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GUIDANCE DOCUMENT ON PHYSICAL TESTING OF CHAIN LUBRICANTS

DAVIDSON S, KAMPS T J, KNOTT A J, SHAYLOR J

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Davidson S, Kamps T J, Knott A J, Shaylor J
Engineering Department

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National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

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Approved on behalf of NPLML by
Bruce Duncan, Group Leader
Mass Metrology Group, Materials and Mechanical Metrology Department

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1 INTRODUCTION

The purpose of this document is to offer guidance on an objective methodology for the real-world testing of bicycle chain lubricants.

Bicycle chains are used to transmit power from a chainring to a rear cog – the power is applied to the chainring by the cyclist via the pedals and crank arms and the rear cog may be one of many of different sizes within a cassette or a single standalone item. In some set-ups, the chain may also pass through a rear tensioning derailleur system, making further contact with two small jockey wheels. Bicycles may also have front derailleur systems to shift the chain between different chainrings but, as these should make no continual contact with the chain during normal operation, they are not further considered.

Lubrication of the chain imparts a number of benefits, including:

- Reduction of friction within the chain, slowing down the wear between the chain's pins, rollers, and plates, extending its life
- Reduction of friction between the chain and the chainring, cog, and jockey wheels, slowing down the wear of both the chain and these other items, again extending their lives
- Protection of the chain from corrosion and ability to act as a barrier to the ingress of, and even help flush out, foreign particles
- For bicycle set-ups with cassettes, smoother gear-shifting performance

One further major benefit resulting from these reductions in friction due to lubrication is an increase in efficiency – the less power that is being lost in heat, wear, and noise, the more that is being transmitted to the cog and the more efficient the transmission system is.

This report does not look into the chain protection or gear-shifting benefits of lubrication – instead it focuses on how a given lubricant performs in terms of minimising frictional losses, and a representative measure of this performance is given by determining the efficiency of power transmission from a chainring to a cog. The procedure to determine this efficiency comprises the following stages:

- Selection and cleaning/de-greasing of one or more bicycle chains
- Inspection of chainring and cogs for condition and wear
- Cleaning/de-greasing of chainring and cogs
- Application of lubrication to chains
- Power transfer efficiency testing of chains and analysis of results

This document does not specify precisely how this work is to be performed but it is vital that, before commencing any work, all potential safety risks should be reviewed and that resulting mitigations should be agreed and documented.

2 TEST PROGRAMME DESIGN

This section discusses how the test programme is designed and the strategic decisions that need to be made related, in particular, to one or multiple chains and the lubrication regime employed.

Ideally, the mechanical system used for this work would introduce no losses so the results would simply be a measure of the lubricant's performance. However, this is not the case as there will be inherent losses, however carefully the system is designed. These losses will include, but are not limited to, the work required to elastically deform both the chain and teeth of the chainring and cog, the work required to accelerate the chain links around the system, and friction in the system's various bearings. Some of these contributions will remain constant for tests with different chains while others will depend on the actual chain itself, as no two chains will be identical.

It is practically impossible to put an absolute value on these combined losses but a limit on their magnitude can be derived from the best-performing lubricant test results. Other lubricants can then be compared against this best-performing benchmark efficiency figure. In the event that a lubricant performs better than the benchmark, this would then become the new benchmark, further reducing the possible magnitude of the system's inherent losses. This document therefore focuses on a methodology for the comparison of two different lubricants. The stability of this benchmark lubricant's performance with time enables two other lubricants to be compared against each other, even if they are not tested at the same time.

2.1 RUN-IN

During the initial motion of a lubricated tribological contact there is wear that occurs on the interacting surfaces. Typically, the running-in process is designed to operate the contact in an ultra-mild to mild wear regime. This permits the surfaces to wear such that they are conformal at an asperity level. The resulting increase in real contact area reduces the local contact pressure, allowing the contact to support the design load at the specific conditions and wear rate. The end of the run-in process is indicated by asymptotic friction data, indicating the contact has reached a steady state.

The wear debris produced during this phase can compromise the lubricant film, so by cleaning the chain after this step the lubricant performance evaluation is not affected by variations in the initial conditions. The advantage of using a run-in oil ensures that an initial set of conditions can be achieved repeatably before testing regardless of the initial surface topography and geometric misalignment.

The run-in process is specific to the surfaces and the contact conditions. Any changes that increase the severity of the contact (the dissipated friction power) therefore induce an additional running in process. As this process "matches" the surfaces, changing an individual component will also result in a run-in process being required. This has implications on the type of method chosen to evaluate a particular chain lubricant.

2.2 CHAIN SELECTION

The duration of the run-in process will depend on the alignment and conformity of the sliding interfaces in the assembly. The manufacturing tolerance of commercially available chains varies considerably between chains of different grades and from different manufacturers but can permit significant chain-to-chain variation – it's also worth noting that lubricant performance is not independent of chain design. Consequently, the specific chain used will have an effect on the measured performance of the lubricant and the test methodology must take this fact into account. This can either be done by using a single chain or by using multiple chains, as detailed in the following.

Single chain

Prior to testing with lubricant A, the chain, chainring, and cog will need to be cleaned, and a reference lubricant applied. The test programme will then proceed with run-in until steady state friction conditions are achieved. The friction data can be compared with a reference to ensure the components are operating as expected. The chain, chainring and cog will then need to be cleaned to remove debris associated with run-in. Following this, lubricant A is applied to the chain and then subjected to the test programme. The chain, chainring, and cog will then need cleaning again, followed by the application of lubricant B to the chain and repetition of the test programme. As the condition and performance of the chain will be changing throughout these tests, a simple comparison of these results would not be enough to determine the difference between the lubricants. Instead, the process should be repeated at least once but preferably multiple times so that a significant series of A-B-A-B-A-B…, or A-B-B-A-A-B-B-A…, results can be recorded – these can then be plotted against time and the underlying variation between the two lubricants determined.

Multiple chains

The effect that an individual chain may have on the results can be mitigated by testing a number of chains, randomly selected from a collection of nominally identical ones, with each lubricant. The optimal number of chains to be tested is likely to be a function of the ratio between the lubricants' reproducibility and the absolute difference between the two lubricants – i.e. more tests will be needed for lubricants whose efficiencies are either closer to each other or have greater scatter around their mean value. The reproducibility of the results for a given lubricant on different chains will enable a test of statistical significance between different lubricants to be made. The reproducibility of results obtained during run-in periods for the same lubricant on different chains may also help identify errors in set-up due to misalignment or faulty parts.

This approach may still require diligent cleaning of the chainring and cog between tests to avoid the presence of residual lubricant present affecting the performance of lubricant in subsequent tests. However, there is an alternative option to pair individual chains with their own specific new chainring and cog for both the run-in and subsequent testing.

Using multiple chains to determine the difference between lubricants is the preferred option, for the following reasons:

- In the single chain case, it is a much more labour-intensive preparation process as, without diligent cleaning of the chain, chainring, and cog, there may be residual and/or degraded lubricant present from previous tests which may affect the performance of lubricant in subsequent tests. Some oils contain additives that react with the component surfaces - when testing these, chemical analysis should be completed to ensure these are removed from the surface.

- Again, in the single chain case, for a significant number of repeated tests to be performed before the chain's performance significantly deteriorates, there is a limited amount of mechanical work that can be done during each test, meaning that the full performance envelope of the lubricant is unlikely to be covered.

- In the single chain case, the repeated cleaning of the chain, chainring, and cog, even if performed perfectly, may degrade performance, particularly if the chain has manufacturer-applied coating.

- There is a running-in period after each test assembly before the friction force achieves its minimum value. This process will affect the first measurement of each lubricant after the run-in process with the reference oil, so the fewer run-in periods an individual chain is subjected to, the better.

3 CHAIN, CHAINRING, COG PREPARATION

3.1 CLEANING

In order to ensure that the lubrication under test is being applied to a consistent substrate (chain/chainring/cog surface) a repeatable and effective cleaning procedure needs to be applied. Even when dealing with unused components a surface coating of hydrocarbon will be present and should be removed before undertaking the lubrication procedure being tested.

As part of a European collaborative research project (NewKILO), extensive testing was done by NPL and project partners into removing hydrocarbon contamination from the surface of mass standards of various metals and alloys (predominantly platinum-iridium, stainless steel and tungsten) [1]. While the research mainly focussed on cleaning a few monolayers from the surface of high accuracy mass standards, the cleaning processes evaluated - and methods developed - can be more generally applied to the removal of hydrocarbon contamination from metallic surfaces.

The most effective and universal method for the cleaning of mass standards was found to be the use of an ultrasonic bath combined with a suitable solvent such as ethanol or acetone. In addition to its effectiveness at removing surface contamination, the use of an ultrasonic bath has the additional advantage that it will also remove contamination from voids within the components. When removing the parts from the solvent, the part should be washed using fresh solvent to ensure that contaminated solvent doesn’t evaporate leaving residue on the cleaned surfaces. However, given the likely level of hydrocarbon contamination on the components being tested the following procedure is recommended;

1. Remove excess oil using a dry, adsorbent cloth
2. Clean the components using detergent in hot water and a brush
3. Place component(s) in an ultrasonic bath to remove the remaining contamination form the surface and from voids within the components.

3.2 SURFACE PRE-TREATMENT

Research into the cleaning of metal surfaces indicated that once cleaned, surface analysis using X-ray photoelectron spectroscopy (XPS) revealed an overlayer of oxide on the metal which was incomplete (i.e. the top surface was a mixture of exposed metal substrate and metal oxide). Treatment of the metal surface by immersion in boiling water for several minutes promoted the growth of a complete surface oxide layer. This has the advantage that the surface layer of the component would be more stable and that it would be easier to clean (since the surface energy would be less and therefore the hydrocarbon contamination would be less tightly bonded).

3.3 GRAVIMETRIC MEASUREMENTS

It is recommended that gravimetric measurements (weighing) are used to assess the effectiveness and repeatability of the cleaning process. If performed at a suitable level of accuracy (a balance resolution of 1 mg or better is recommended) gravimetric measurements can confirm that a suitable level of residual hydrocarbon contamination has been removed. More widely regular gravimetric measurements can be used to assess the retention of lubrication on the components during use and to check for wear on components once cleaned. A threshold for excessive wear should be established by confirming gravimetric mass loss with optical analysis. Worn chainrings and cogs have a modified pitch which has a deleterious effect on chain engagement and therefore friction losses.

4 LUBRICATION PROCEDURE

4.1 LUBRICATING OILS

4.1.1 Properties

The friction and wear performance of a lubricating oil is attributed to the bulk properties of the base oil, typically its viscosity, and the additive chemistry. The viscosity varies with temperature and pressure both globally and locally in the local contact. Additive chemistry forms protective films that are either physically adsorbed or chemically absorbed onto the surface. Activation of the additive chemistry requires a particular energy threshold to be exceeded and is derived from the interaction of the sliding surfaces in the interface. Both the viscosity and the additive chemistry influence the friction loses and wear of components in a chain drive.

4.1.2 Cleaning

Chains are supplied covered in the manufacturer’s lubricant; it is important that this is removed for reasons explained in Section 3. Manufacturers may specify a lubricant which is matched to the coating on the surface of the chain. These coatings can be produced from a variety of chemistries, which influence the formation of protective additive films. Also the potential for the chain coating to be modified or removed by the solvent used to clean the chain should be considered. The chain coating will impact the measured performance of specific lubricant and is therefore a variable that must be controlled but is also a source of experimental bias.

4.1.3 Application

In preparing a chain with lubricating oil, the temperature should be controlled to ensure that viscosity is sufficient to allow it to flow into the contact. The viscosity of chain lubricants varies as does their viscosity index which is the relationship between the oil viscosity and temperature. If elevated temperatures are used, this should be controlled carefully to ensure the process is repeatable as it will impact on the formation of protective additive films before testing.

Repeatable lubrication of a clean chain is reliably achieved by full immersion and chain articulation, usually at room temperature. This method requires a large quantity of lubricant compared with localised dripped application but it does ensure that the lubricant can enter all the sliding interfaces and that there is sufficient lubricant to saturate them. Similar repeatability can be achieved using the drip approach but this requires careful attention to the procedure by the operator.

4.1.4 Test assembly

Some lubricant additives can be activated whilst handling the chain during set-up. This is mostly likely to occur if the specified chain tension is reached. Care should be taken to treat all chains to the same process such that variations in the history of the surface and lubricant environment are minimised.

The amount of lubricant that is retained once the chain is being used to transmit power depends on a variety of factors and will vary between lubricant formulations. This will affect the durability of the friction performance achieved; however, this will only be a factor when considering long duration tests.

4.2 LUBRICATING WAXES

Lubricating waxes are applied to chains at elevated temperatures as liquids. One method involves placing the wax and chain together in a container and then heating the wax using a water bath. The container is removed and the chain articulated to help the wax flow into the sliding chain interfaces. This process is repeated several times informed by empirical experience.

During testing only wax that is already present in the tribological interfaces can lubricate as the global temperature is unlikely to be sufficient to allow the wax to melt and flow into the contact. However the high local contact pressure in the contacts will cause local softening. Therefore during application it is important to ensure that the wax penetrates the contacts repeatably. Additional wax on the non-contacting surfaces of the chain is unlikely to affect its friction performance.

5 POSSIBLE CHAIN DRIVE LOSS MEASUREMENT TEST RIG DESIGNS

A number of different types of apparatus for measuring losses in chain drives, including the effect of lubrication, have been developed – these are summarised, together with their pros and cons, in the following:

5.1 PENDULUM RIGS

These rigs [2] [3] set a mass swinging in a pendulum motion either from the end of a chain wrapped around a sprocket or, in a tensioned low-friction dual sprocket set-up, from the centre of the upper sprocket. A laser interferometer is used to measure the oscillatory decay of the pendulum, where the decay rate is a function of the friction within the chain / sprocket interfaces.

Very low measurement uncertainty is achievable using these methods. However, as the load and sliding velocity in the tribological contact are not representative of real-world conditions, the measured lubricant performance cannot necessarily be extrapolated.

5.2 DYNAMOMETER RIGS

These rigs employ torque and velocity measurement transducers to determine the power being applied to, and (for some designs) extracted from, the system under test. There are two major types of such rigs.

5.2.1 Full Tension Test (torque recirculating)

In these tests [4], the driving and driven cogs are forced apart to introduce tension in both spans of the chain between them. The input power is simply that required to overcome the friction introduced by this force and can be determined as a function of both force and cadence. This has the significant advantage that the torque transducer used to measure the friction loss can have a smaller range and therefore increased resolution and reduced uncertainty. This is particularly useful when quantifying the relatively small changes in torque achieved by the lubricant. The major disadvantages are that the chain is not transmitting real-world power levels and that its lower span is as highly tensioned as the upper one. These affect the duty cycle and subsequent thermal recovery of the contacts, producing conditions unrepresentative of the real world.

5.2.2 Full Load Test (torque transmission)

In these tests [2] [5] [6], both the input and output power are measured, with the intermediate system being representative of a real-world transmission set-up. Another advantage of this type of system is that it is possible to introduce realistic dynamic content to the control loop, further replicating the duty cycle that the chain, and other components, would see in practice. The disadvantages are the cost and complexity of the design and torque measurement systems, coupled with the high-power requirements for both the drive and brake systems.

6 TEST EQUIPMENT REQUIREMENTS

6.1 POWER TRANSFER EFFICIENCY.

The test equipment should be designed in a way that enables the lubricated chain to be loaded in a manner that is representative of the loading it would experience during its use on a bicycle, including a means for setting or maintaining chain tension – of the rigs described in Section 5, only the Full Load Test type (Section 5.2.2) meet this requirement. The magnitudes of the forces and speeds to which it is subjected will vary between different cycling applications – this will be covered further within Section 7 – but the basic principle of the chain being driven through a larger chainring with the power being extracted via a smaller cog remains.

In order to determine the efficiency of this power transfer, measurements of the power being applied to the chainring and of the power being applied to the cog need to be made. The power transmitted via a shaft is the product of the torque and angular velocity, as given in equation (1).

$$P = T\omega \tag{1}$$

where: P = power, in W
T = torque, in N·m
ω = angular velocity, in rad·s^{-1}

Using subscripts of 1 and 2 to relate respectively to input (chainring) and output (cog) measurements, the power transfer efficiency E, expressed in percentage terms, is given by equation (2).

$$E = 100 \times \frac{P_2}{P_1} = 100 \times \frac{T_2\omega_2}{T_1\omega_1} = 100 \times \frac{T_2}{T_1} \times \frac{\omega_2}{\omega_1} \tag{2}$$

6.2 TORQUE MEASUREMENT.

The instrumentation should be designed such that the values of torque being applied to the chainring and to the cog can be measured. This is likely to involve the use of two torque transducers: one located between the system used to provide input power (most likely a motor drive system) and the chainring; and the other located between the cog and whatever system is being used to provide the required resistance (this could be another motor, a bicycle trainer, a brake system etc.). The data from these transducers should be monitored and recorded throughout the testing, for real-time and/or subsequent analysis. Based on the recommended test protocol (see Table 1), the chainring and cog torque transducers should have capacities of at least 95 N·m and 32 N·m respectively.

It should be noted that the values of torque applied to the two transducers will be higher and lower than the values applied to the chainring and cog respectively – this is because there will be losses due to friction in the bearings and couplings between the transducers and their respective ends of the chain drive system. Efforts should be made to minimise and quantify the magnitude of these losses, which are likely to be dependent on a number of factors including, but not limited to: speed; torque; and misalignment (angular and lateral) between the transducer and chain rotation axes.

This document does not specify a required performance level for this torque measurement, although it should be borne in mind that the uncertainty associated with an individual lubricant's calculated efficiency will be directly related to the torque measurement uncertainty. However, when comparing lubricants, it may be that systematic components of the torque transducers' uncertainties have at most a minor effect on the uncertainty associated with the difference in lubricant performance.

6.3 ANGULAR VELOCITY MEASUREMENT.

As can be seen from equation (2), to determine efficiency, only the ratio between the output and input angular velocities is required rather than measurement of the velocity itself. If it can be demonstrated that, at a given specified speed, the rig is running in a smooth and constant manner such that there is insignificant variation in the chain velocity, this ratio can simply be determined as a constant value equal to the ratio of teeth between the chainring and the cog.

If the control of the system is such that there is significant variation in the chain velocity, these two angular velocities will both need to be measured.

7 TEST PROTOCOL

7.1 RUN-IN

Prior to performing the main test protocol, the newly-lubricated chain shall be installed in the rig, on a clean and dry chainring and cog, and exercised for a set period of time at specified speed and power values. The chain shall be aligned perpendicularly to both driveshafts and tensioned to a set value in a repeatable manner. It is recommended that this run-in period last for 10 minutes at the maximum power level to be experienced in subsequent testing, being delivered at a chainring speed of 90 rpm, equivalent to an applied torque of about 64 N·m for the recommended maximum power level of 600 W. The chain should then be removed from the rig, cleaned to remove any debris produced during this high-power stage, re-lubricated, re-installed in the rig at the same tension and alignment settings, and run for 5 minutes at a speed of 90 rpm and a power level of 300 W, equivalent to a torque of about 32 N·m.

As explained in Section 2.1, the end of the run-in process is indicated by asymptotic friction data – it should be checked that this stage has been reached before bringing the movement to a halt. The equipment is now ready for the main testing to start, although care must be taken to ensure that the system is in such a mechanical state that the torque transducers are giving valid zero readings or can be sensibly tared within the subsequent data analysis.

7.2 MAIN TEST PROCEDURE

There is a very wide range of application conditions for bicycle chains, and it is impossible for all to be covered within a single test protocol. This document therefore gives a recommended set of tests – this can serve as the basis for any amended set of tests as agreed between the customer and test provider. The rationale behind the selected values is as follows:

- The recommended chainring/cog combination of 42/14 is based on widely-available single-speed bicycle transmission systems, giving a gear ratio of 3:1

- A standard cycling cadence (chainring speed) ranges from 60 rpm to 90 rpm for a recreational cyclist up to 90 rpm to 110 rpm for an elite cyclist – this full range corresponds to road speeds of 14 mph to 26 mph for standard 700x25C tyres and the specified 3:1 gear ratio

- The majority of, though by no means all, flat road cycling is likely to be in the speed range from 15 mph to 25 mph, which roughly equates to a power range of 100 W to 300 W - however, it may also be of interest to see how lubricants behave at significantly higher power levels, as occasionally produced by elite cyclists

Table 1 suggests a set of fixed points at which the lubricant performance should be determined, and the protocol is shown graphically in Figure 1. The test is carried out in six consecutive sectors, each run at a specified cadence – note that these cadences are arranged such that they are neither monotonically increasing nor decreasing, to introduce some randomisation into the test conditions. Within each sector, the applied power is increased, then decreased, then increased again in discrete steps – at each step, once the applied power has stabilised, readings should be taken for a statistically-significant steady state period, the length of which will depend in part on data acquisition rate, transducer noise, filter settings, and any periodic signal content.

Table 1 Test parameters

Test sector	**Cadence / rpm**	**Input power / W**	**Equivalent input torque / N·m**
1	80	100 - 200 - 300 - 400 - 500 - 600 - 500 - 400 - 300 - 200 - 100 - 200 - 300 - 400 - 500 - 600	12 - 24 - 36 - 48 - 60 - 72 - 60 - 48 - 36 - 24 - 12 - 24 - 36 - 48 - 60 - 72
2	110	100 - 200 - 300 - 400 - 500 - 600 - 500 - 400 - 300 - 200 - 100 - 200 - 300 - 400 - 500 - 600	9 - 17 - 26 - 35 - 43 - 52 - 43 - 35 - 26 - 17 - 9 - 17 - 26 - 35 - 43 - 52
3	70	100 - 200 - 300 - 400 - 500 - 600 - 500 - 400 - 300 - 200 - 100 - 200 - 300 - 400 - 500 - 600	14 - 27 - 41 - 55 - 68 - 82 - 68 - 55 - 41 - 27 - 14 - 27 - 41 - 55 - 68 - 82
4	100	100 - 200 - 300 - 400 - 500 - 600 - 500 - 400 - 300 - 200 - 100 - 200 - 300 - 400 - 500 - 600	10 - 19 - 29 - 38 - 48 - 57 - 48 - 38 - 29 - 19 - 10 - 19 - 29 - 38 - 48 - 57
5	60	100 - 200 - 300 - 400 - 500 - 600 - 500 - 400 - 300 - 200 - 100 - 200 - 300 - 400 - 500 - 600	16 - 32 - 48 - 64 - 80 - 95 - 80 - 64 - 48 - 32 - 16 - 32 - 48 - 64 - 80 - 95
6	90	100 - 200 - 300 - 400 - 500 - 600 - 500 - 400 - 300 - 200 - 100 - 200 - 300 - 400 - 500 - 600	11 - 21 - 32 - 42 - 53 - 64 - 53 - 42 - 32 - 21 - 11 - 21 - 32 - 42 - 53 - 64

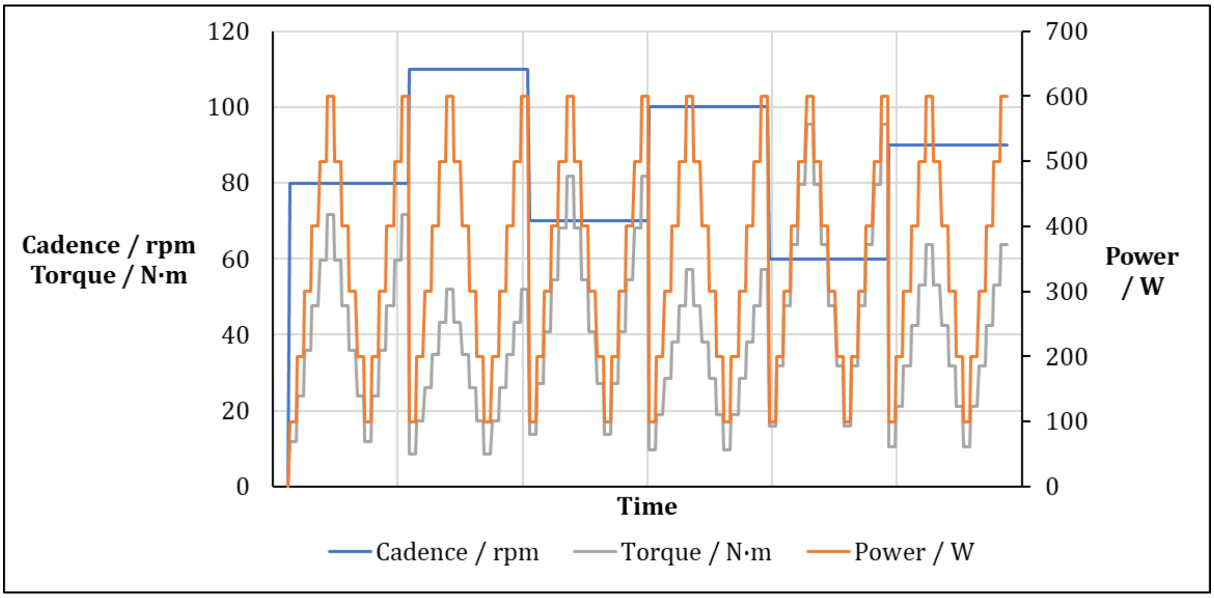

Figure 1 Graphical representation of test protocol.

8 ASSESSMENT OF RESULTS

8.1 AVERAGING CONSIDERATIONS

When assessing the acquired traces from the torque transducers and, if applicable, rotational speed measurement systems, it is possible, depending on the exact system arrangement and resistance methodology, that there will be some periodic content within the traces, and so some averaging approach will need to be employed to derive a single figure.

It is also possible, based on the control mode, that the periods of the torque and speed traces will be correlated, either positively (a greater input torque causing the system to spin faster) or negatively (a greater resistance torque slowing the system down). If this is the case, it is not appropriate simply to multiply the mean torque and speed values to obtain the power, as the resultant value will be either underestimated (for positively correlated values) or overestimated (for negatively correlated ones), as shown in Figure 2 and Figure 3, for torque varying between 20 N·m and 50 N·m, and speed varying between 8 $rad{\cdot}s^{-1}$ and 9 $rad{\cdot}s^{-1}$.

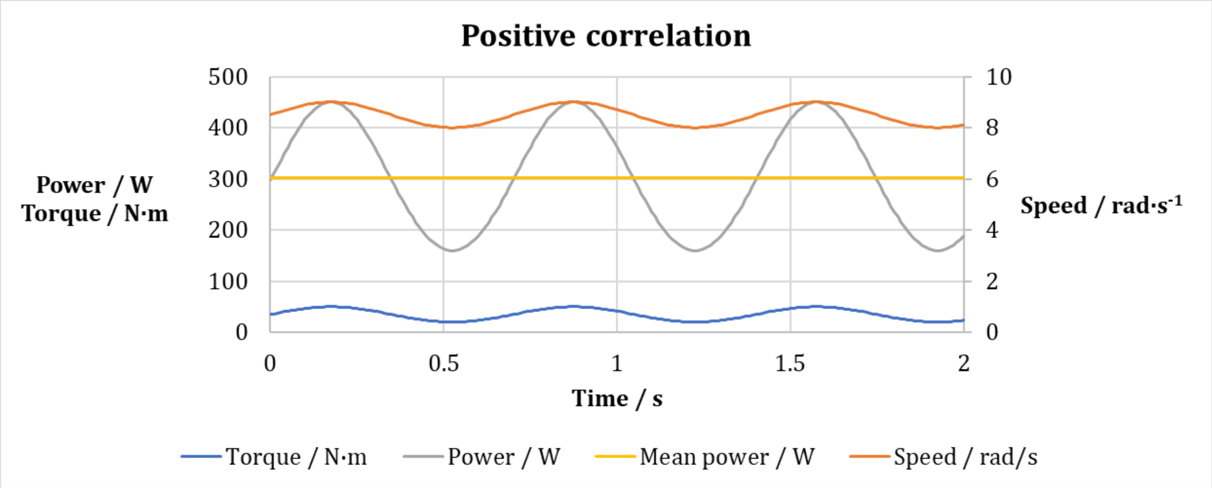

Figure 2 Mean power = 301.25 W, mean torque × mean speed = 297.5 W.

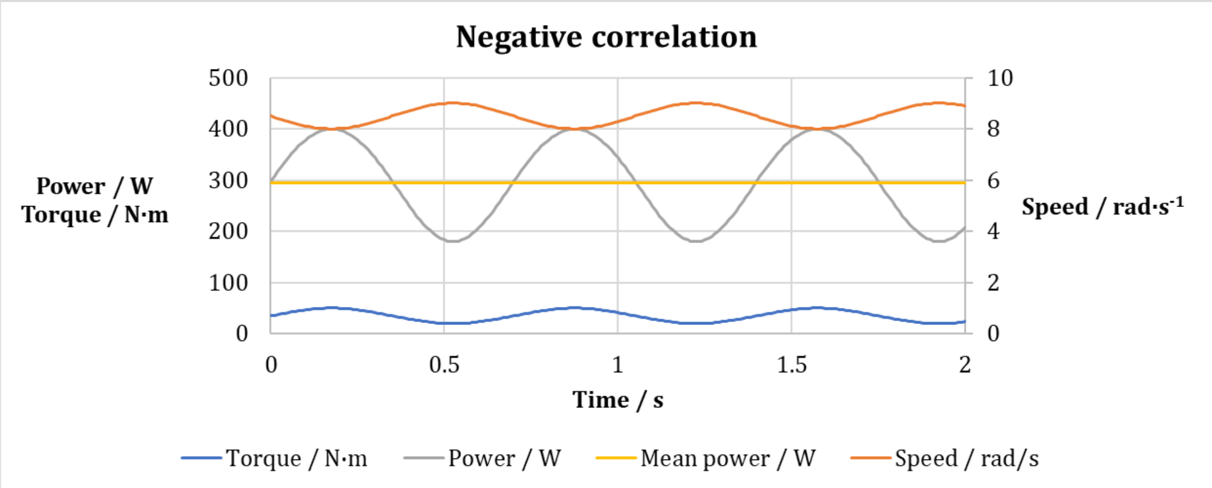

Figure 3 Mean power = 293.75 W, mean torque × mean speed = 297.5 W.

In these cases, instantaneous power values should be obtained by multiplying the raw torque and speed values – it is the average value of this power trace that is the best unbiased power estimate.

As specified in Section 7.2, readings should be taken throughout a steady state period of statistically significant length at each level. Analysis of the data should be based on the data within this period, taking care to ensure that no content affected by previous or subsequent level changes is included. Where there is periodic content within the signals, this time range should be further reduced to include only an integer number of periods.

8.2 PRESENTATION OF RESULTS

As detailed in Section 2, this document focuses on a methodology for the comparison of two different lubricants, so the results are presented on that basis.

The results from each lubricant are first separately calculated, based on the test procedure described previously. These results can be plotted in three different ways:

- Efficiency as a function of cadence, with a separate line for each power level
- Efficiency as a function of power, with a separate line for each cadence value
- Efficiency as a function of cadence and power, with a separate line for each efficiency level

Examples of these three plot types are given in Figures 4 to 6, for the same example data.

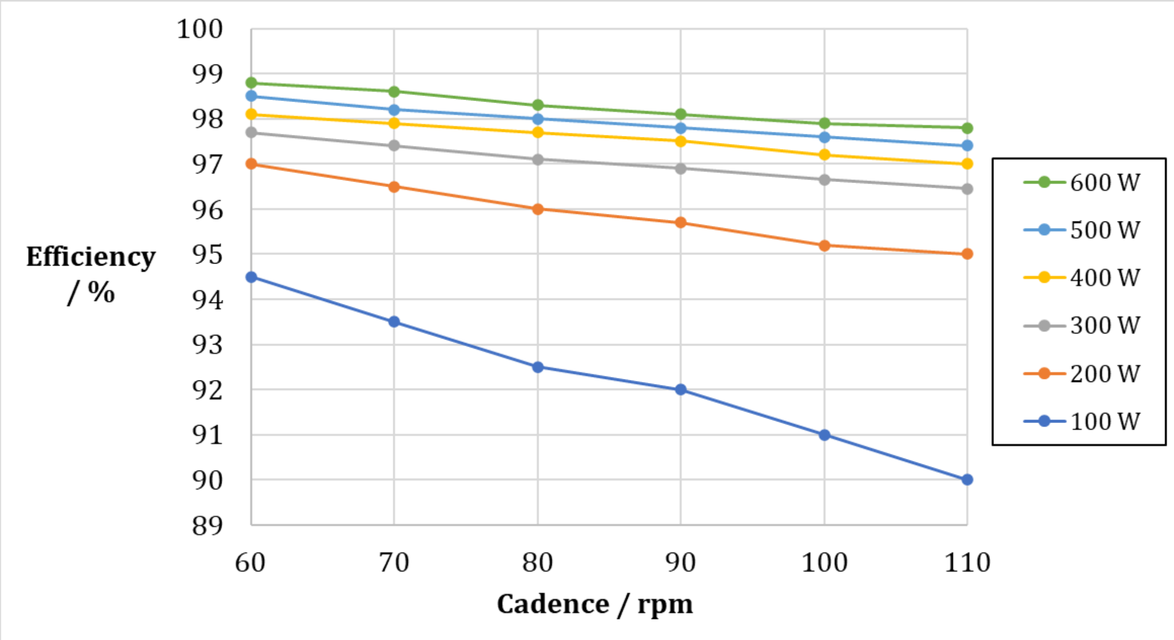

Figure 4 Efficiency as a function of cadence, at selected power levels.

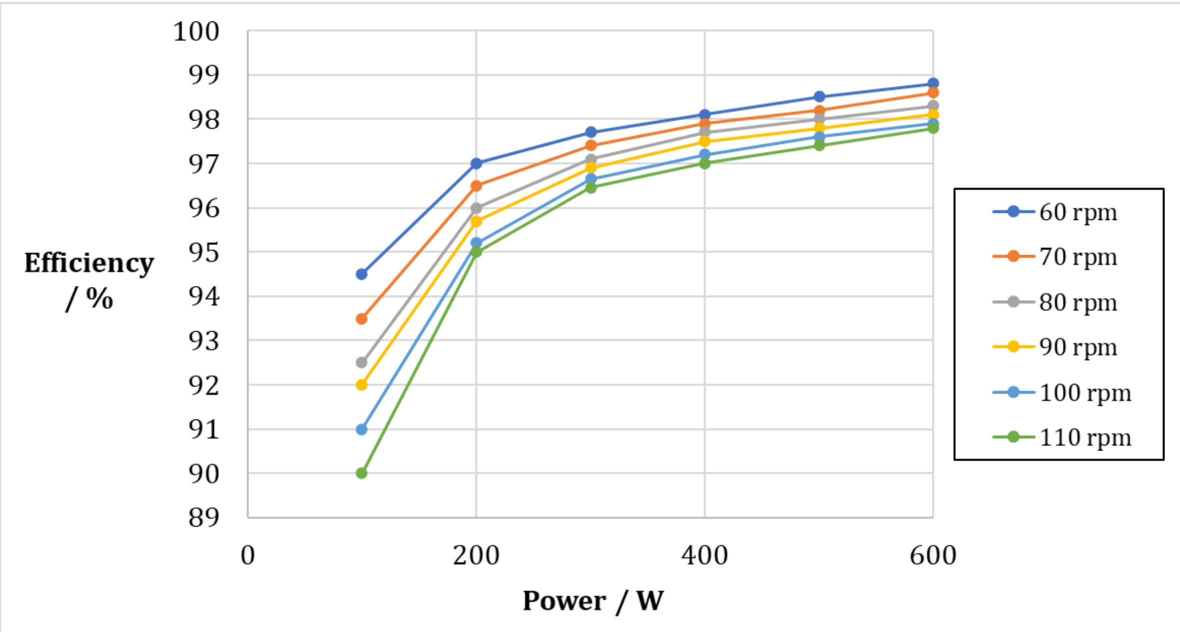

Figure 5 Efficiency as a function of power, at selected cadences.

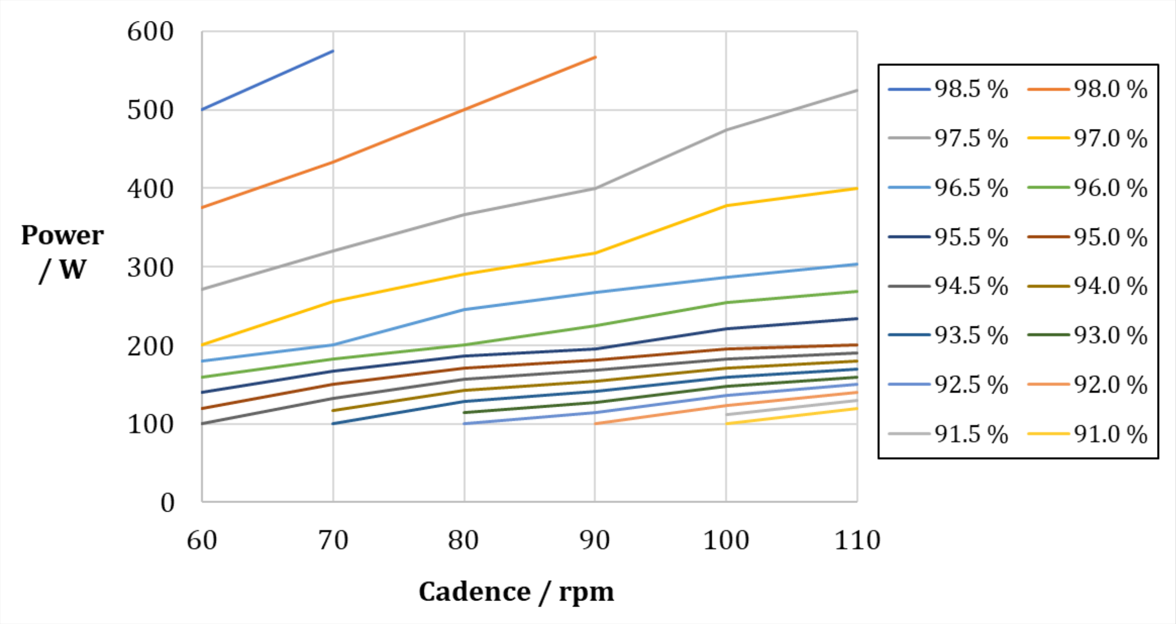

Figure 6 Efficiency levels plotted on a power-cadence map.

The points plotted in Figure 4 and Figure 5 are actual data, whereas the values in Figure 6 are derived from linear interpolation between obtained data points. This third type of graph, or a shaded version of it, may be useful for a quick synopsis of how a given lubricant performs but its use in quantitatively comparing two different lubricants is more limited.

Of the other two graphs, either could be used as the basis for a comparative plot – in the following, an approach using cadence as the x-axis input parameter, as in Figure 4, is employed.

Assume two lubricants A and B giving the characteristics shown in Figure 7 and Figure 8.

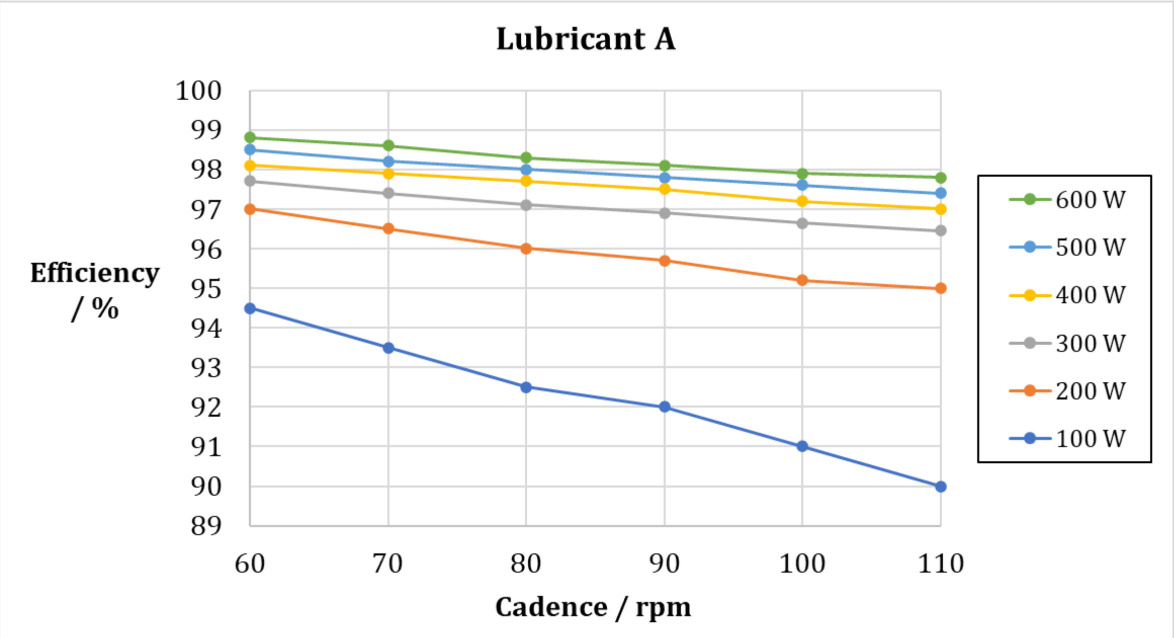

Figure 7 Efficiency of lubricant A as a function of cadence, at selected power levels.

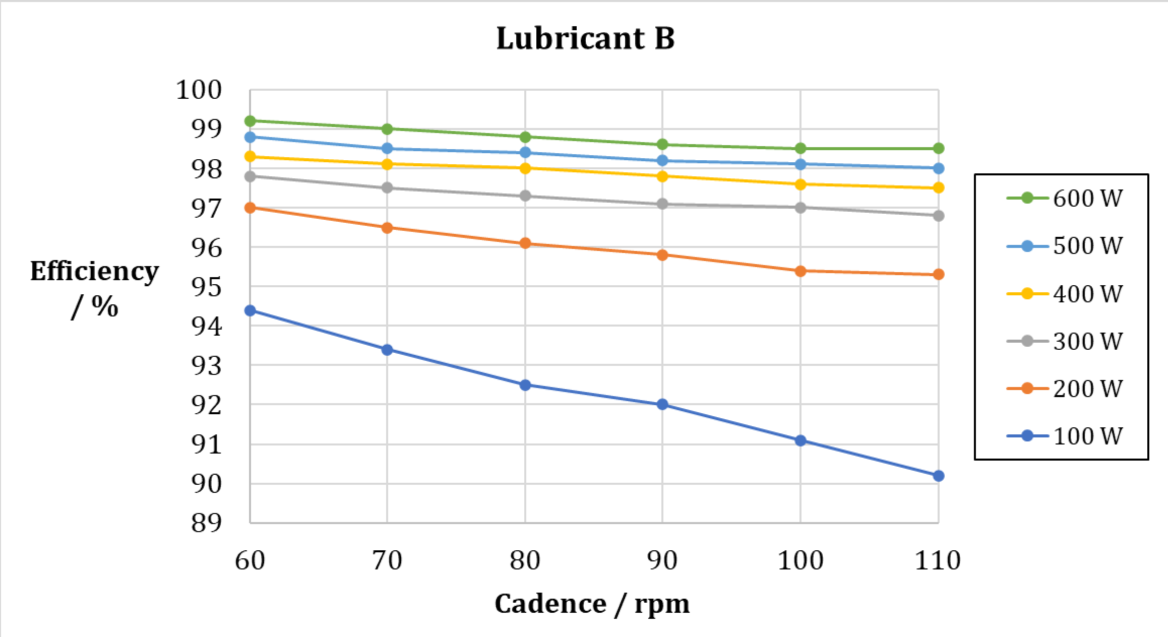

Figure 8 Efficiency of lubricant B as a function of cadence, at selected power levels.

The difference between the performance of the two is then simply the difference in efficiency at each data point, as shown in Figure 9.

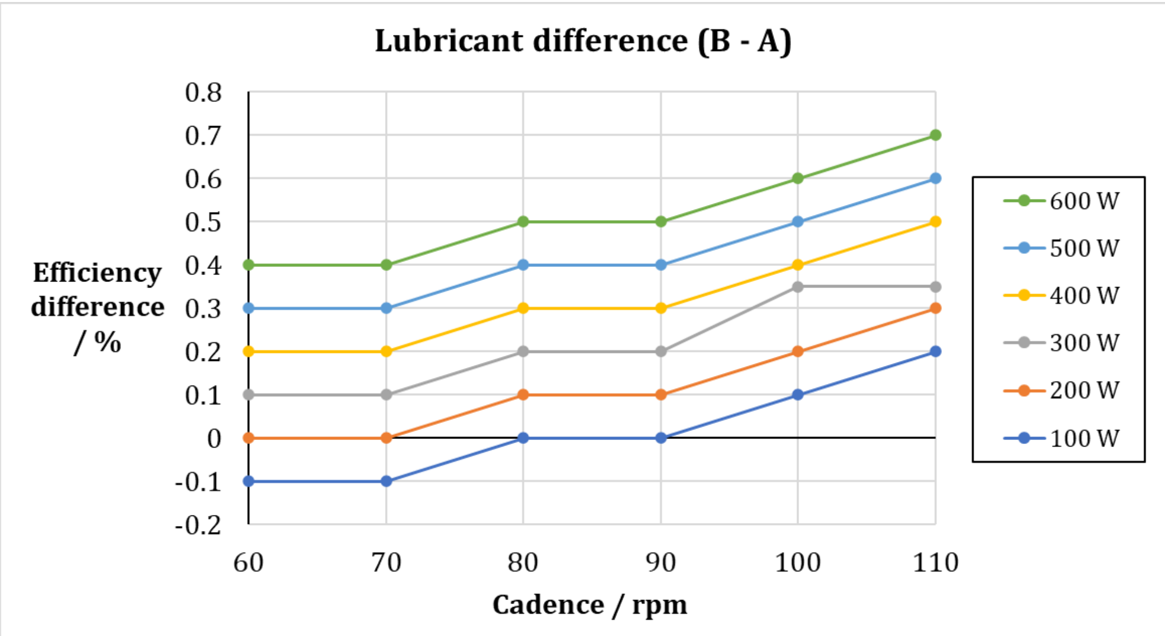

Figure 9 Difference between lubricants A and B.

Once a single lubricant has been thoroughly investigated and shown, in conjunction with a given chain and cleaning procedure, to give consistent results over time, any other lubricant can be measured against this one. As explained in Section 2, the stability with time of a specific lubricant's performance enables two other lubricants to be compared against each other, even if they are not tested at the same time.

8.3 UNCERTAINTY OF RESULTS.

As discussed previously, the measurement protocol outlined is designed to enable comparison between two different lubricants. The uncertainty associated with these results will be significantly smaller than the uncertainty associated with the absolute efficiency value of a single lubricant, but both uncertainty estimations will be discussed here.

8.3.1 Uncertainty associated with difference between lubricants

The major contribution to the uncertainty associated with the difference between two lubricants' performance is the reproducibility of the system. One method to evaluate this would be to follow the lubricant comparison protocol given above, but using the same lubricant as both Lubricant A and Lubricant B. If the system's performance was perfectly reproducible, and the lubricant samples were not significantly different, identical results should be obtained. Any variation in results would therefore be a measure of non-reproducibility of the system. Such tests could be regularly carried out over a period of time, giving a better estimate of the variability of the measurement system – environmental factors should be kept constant during these repeat tests.

It is likely that the reproducibility of the system will vary as functions of both cadence and power (or torque) – this variation should be characterised, ideally in terms of a standard deviation describing the distribution either side of a mean efficiency value.

Additionally, for a given lubricant comparison (neither of which need be the one used to determine the system's reproducibility – this should be lubricant-independent), a repeat test of the first lubricant after the second lubricant (i.e. Lubricant A – Lubricant B – Lubricant A) would give additional confidence in the system's performance throughout the tests.

At a given combination of cadence and power, the test as to whether the measured difference between the efficiency values of two different lubricants is statistically significant will be based on the system's reproducibility. As a rule of thumb, the difference is significant at a level of confidence of 95 % if it exceeds twice the standard deviation associated with the system reproducibility.

8.3.2 Absolute uncertainty associated with a single lubricant's efficiency

As previously discussed, the uncertainty associated with the absolute efficiency value determined for a single lubricant will contain many additional uncertainty contributions. This section details these components and suggests some methods for estimating their magnitudes.

The efficiency calculation is based on the measured reduction in power, so the two areas to focus on are the power measurements themselves and the other potential mechanisms for power consumption between the two power measurement locations.

<u>Power measurements</u>

Any uncertainty in the measurement of input and/or output power will contribute to the uncertainty of the lubricant efficiency. If, is as likely, the power is being calculated from the product of torque and rotational speed, the uncertainty associated with each of these parameters needs to be incorporated within the uncertainty budget. The torque uncertainty should be based on the transducer's calibration uncertainty with additional contributions relating to sensitivity drift since calibration, variation in loading conditions (bending), temperature, hysteresis, and any other parameters that may vary from its calibration condition – torque measurement uncertainty is also affected by set-up and applied duty cycle [7] [8]. It is important to ensure that the correct zero value is recorded by the torque transducers – backlash in the system can lead to a zero offset that will affect every calculated torque value.

The rotational speed of the input and output shafts should also be traceably measured – although, as explained in 6.3, it may be allowable simply to determine the speed ratio based on the gearing employed.

Power consumption mechanisms

Anything that could heat up or emit a sound within the system is a potential power consumption mechanism. The main one of these is likely to be friction, both in the system's bearings and within the whole chain drive arrangement. The aim of the lubricant is to minimise the power losses both within the chain and between the chain and the chainring, cog, and jockey wheels.

One method to assess potential frictional losses in the system is to lock the output shaft and apply an input torque – the ratio between the static torque values should be equal to the gearing ratio, with any reduction in output torque due to static frictional losses.

During movement, both the chain and the teeth of the chainring and cog are being subjected to periodic elastic deformation – this requires work, very little (if any) of which will be returned to the system during elastic recovery. For a given mechanical design of chain and other components, and at a specified cadence and power level, this power loss will remain constant, being unaffected by chain lubrication. The two driveshafts (one input and one output) will also be similarly affected by elastic bending and deformation, the magnitude of which will be determined by their geometry and the bearing systems employed to constrain them.

If the chain is thought of as a set of individual masses, work is also being done to accelerate, or change the velocity of, these masses as they move around the chainring, cog, and jockey wheels – the faster the chain is moving, the more energy is required to accelerate these individual masses, and this is another power loss that cannot be reduced by lubrication or other means.

Any instability or oscillation of the chain during testing will also require additional energy input to maintain its motion – this may be related to the tension in the chain which will also be related to the level of friction between the chain and its drive components.

Any angular and/or lateral misalignment of the chainring and cog will lead to additional friction both within the chain and between the chain and their teeth.

These contributions all relate to steady state motion of the rig – during increases of cadence, additional energy, and associated power losses, will be required to accelerate the rotating components, while reductions in cadence will see apparent power gains. This protocol is therefore only suitable for steady state regimes.

9 REPRODUCIBILITY CONSIDERATIONS

Summary of factors affecting the reproducibility of results which are stated throughout the document.

Table 2 Reproducibility considerations

Factor influencing power loss	**Reference**	**Method to quantify the potential power loss**
Work required to elastically deform both the chain and teeth of the chainring and cog	Sections 2 and 8.3.2	Mechanical analysis of system
Work required to accelerate the chain links around the system	Sections 2 and 8.3.2	Mechanical analysis of system
Friction in the system's various bearings	Sections 2 and 8.3.2	Design rig to allow direct torque measurement either side of bearing
Variation in chain tension	Section 6.1	Set a chain at different levels of tension and determine its efficiency as a function of tension
Instability/oscillation of the chain during testing (linked to chain tension)	Section 8.3.2	Monitor efficiency as a function of cadence while passing over unstable portion. Mechanical analysis of system
Overloading of components during setup (consideration for pressure activated lubricating compounds)	Section 4	
Misalignment of chainring and cog (angular and lateral)	Section 8.3.2	Determine effect of deliberate misalignment by known amounts on power efficiency
Incorrect preloading of torque transducers (torque level, duration, and direction)	Section 6.1	

10 LUBRICATION COMPARISON PROCEDURE

This section summarises the steps required to carry out a comparison of two chain lubricants, referencing the previous sections where appropriate.

1. Obtain 2*n* nominally-identical new chains from supplier (where *n* is any positive integer, but ideally at least 3)
2. Clean all chains following procedure in Section 3
3. Lubricate all chains with a standard run-in oil following guidance in Section 4.1.3
4. Run in all chains following procedure in Section 7.1
5. Clean all chains following procedure in Section 3
6. Lubricate *n* chains with Lubricant A and *n* chains with Lubricant B following guidance in Section 4.1.3

7. Test all 2*n* chains, alternating between Lubricants A and B, following procedure in Section 7.2 – between tests, clean all drive chain components (chainring, cog, jockey wheels etc)
8. Analyse results as described in Section 8

11 OTHER PARAMETERS

Although this procedure has been specifically developed to describe a methodology for the real-world performance comparison of two different chain lubricants, a similar methodology could also be employed to compare the performance of individual drive chain components. For example, to compare two different chainrings, exactly the same procedure could be followed, but with the following differences:

- At step 4, ensure that each chainring is used for at least one of the run-in exercises
- At step 6, all 2*n* chains to be lubricated with the same lubricant
- At step 7, chainrings (rather than lubricants) to be alternated between tests

It might also be possible to modify this procedure such that the same chain is used for all tests, either with or without cleaning and re-lubrication between tests – the issue here would be degradation of the chain performance with time but, if enough tests were performed with each chainring and the results from each proved to be repeatable (or linearly changing), it would be possible to mitigate any such effects.

12 CONCLUSIONS

This report has detailed, with supporting explanations, a suggested methodology for the comparison of bicycle chain lubricants. A multiple chain approach is recommended to reduce the amount of time spent on labour-intensive chain cleaning. The outlined method can also be adapted to enable investigation of other system components.

Using such a methodology, or a modified version of it, could enable many drive chain investigations to be performed, including:

- Lubricant comparison
- Comparison of other drive train components, such as cogs, chainrings, and jockey wheels
- Degradation of lubricant performance over time, both with and without use
- Degradation of chain performance over time

The basic approach is to develop a very repeatable measurement system such that the effects associated with the variation of a single component, be it a chainring or lubricated chain, are statistically significant in relation to the system's repeatability. Care must be taken to ensure that no changes other than the intended one are introduced during such testing – for example, the investigation of the effects of a new chainring tooth profile may be compromised by the misalignment or imperfect mounting of the chainring itself.

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