, which emphasize the importance of incorporating operational variability into degradation trend analysis [14]. Representative test vehicles operating under the defined terrain conditions are shown in Figure 1, illustrating the actual fleet units used in the field evaluation.


(a)


(b)


(c)


(d)

Figure 1. Selected test vehicles: (a) Bus 88815 (Yuchai engine), (b) Bus 8188 (Weichai engine), (c) Bus 818 (Cummins engine), and (d) Bus 8840 (Weichai engine)

2.3 Lubricant selection and characterization

A single-batch SAE 15W40 API CI-4 mineral multigrade diesel engine oil was used for all test units to eliminate formulation variability. The selection of CI-4 classification oil reflects its suitability for high-soot, exhaust gas recirculation (EGR) diesel engines and high-load operating conditions. CI-4 oils contain enhanced dispersant–detergent systems, oxidation inhibitors, and anti-wear additives such as zinc dialkyldithiophosphate (ZDDP), which contribute to oxidation control and wear protection during extended service [8]. Establishing baseline physicochemical properties is necessary for evaluating degradation behavior, as extended drain assessment is based on deviations relative to fresh oil values [17]. The baseline properties of the fresh lubricant used as reference values are summarized in Table 2.

Table 2. Fresh oil baseline properties

Property	Method	Value
Kinematic Viscosity @ 40°C	ASTM D445	115 cSt
Kinematic Viscosity @ 100°C	ASTM D445	15.1 cSt
Viscosity Index	ASTM D2270	137
Flash Point	ASTM D92	>200°C
Total Base Number (TBN)	ASTM D2896	10.3 mg KOH/g
Density @ 15°C	ASTM D4052	0.8757 kg/L

2.4 Sampling plan and sample integrity controls

2.4.1 Sampling intervals

Oil samples were collected at predefined mileage intervals of 0 km (fresh oil baseline), 5,000 km, 10,000 km, 15,000 km, and 20,000 km. The baseline sample established the reference physicochemical properties of the fresh lubricant, against which subsequent deviations were evaluated. Sampling at uniform 5,000 km intervals enabled longitudinal monitoring of degradation under actual operating conditions. The repeated-measures design allows evaluation of parameter trends (e.g., viscosity change and TBN depletion) as a function of accumulated mileage using regression analysis. This approach supports estimation of degradation rates and identification of trend progression, rather than relying solely on single-point threshold limits. Time-series sampling is recommended in oil condition monitoring (OCM) to capture gradual physicochemical changes and reduce uncertainty associated with isolated measurements [1], [14].

2.4.2 Sampling procedure

Sampling was conducted at or immediately after operating temperature to minimize stratification effects, including particle settling and separation of lighter fuel fractions. Representative sampling is critical, as improper procedures can lead to misleading contamination results [20]. Sampling at operating temperature also improves the accuracy of particle distribution measurements and reduces bias associated with settling. Samples were collected using vacuum extraction through the dipstick tube under controlled conditions, including the use of single-use tubing, sterile containers, proper labeling, and sealed transport. These procedures are consistent with established oil analysis sampling practices and standards [20].

2.4.3 No oil/filter replacement

No oil replacement, top-up, flushing, or filter change was performed during the 20,000 km evaluation period. This design represents a conservative stress condition for extended drain evaluation, as filter replacement may reduce circulating wear particles and soot, potentially masking degradation trends. Maintaining a constant system configuration throughout the monitoring interval is necessary to ensure consistent interpretation of degradation behavior [1].

2.5 Laboratory testing and analytical standards

All laboratory analyses were conducted using standardized ASTM International methods commonly applied in diesel engine used oil analysis (UOA). The selected methods include ASTM D445 for kinematic viscosity and ASTM D2896 for Total Base Number (TBN). These parameters represent key indicators of lubricant condition and are widely used in heavy-duty diesel monitoring programs. All ASTM procedures were conducted following the latest published standard revisions. Measurements were performed under controlled laboratory conditions in accordance with standard calibration and quality assurance procedures to ensure consistency and comparability of results.

2.6 Acceptance criteria and justification

Oil condition at each sampling interval was evaluated against commonly accepted functional limits for key parameters. TBN retention was interpreted using the guideline of maintaining approximately 50% of the fresh oil value to ensure sufficient alkalinity reserve for acid neutralization [21]. Viscosity was assessed based on deviation from fresh oil values to determine whether the lubricant remained within an acceptable operating range.

2.7 Statistical analysis

To quantify degradation behavior and assess terrain effects, each oil parameter was modeled as a function of accumulated mileage using linear regression:

$$Y = \beta_0 + \beta_1 X + \varepsilon \quad (1)$$

where Y represents the oil condition parameter (e.g., TBN or viscosity), X denotes mileage, β_0 is the intercept, β_1 represents the degradation rate (slope), and ε is the random error term.

Differences between terrain conditions (inclined versus plain) were evaluated using analysis of variance (ANOVA) applied to regression slopes at a significance level of $\alpha = 0.05$.

3. Results and discussion

3.1 Kinematic viscosity at 40°C and 100°C

Viscosity at both 40°C and 100°C remained within the ±15% deviation limit throughout the 20,000 km service interval for all test units. At 100°C, the measured values consistently remained within the SAE 40 viscosity grade range, indicating that no significant thinning or excessive thickening occurred during operation. The observed viscosity stability suggests that the lubricant maintained sufficient hydrodynamic film integrity and load-carrying capacity under extended service conditions. No evidence of fuel dilution–induced viscosity reduction or oxidation- and soot-related thickening was detected within the monitoring period. Comparison between inclined and plain terrain groups showed no statistically significant difference in viscosity trends, indicating that variations in load and operating temperature did not result in measurable shear or thermal degradation within the evaluated interval. This behavior implies that the lubricant formulation retained its viscosity control characteristics under mixed duty cycle conditions. Viscosity at 40°C ranged from approximately 104 to 113 cSt, while viscosity at 100°C ranged from 13.3 to 14.7 cSt across all sampling intervals.

The trends shown in Figures 2 and 3 confirm the stability of viscosity across all test units throughout the monitoring period. Minor variations observed between sampling intervals remained within acceptable limits and did not indicate abnormal degradation behavior. Statistical analysis confirmed that differences between terrain groups were not significant ($p > 0.05$). This suggests that the lubricant maintained its viscosity control characteristics, with no evidence of significant thinning due to fuel dilution or excessive thickening associated with oxidation and soot accumulation. Similar viscosity stability under extended drain conditions has been reported in previous studies [18].

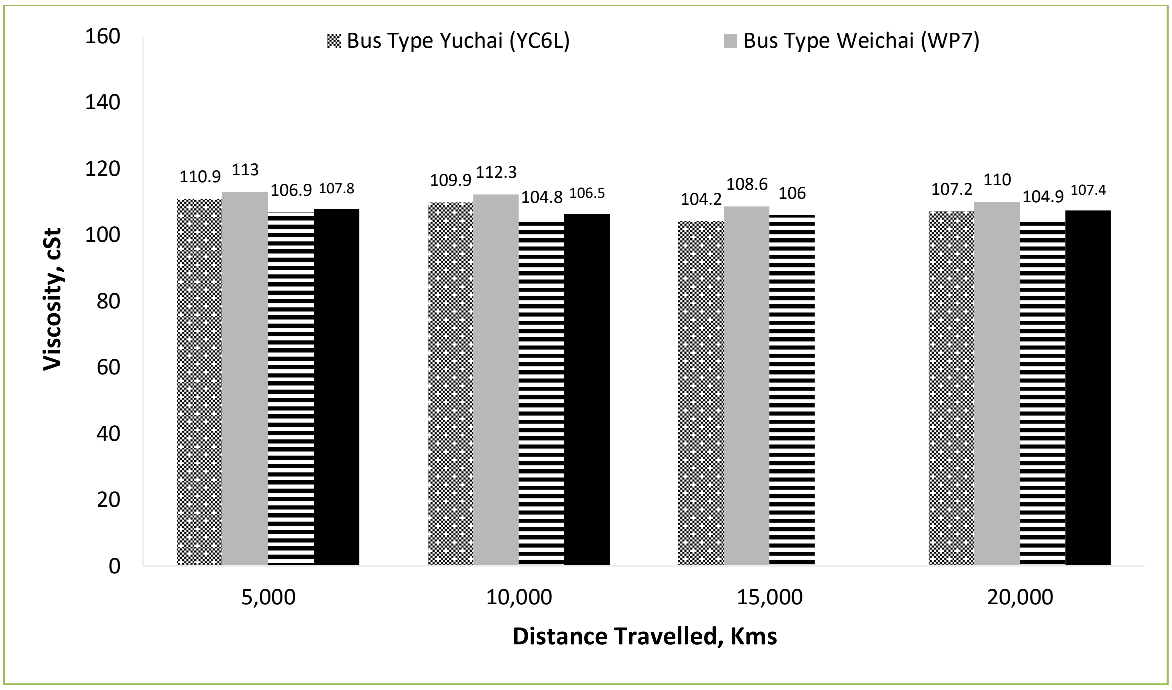

Figure 2. Variation of kinematic viscosity at 40°C as a function of mileage for all test units

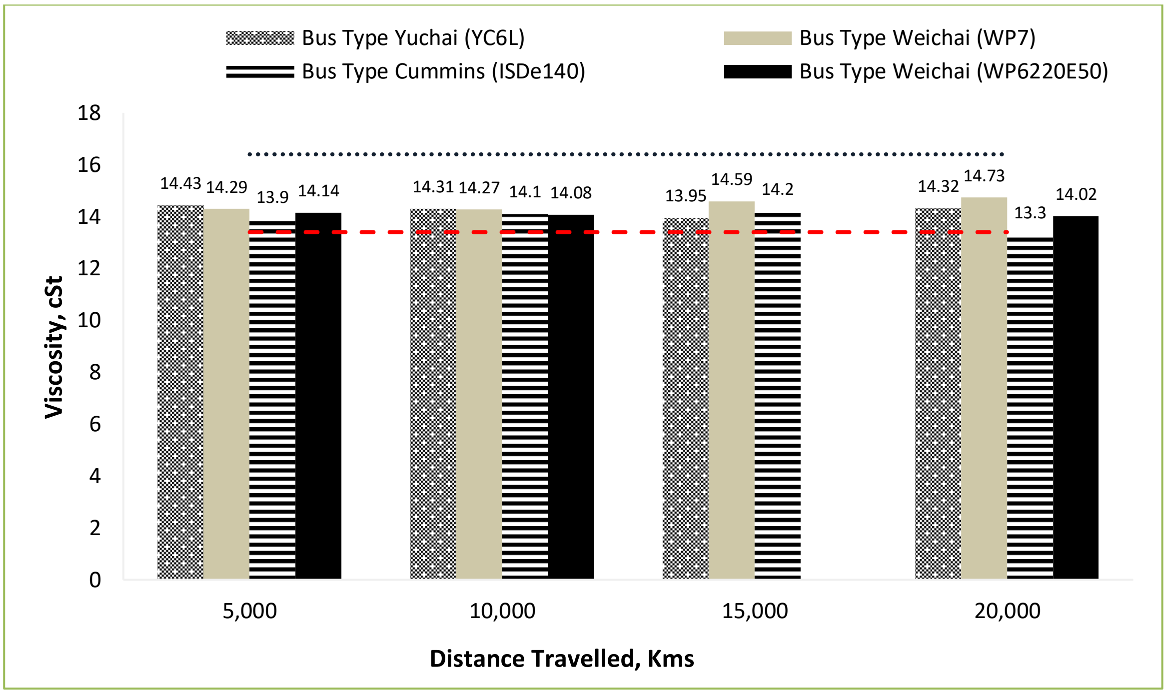

Figure 3. Variation of kinematic viscosity at 100°C as a function of mileage for all test units

3.2 Total Base Number (TBN)

The Total Base Number (TBN) values for all test units remained above the condemning limit of 5 mg KOH/g (50% of the fresh oil value of 10.3 mg KOH/g) throughout the 20,000 km drain interval (Figure 4). A gradual decrease in TBN was observed with increasing mileage, indicating controlled consumption of alkaline detergent additives during operation. TBN decreased from an initial value of 10.3 mg KOH/g to approximately 8.0–9.9 mg KOH/g at 20,000 km.

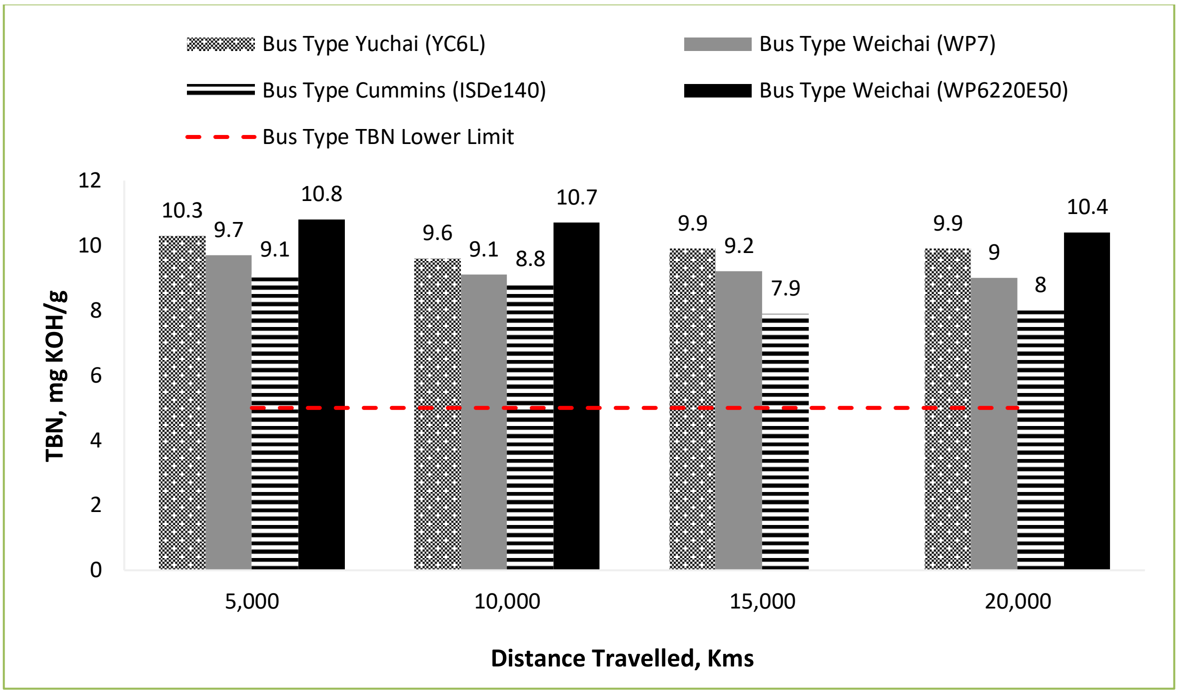

Figure 4. Variation of Total Base Number (TBN) as a function of mileage for all test units

The observed depletion trend was approximately linear, suggesting that acid generation remained within the neutralization capacity of the lubricant. TBN reduction is primarily associated with neutralization reactions between alkaline additives and acidic combustion by-products; excessive depletion may increase the risk of corrosive wear in engine components. In this study, TBN values did not approach critical levels, indicating that the alkalinity reserve remained sufficient throughout the monitoring period. No abnormal or accelerated depletion behavior was observed across the test units, including those operating under inclined terrain conditions. This indicates that variations in load and operating temperature did not significantly influence the rate of additive depletion within the evaluated interval. The results demonstrate that the lubricant maintained adequate chemical stability and acid neutralization capacity up to 20,000 km under mixed operating conditions.

3.3 Overall physicochemical performance

Terrain conditions influenced degradation behavior through variations in engine load and thermal exposure. Units operating on inclined routes were subjected to sustained gradients and higher torque demand, resulting in increased brake mean effective pressure (BMEP) and elevated lubricant temperature compared to those operating on predominantly flat routes. This difference in operating severity was reflected in slightly higher rates of physicochemical change under inclined conditions. Viscosity exhibited marginally greater deviation from baseline values, indicating increased shear and thermal stress, while TBN showed a steeper depletion trend consistent with enhanced neutralization of acidic combustion products. Despite these differences, all measured parameters remained within acceptable service limits throughout the 20,000 km interval. The results indicate that terrain acts as a secondary factor influencing degradation rate rather than a limiting factor for lubricant serviceability within the evaluated interval. Statistical analysis similarly indicated no significant difference in TBN depletion rates between terrain conditions ($p > 0.05$). While extended drain operation was feasible under both conditions, inclined operation led to moderately accelerated lubricant aging. These findings support the implementation of terrain-sensitive monitoring strategies in condition-based maintenance programs for mixed-duty fleet operations.

4. Conclusion

This study evaluated the performance of SAE 15W40 API CI-4 mineral diesel engine oil under an extended drain interval of 20,000 km in public transport buses operating under inclined and plain terrain conditions. Oil condition monitoring conducted at 5,000 km intervals showed that all key physicochemical parameters remained within acceptable service limits throughout the evaluation period. Kinematic viscosity at 40°C and 100°C remained within ±15% of the fresh oil values, indicating stable lubrication performance without evidence of fuel dilution, oxidation-induced thickening, or shear degradation. Total Base Number (TBN) remained above 50% of the fresh oil value, demonstrating that sufficient alkalinity reserve was retained to neutralize acidic combustion by-products. Depletion trends were gradual and consistent, indicating controlled additive consumption. No statistically significant differences were observed between inclined and plain terrain operations ($p > 0.05$), indicating that variations in load and operating severity did not critically influence lubricant degradation within the studied interval. The findings confirm that extended drain operation up to 20,000 km is feasible under monitored conditions without compromising lubricant performance. The findings support the use of condition-based maintenance for optimizing drain intervals in mixed-duty fleet operations. Continued oil condition monitoring is recommended to ensure reliability and to identify the onset of critical degradation under longer service durations.

Author's declaration

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Data availability

Data are available from the author upon reasonable request.

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Conflict of interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical clearance

Not applicable.

AI statements

Artificial intelligence tools were not used in the design, data collection, analysis, or interpretation of results for this study. AI-assisted tools were used only for language editing and grammar refinement, without affecting the scientific content or conclusions of the manuscript.

Publisher's and Journal's Note

Researcher and Lecturer Society as the publisher, and the Editor of Innovation in Engineering state that there is no conflict of interest towards this article publication.

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