Lubricant Performance in Bicycle Roller Chains

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Abstract

Lubricant selection plays a crucial role in optimizing bicycle drivetrain efficiency by minimizing energy losses due to friction. Despite extensive research on aerodynamics, the characterization of lubricants for cycling remains underexplored. This study evaluates the performance of various lubricants, including wax-based and dry-based options, under realistic cycling conditions using a custom-designed testing rig. New Shimano Ultegra 11-speed chains were stripped of factory lubricants and treated with commercially available and custom lubricants. The performance of these lubricants was assessed through repeated efficiency tests and wear cycles. The results indicate that the best wax-based lubricants were highly durable, repeatable, and provided consistent drivetrain efficiency over a long period (>60hrs), although some required a breaking-in period to reach maximum performance. Dry-based lubricants were less repeatable, and their performance deteriorated quickly (<30hrs). Interestingly, one dry lubricant outperformed the best wax-based lubricant under higher-speed conditions, suggesting that lubricant choice can be tailored to specific riding conditions to maximize efficiency. The insights gained from this study provide valuable guidance for cyclists, mechanics, and manufacturers in selecting and applying lubricants to enhance drivetrain efficiency and longevity, ultimately contributing to improved cycling performance and reduced component wear.

Keywords: cycling, lubrication, roller-chain efficiency

1 Introduction

The efficiency of a bicycle's drivetrain, consisting of the chain, sprockets, and derailleur, plays a crucial role in optimizing cycling performance. An efficient drivetrain minimizes energy losses through friction, allowing the cyclist to transfer more of their power from their legs to the wheels. A cyclist on a more efficient drivetrain will have to expend fewer watts to go the same speed as compared to someone on a less efficient drivetrain. Lubrication is a major factor influencing drivetrain friction, as inadequate or improper lubrication can lead to increased component wear, reduced efficiency, and even premature component failure.

While aerodynamics accounts for the majority of resistance felt by cyclists, with approximately 90% of resistance attributed to aerodynamic factors, the remaining resistance is due to drivetrain and rolling resistance [1]. Extensive research has been conducted to optimize aerodynamics, but relatively little has been done to characterize lubricants over long periods of time specifically for cycling applications.

The choice of lubricant can significantly impact the drivetrain's efficiency. Factors such as the lubricant type, additives, and resistance to contamination from dirt and water can all affect its performance. Therefore, understanding the differences between various lubricants and their suitability for specific riding conditions is essential for optimizing drivetrain efficiency.

Despite the importance of lubrication in cycling, there has been limited scholarly published work on the longevity of cycling lubricants. However, some relevant work has been presented by various online resources such as Zero-Friction Cycling [2], Friction Facts [3, 4], and Wippermann [5]. Additional testing has been done by The Efficiency Testing Centre [6] and Absolute Black [7], but their findings have not been openly published in peer-reviewed journals.

Aubert *et al.* [8] conducted a review of tribological devices used for efficiency analysis and categorized them into different types. The authors suggested that a "Full Test Rig" (FTR), which fully simulates all components of a cycling drivetrain with high repeatability and reproducibility, is the best setup to use. The FTR is a complete cycling drivetrain, including the chain, sprockets, and derailleur, as opposed to other types of rigs that only test smaller subsets of the drivetrain or do not include all the same components. While these smaller rigs may be more sensitive, they are less representative of real-world cycling conditions. The current work presents an FTR setup to ensure the most accurate and applicable results.

Previous scholarly work performed on cycling drivetrain efficiency using representative testing rigs has not focused on the time component, and instead focused on single snapshot of efficiency under various conditions [9–14].

Previous studies have employed a pendulum method to isolate chain efficiency, enabling higher fidelity results compared to more representative testing rigs [15, 16]. While these works are valuable for isolating specific factors influencing efficiency, they do not capture the full complexity of a cycling drivetrain or the changes in lubricant performance over extended periods of use.

Zero-Friction Cycling [2] investigated the number of kilometers a chain can be ridden before reaching 0.5% elongation, depending on the specific chain and lubricant combination used. While this work covers a wide range of chains and lubricants and provides insights into which combinations allow for longer chain lifetimes, it does not provide detailed information on the efficiency change over time.

Friction Facts [3], which merged with CeramicSpeed [4] and continued publishing data, has shared a variety of data on chain longevity and efficiency. They utilized two testing rigs: one for measuring chain efficiency and another for inducing wear on the chain through simulated cycling conditions. In their efficiency tests, various lubricants were tested on top-of-the-line chains from three different manufacturers, and the average “watts expended” was calculated. For their longevity testing, the efficiency of a chain was measured, then subjected to 60 minutes of running with water and dirt applied, and retested for efficiency to determine the difference. Their results for both efficiency and longevity showed that paraffin wax was superior to all other tested lubricants [17].

Wippermann [5] conducted longevity testing on chains to characterize how long certain chains lasted until 1% elongation was measured. Water, oil, and sand were applied to the chains on their testing rig to accelerate wear and simulate real-world cycling conditions. These tests focused on the durability of the chain material itself rather than the efficiency of the chain and lubricant combination.

This paper aims to expand upon prior work to provide a comprehensive analysis of cycling lubricants and their performance under a wide range of cycling conditions. By employing a novel testing methodology, this research offers a detailed examination of how chain efficiency evolves over time and how it is affected by various riding conditions. As compared to the prior art, this study provides a granular exploration of the relationship between lubricant type, riding conditions, and chain efficiency. The findings of this study contribute to the body of knowledge on cycling lubricants and provide actionable information for cyclists, mechanics, and manufacturers to make data-driven decisions regarding drivetrain maintenance and lubricant choice. This research aims to empower the cycling community with the knowledge necessary to maximize drivetrain efficiency, enhance performance, and extend component longevity.

2 Materials

All tests were run using new Shimano Ultegra 11-speed chains (CN-HG701-11), with a Shimano SLX 11-speed derailleur. The lubricants used in this study, presented in **Table 1**, comprise a range of waxes, wax-blends, and a dry lubricant. Some of these lubricants are commercially available and marketed specifically for bicycle use, while others are obtained as bulk material directly from formulators. Wax-based lubricants rely on the inherent lubricity of the wax itself, as well as any additional additives, to reduce friction in the drivetrain. Dry-based lubricants consist of a mixture of solvents and lubricating components. When applied to the chain, the solvents evaporate, leaving behind only the lubricating components to reduce friction.

Table 1: Lubricants Tested

Sample Number	**Lubricant**
1	Wax blend of paraffin, sunflower, carnauba
2	160F melt paraffin lubricant
3	Sunflower wax lubricant
4	160F melt wax based lubricant (commercial grade)
5	Wax based formula with ceramic particles, dry lubricant (commercial grade)
6	140F Melt Wax based lubricant (commercial grade)
7	Alpha Olefin Wax-based lubricant
8	195F Melt micro-crystalline wax-based lubricant
9	Wax based formula, dry lubricant (commercial grade)

3 Methods

3.1 Testing Rig

The testing rig used in this study was adapted from prior work focusing on smart trainer testing [18] and expanded to evaluate cycling drivetrains. **Fig. 1** shows the main components of the testing rig, which are explored in more detail in a separate publication [19]. The testing rig can test and analyze the efficiency of bicycle roller chains under various conditions from $100-1,000[W]$ and cadences $0-360[rpm]$ which covers most conditions cyclists should encounter. The testing rig was configured with a 42-tooth front chain ring (SRAM Red) which drives a cassette (SRAM CS-PG-1130-A1). The chosen gear reduction was $42 : 17 = 2.417$, which aligns with typical drivetrain configurations for road cycling and allows for realistic testing of a wide range of speed and resistance conditions (detailed in Section 3.3). Tests were performed in clean laboratory environment at ambient temperature of $21°C$. The gear ratio and chain ring sizes were kept constant for all tests, and the effects of cross-chaining were eliminated to reduce component wear by aligning the sprockets for the gear ratio.

3.2 Chain Lubrication

Before testing any lubricant, a new chain was stripped of its factory lubricant using a multi-stage process informed by a previously established methods [20].

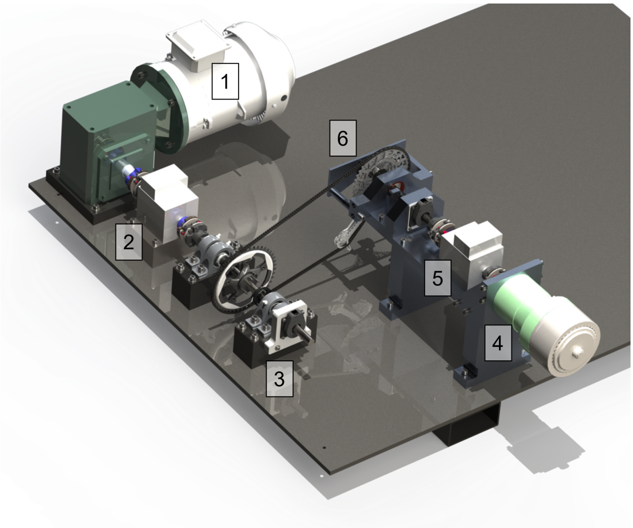

Fig. 1: Testing rig: 1) Motor, 2) input power torque transducer, 3) rotary encoder, 4) Electromagnetic brake, 5) output power torque transducer, 6) standard cassette and derailleur

The chain was subjected to multiple mineral spirit baths with ultrasonic agitation, followed by a denatured alcohol rinse and oven drying to remove all moisture, and cooling to room temperature.

A waxing method, similar to established methods [21], was employed for the application of the wax lubricants. The wax was placed in a small dish and heated in an industrial oven alongside the chain until the wax reached a fully molten state at approximately $80°C$. To ensure uniform distribution of any additives, the molten wax was agitated. Subsequently, the chain was fully immersed in the liquid wax bath and agitated to ensure complete coverage of all surfaces. The chain was removed from the wax bath and hung to cool to room temperature before proceeding with the testing procedure.

The application of the dry lubricants was performed following the instructions provided by their respective manufacturers. For sample #5, the chain was installed on the testing rig, and a thick drop of lubricant was placed onto each link. This process was repeated three times, and the chain was allowed to sit for a minimum of three hours before commencing the testing. In the case of sample #9, the chain was first installed on the testing rig, then the lubricant was dripped from the bottle onto the chain while it was running slowly. After application, the chain was wiped with a cloth to remove any excess lubricant and allowed to rest for 1.5 hours before initiating the testing procedure.

3.3 Testing Procedure

The chain efficiency characterization procedure was designed to evaluate the chain's performance under a wide range of common cycling scenarios. This involved varying the cadence between 60 and 120 revolutions per minute (RPM) in 10 RPM increments and power levels ranging from 200 to 500 watts (W) in 100 watt increments. The test matrix included all permutations of these RPM and power levels, excluding those limited by either being below the minimum torque that could be provided by the testing rig's brake or exceeding the maximum safe torque level for the testing rig's torque transducer. A single "characterization" test is considered completed when every point in **Fig. 2** has been tested and analyzed using the methods in Section 3.4.

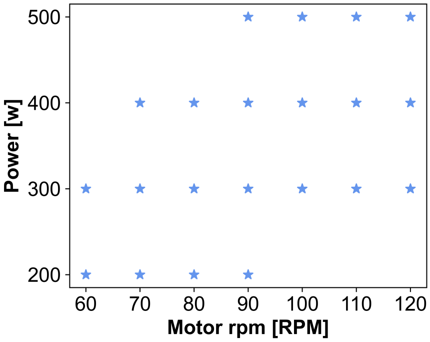

Fig. 2: Testing conditions used for efficiency characterization

Each test condition in **Fig. 2** was maintained for a duration of 60 seconds to ensure stable and representative data collection. The steady-state region of each test, where the power values had stabilized, was used to calculate the average power before and after the chain, which was then used to calculate the efficiency. This approach minimized the influence of transient effects and provided a more accurate representation of the chain's performance under the given conditions. Further details regarding the data analysis and extraction of steady-state test sections can be found in a separate paper [19].

In addition to the characterization test, a wear testing procedure was implemented to simulate sustained usage of the chain before conducting subsequent characterization tests. The wear tests involved running the chain at a constant power of 250 watts and a cadence of 100 RPM for a period of one hour. This combination of power and cadence was selected to represent a common and moderate level of cycling intensity, ensuring that the chain experienced realistic wear conditions.

Each chain and lubricant combination was tested using both characterization tests and wear tests. The chain was first tested using a characterization test, followed by a wear test, and then the process was repeated. This characterize-wear cycle was continued until a significant change in chain efficiency, typically around 1%, was observed, or until a distinct trend was identified.

3.4 Metrics of Merit

The chain efficiency was characterized using the "DC Metric" (Dowd-Cavanaugh) slope and intercept values. The DC Metric, further detailed in [19], was developed to describe chain efficiency under any given testing condition using only two values. Points from a characterization test (Section 3.3) were plotted with the DC Metric on the X-axis (**Eq. 1**) and chain efficiency on the Y-axis. An ordinary least squares (OLS) linear regression was then applied to these points, yielding an intercept and slope value, as illustrated in **Fig. 3**. Using these intercept and slope values, the efficiency of the chain under any given condition can be calculated using **Eq. 2**.

$$DC_{metric} = \frac{RPM^{0.3}}{Torque} \tag{1}$$

$$\eta_{chain} = DC_{slope} \cdot DC_{metric} + DC_{intercept} \tag{2}$$

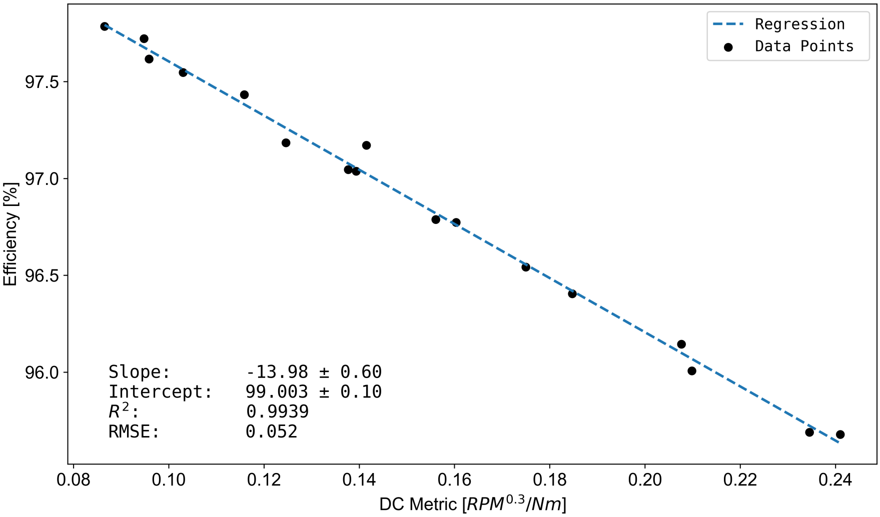

Fig. 3: Chain characterization data points with overlaid ordinary least squares linear regression of the DC metric vs efficiency, resulting in a slope and intercept value

For illustration purposes, the plots shown in Section 4 calculate the efficiency under various conditions. To facilitate understanding, the approximate road gradient and speed of these conditions are provided, calculated using the ANT+ equations from Garmin [22]. These equations, commonly used in virtual racing to simulate virtual avatar speed, offer a general estimation of a cyclist's speed given power and cadence under standard resistances.

3.5 Statistical Analysis

The uncertainty of the slope and intercept values was calculated using a standard margin of error calculation from OLS regression. The t_{crit} was calculated using the Percent Point Function (PPF) with $\alpha = 0.05$ and ν set to the residuals from the OLS (**Eq. 4**). SE was the standard error from the OLS (**Eq. 3**). The margin of error was calculated using **Eq. 5**.

$$SE = \frac{\sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{n-2}}}{\sqrt{\sum(x_i - \bar{x})^2}} \tag{3}$$

$$t_{crit,\alpha/2} = t_{ppf}(1 - \alpha/2, \nu) \tag{4}$$

$$MOE = t_{crit,\alpha} \cdot SE \tag{5}$$

4 Results

All results are presented with their associated uncertainties, expressed as the margin of error from the OLS regression as explained in Section 3.5. A 3-point averaging window was applied to better represent the overall trend of the data.

Fig. 4 illustrates the results of a repeated application of a single dry-based lubricant to a bicycle chain. The procedure involved applying the dry lubricant to the chain, running the chain for several hours, and then completely stripping the chain of lubricant using the cleaning procedure. This procedure was repeated three times.

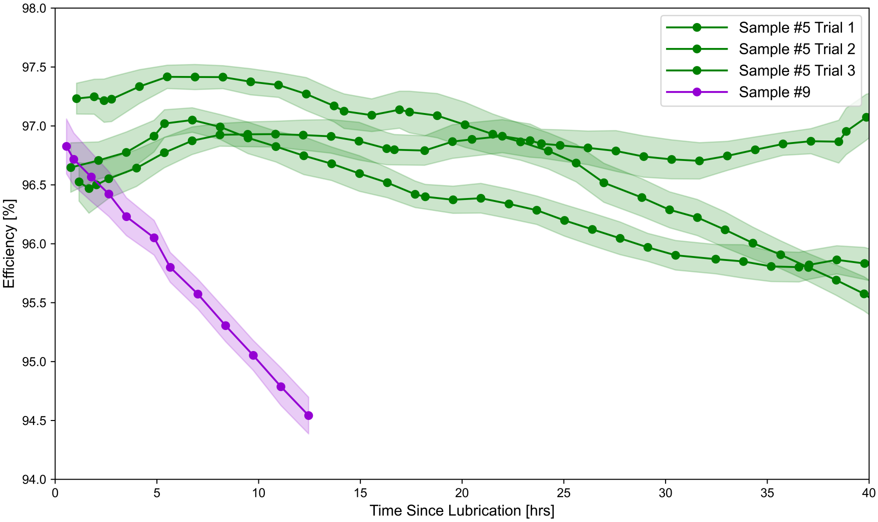

Fig. 4: Dry-based lubricant comparison, including repeatability over three trials (shown in the "flat" condition)

Fig. 5 presents the results of repeated applications of a wax-based lubricant to two chains. The sample #6 Trial 1 chain underwent a sequence of waxing, testing, stripping, and re-waxing, followed by another round of testing (Trial 2). The second chain was subjected to a single cycle of stripping and waxing (Trial 3). The figure displays the chain efficiency data for each of the three trials, allowing for a comparison of the wax-based lubricant's effectiveness across multiple applications and different chains. **Figs. 4** and **5** are plotted with the same X and Y axis bounds for easier comparison.

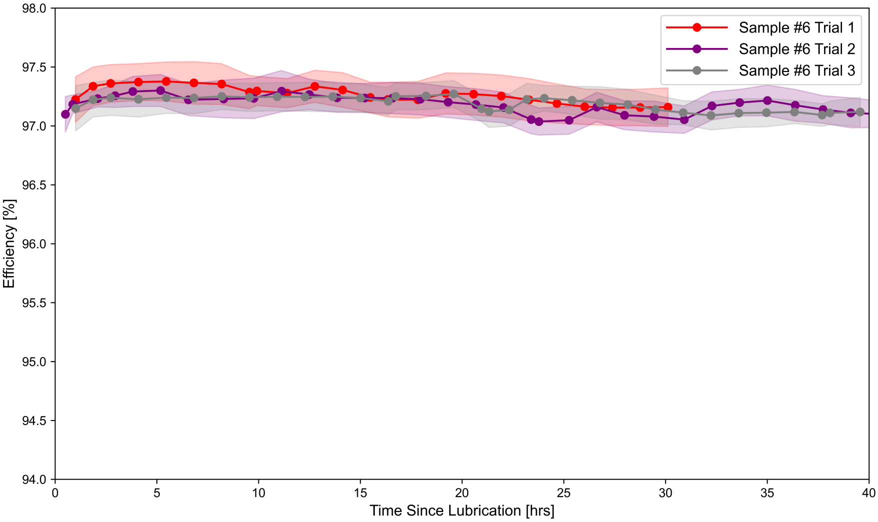

Fig. 5: Wax-based lubricant repeatability over three trials (shown in the "flat" condition)

Condition	**Power [W]**	**Cadence [rpm]**	**Gear**	**Grade [%]**	**Speed [kph]**	**DC**
Uphill	300	60	42:17	5.3	19.6	0.094
Flat	300	90	42:17	2	29.3	0.159
Downhill	300	120	42:17	-0.7	39.1	0.231

Table 2: Simulated conditions for efficiency evaluation

Figs. 6, **7**, and **8** present the efficiency of all tested lubricants under various simulated conditions (as detailed in Table 2) with the same Y-axis range for ease of comparison. **Fig. 6** illustrates the efficiency of a cyclist in an uphill scenario, characterized by a DC value of 0.094. This low DC value represents the a higher-resistance and lower speed experienced by a cyclist experiencing an uphill gradient. **Fig. 7** depicts the efficiency of a cyclist maintaining a steady pace on a nearly flat road, with a DC of 0.159. This moderate DC value reflects the medium resistance level and speed. **Fig. 8** showcases the efficiency of a cyclist in a downhill scenario, where the DC reaches 0.231. The high DC value represents the higher-speed, low-resistance condition associated with a downhill gradient. These figures collectively provide a comprehensive overview of the lubricants' performance over time across a range of realistic cycling conditions.

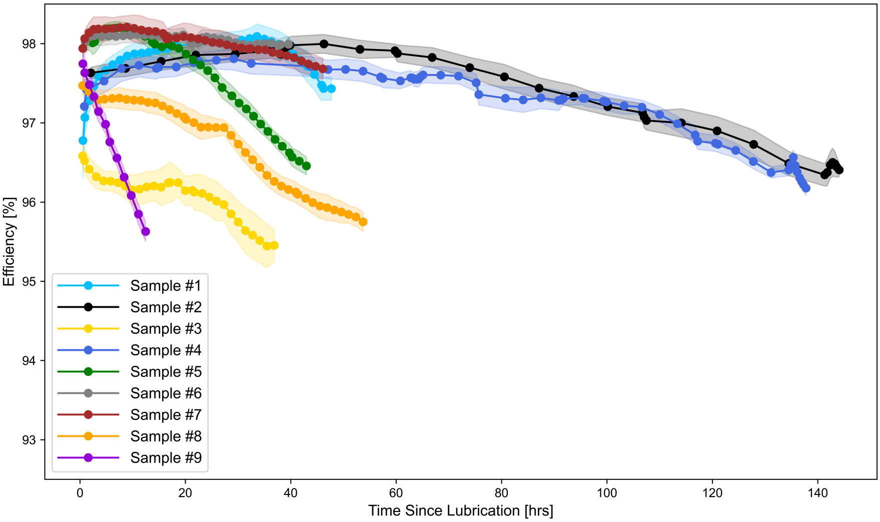

Fig. 6: Comparison of various lubricant efficiencies in the "uphill" example case

5 Discussion

The repeatability results presented in **Figs. 4** and **5** highlight the significant differences between wax-based and dry-based lubricants in terms of repeatability and efficiency. The dry-based lubricants (**Fig. 4**) exhibit substantial inconsistency in chain efficiency across the three runs, despite the application process being tightly controlled. This variability suggests that the performance of dry-based lubricants may be inherently less stable over time. In contrast, the wax-based lubricant comparison (**Fig. 5**) demonstrates remarkable consistency, including overlapping confidence intervals. This observation underscores the superior repeatability of wax-based lubricants, which is a crucial factor in maintaining consistent chain performance.

The **Figs. 6**, **7**, and **8** illustrate the differences of efficiency under a variety of riding conditions. There is a notable difference in efficiency between the uphill case where efficiency maximum is over 98%, whereas in the downhill case the efficiency peaks at only 96.6%. Additionally, the dry-based lubricants performed slightly better at higher speeds, likely due to the higher viscosity

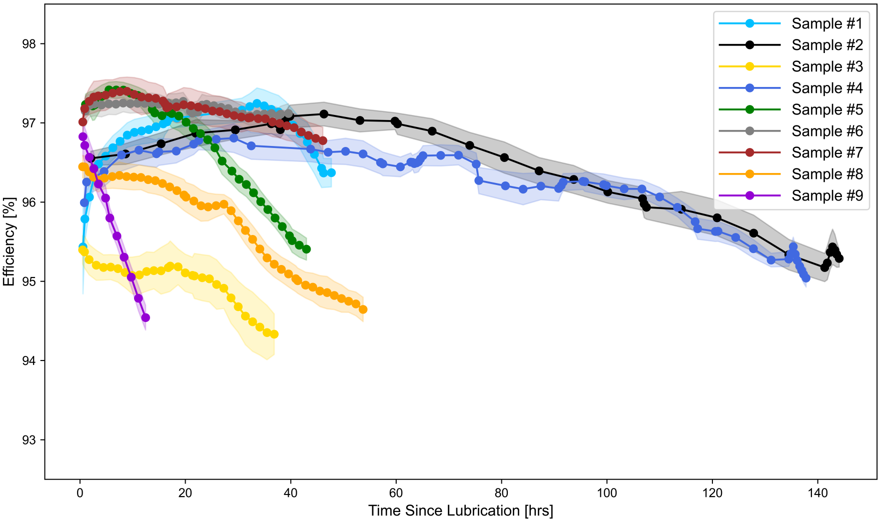

Fig. 7: Comparison of various lubricant efficiencies in the "flat" example case

of the waxes which may slow down chain link articulation at higher speeds compared to the dry-based lubricants which use dry lubricating particles to reduce friction. While a small difference, it is an interesting finding that the dry lubricants work better under faster conditions.

This insight opens up the possibility of strategically selecting lubricants based on the characteristics of a given race. For instance, in events with predominantly high-speed sections, such as time trials or downhill stages of road races, the use of dry-based lubricants could provide a slight advantage in terms of efficiency. Conversely, in races with more varied terrain and slower speeds or dominated by climbs, wax-based lubricants may be preferable due to their superior efficiency in high-torque conditions, as well as their consistent performance across a wider range of conditions. Further research exploring the nuances of lubricant choice in different racing scenarios could yield valuable insights for optimizing bicycle chain efficiency and ultimately enhancing race performance.

The wax-based lubricants exhibit varying trends in reaching their maximum efficiency. The wax-based samples #2 and #4 required approximately 50 hours of running time to attain their peak efficiency levels. This gradual improvement suggests that these lubricants may have a breaking-in period, during which the wax is working itself into the interfaces leading to progressively reduced friction. In contrast, sample #6 achieved maximum efficiency almost immediately, indicating significant differences between different formulae of wax-based lubricants.

The identification of distinct groups of waxes – those excelling in longevity, others in initial performance, and some with generally poor performance –

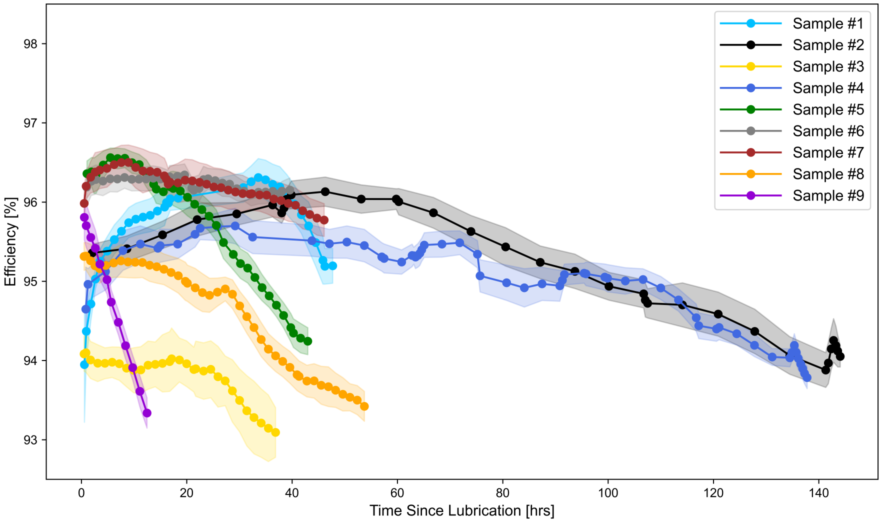

Fig. 8: Comparison of various lubricant efficiencies in the "downhill" example case

highlights the complexity of lubricant formulation and the potential for optimization. To build upon these findings, future research is planned to expand the testing of various waxes and wax combinations. By systematically evaluating a broader range of wax-based lubricants, it may be possible to identify specific formulations that synergistically combine the desirable properties of longevity and initial performance. This optimization process could lead to the development of advanced wax-based lubricants that provide superior overall performance, catering to the diverse needs of cyclists across different riding conditions and disciplines.

6 Conclusion

This study has demonstrated the varying performance characteristics of different wax-based and dry-based lubricants over time. Wax-based lubricants exhibit consistent efficiency and durability, making them suitable for prolonged use under diverse cycling conditions. In contrast, dry-based lubricants may offer superior performance in high-speed scenarios for short periods. These findings provide valuable insights for cyclists, mechanics, and lubricant manufacturers, enabling more informed decisions on lubricant selection tailored to specific riding conditions and performance goals.

Acknowledgements

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Conflict of Interest

Josh Poertner is the owner of the lubricant brand SILCA, and provided some of the lubricants tested in this study. To ensure the impartiality and integrity of the research, Mr. Poertner was not involved in the design, execution, data collection, analysis, or interpretation of the study results. The authors declare that Mr. Poertner's association with SILCA did not influence the findings presented in this paper, and all data has been reported accurately and transparently without interference.

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