Research and Development Project

Group Report

Comparative Tribological Benchmarking of Industrial and Food-Grade Greases for Industrial Robot Gear Applications

Course: Research and Development Project in Mechanical Engineering with Industry

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Abstract

This project presents a comparative tribological benchmarking study of two lubricating greases for industrial robot gear applications. MolyWhite RE No.00 was used as the industrial reference grease, while CIBUM RoboSafe FG was evaluated as a candidate food-grade grease. The motivation was to investigate whether a food-grade grease can provide acceptable friction stability and surface protection compared with the current industrial reference grease under controlled laboratory conditions.

The experiments were carried out using a Bruker UMT TriboLab in a rotary ball-on-disc configuration with a 100Cr6 steel ball and 100Cr6 steel disc. The test matrix included different normal loads, rotational speeds, track radii and durations, with the main comparison focused on the 70 N high-load region, corresponding to a calculated maximum Hertzian pressure of approximately 2.57 GPa. The coefficient of friction (COF) was processed using a stable analysis window after removing the first 300 s run-in period. The main stability indicators were stable mean COF, standard deviation, coefficient of variation (CV) and drift. Post-test visual inspection of the ball and disc surfaces was also used because low COF alone does not necessarily mean good wear protection.

The industrial reference grease showed its most useful stable benchmark at 70 N and 125 rpm, where MW-T14 produced a low and stable COF response. At 70 N and 150 rpm, MolyWhite became more unstable and showed visual surface concern. RoboSafe FG showed its strongest result at 70 N and 150 rpm, where RSFG-B3-T18 produced low mean COF, very low CV and acceptable visual appearance. However, at higher speeds, visible surface concern appeared even when the COF remained smooth. Therefore, RoboSafe FG is considered a promising food-grade candidate, but it cannot yet be approved as a direct replacement without quantitative wear measurement and application-level validation.

1 Introduction

1.1 Background

Grease lubrication is widely used in gears, bearings and other mechanical components because grease can remain close to the contact region better than liquid oil and can provide both lubrication and partial sealing against contamination. However, grease behaviour is more complex than simple oil lubrication because grease is not only a base oil. It is a structured lubricant made from base oil, thickener and additives, and its performance depends on how these components respond to load, speed, temperature and shear during operation [1]. In grease-lubricated contacts, the base oil mainly contributes to film formation, while the thickener controls the consistency, oil release and replenishment behaviour of the grease. Additives may also influence friction, boundary-film formation and wear protection.

This is important in industrial robot gear reducers because the contact conditions are severe and repetitive. Gear contacts experience repeated rolling and sliding motion, high local contact pressure, limited lubricant space and continuous redistribution of grease during operation. In such contacts, the lubricant must not only reduce friction, but also prevent surface damage and maintain stable lubrication over time. If the grease is pushed away from the contact, or if the released oil film is not thick enough to separate the surfaces, the system may move toward mixed or boundary lubrication, where asperity contact and material removal can occur.

In this project, the performance of two greases is investigated for industrial robot gear applications. The industrial reference grease is MolyWhite RE No.00, while the food-grade candidate grease is CIBUM RoboSafe FG. Both greases are semi-fluid NLGI No.00 greases with similar base-oil viscosity around 32 mm^2/s at 40 °C, but they differ in thickener chemistry and additive concept. MolyWhite RE No.00 is a lithium-soap-based industrial reduction-gear grease containing synthetic hydrocarbon/mineral oil and molybdenum-based chemistry, while CIBUM RoboSafe FG is a fully synthetic PAO-based anhydrous-calcium food-grade grease. Therefore, this comparison is not only between an industrial grease and a food-grade grease, but also between two different grease technologies.

This creates a clear knowledge gap for the present project. Although grease lubrication, food-grade lubricants and ball-on-disc testing have been studied separately, the specific question in this work is more application-focused: whether a food-grade grease can approach the behaviour of an industrial molybdenum-containing reduction-gear grease under the same controlled steel contact conditions. This makes the project useful both as an industrial screening study and as a small tribological benchmarking investigation.

1.2 Industrial Motivation

The industrial motivation for this project comes from the need to evaluate whether a food-grade grease can be a realistic alternative to the current industrial robot gear grease. In food and pharmaceutical production environments, lubricant safety is important because accidental lubricant leakage or contamination may create hygiene and product-safety concerns. However, safety approval alone does not prove that a lubricant is suitable for a highly loaded robot reducer. The grease must still provide stable friction behaviour, load-carrying ability and surface protection.

NSF H1 registration is relevant because it applies to lubricants that may be used where incidental food contact can occur. However, this safety requirement can also limit the type of additive chemistry available compared with many industrial lubricants. For this reason, the replacement question is not only about food safety. The food-grade grease must also provide enough friction stability, load-carrying behaviour and surface protection to be considered realistic for robot reducer use. This is especially important in the present comparison because the two greases have different chemistry, as summarised in Table 1. MolyWhite contains an organic molybdenum compound according to the supplier datasheet, whereas RoboSafe FG is the food-grade candidate grease. NSF H1 registration is relevant for lubricant use in applications where incidental food contact may occur [3].

The current industrial grease is used as the benchmark because it represents the existing lubrication solution for reduction-gear applications. A possible replacement grease must therefore be compared against the reference grease under the same test conditions. The goal is not only to check whether the food-grade grease gives low friction, but also whether it can maintain friction stability and avoid visible surface damage under similar load and speed conditions. This is especially important because robot reducer contacts can operate under high local contact pressure, even when the externally applied laboratory load is much lower than the force level in the real gear system.

Previous food-grade grease studies also use both friction and wear evidence to judge performance, including COF, wear morphology, wear volume and load-carrying behaviour [5]. Therefore, the present project uses a combined evaluation based on COF stability and post-test visual surface observations.

1.3 Problem Statement

The main problem addressed in this project is whether CIBUM RoboSafe FG can provide comparable or better tribological performance than MolyWhite RE No.00 under the same laboratory test conditions. A simple comparison based only on average coefficient of friction is not sufficient. A grease may show a low and smooth COF curve because oil is still present in the contact, while the protective film may still be too thin to prevent surface damage. In that case, the friction signal may look acceptable, but the surface may still experience wear or material removal.

Therefore, the grease performance must be judged using two main criteria: friction stability and surface protection. Friction stability is evaluated from the COF curve during the test, while surface protection is evaluated from visual inspection of the ball and disc after testing. A test condition is treated as acceptable only when the COF remains reasonably stable and no clear visual material removal is observed. This combined decision basis is important because the project aims to identify a grease that is not only efficient from a friction point of view, but also protective for steel contact surfaces.

1.4 Research Question

The main research question of this project is:

> How do the industrial grease and the food-grade grease perform under the same tribological test conditions, and which one provides better friction stability and surface protection?

More specifically, the practical comparison is whether RoboSafe FG can give a stable mean COF close to the selected industrial benchmark, with CV below approximately 10% and no clear visual material removal under the main high-load test region. The CV threshold is used here as a practical screening indicator rather than as a final approval limit. A condition is only treated as acceptable when the COF response is stable and the post-test surface inspection does not show clear visual material removal. This makes the research question measurable using the COF statistics and post-test surface observations.

To answer this question, the study focuses on the following supporting points:

- How does the coefficient of friction change under different load and speed conditions?
- Which grease provides a more stable COF response during the stable part of the test?
- Does a low COF also correspond to acceptable post-test surface condition?
- Can the food-grade grease perform acceptably at or near the selected industrial benchmark condition?

1.5 Scope of the Study

This study should be understood as a first-stage tribological screening and benchmarking study, not as a full gearbox qualification test. The experiments are performed using a Bruker UMT TriboLab in a rotary ball-on-disc configuration. In this setup, a steel ball is pressed against a rotating steel disc while grease is applied to the contact region. This creates a controlled point-contact condition where load, rotational speed, track radius and test duration can be kept consistent between the two greases.

The ball-on-disc method is useful because it allows the two greases to be compared under the same laboratory contact geometry and test conditions. This reduces the number of uncontrolled variables and makes the comparison more systematic. However, the method does not fully reproduce the actual contact inside a Nabtesco-type robot reducer. Real gear contacts involve gear-tooth geometry, rolling-sliding motion, changing contact pressure, surface roughness, grease confinement, temperature rise and repeated grease redistribution. Therefore, the present results are interpreted as comparative screening results rather than direct gearbox validation.

The current work is limited by room-temperature testing, manual grease application and mainly visual post-test surface assessment. Quantitative wear measurements such as wear-track width, wear depth, wear volume and ball wear scar diameter were not fully included. Therefore, the present study can identify promising friction behaviour and visible surface concerns, but further wear measurement, four-ball testing, repeated trials and more application-relevant validation are required before making a final replacement recommendation.

2 Tribological Background and Literature Review

This chapter summarises the tribological concepts needed to interpret the experimental results. The focus is not to review all grease-lubrication literature, but to select the theories that are directly relevant to this project: grease film formation, contact pressure, surface roughness, lubrication regime, friction stability and wear observation. These topics are used later to explain why a grease can show stable COF but still create visible surface concern.

2.1 Grease Lubrication in Robot Gear and Steel Contact Applications

Lubricating grease is a structured lubricant made mainly from base oil, thickener and additives. The base oil helps form the lubricating film, the thickener gives the grease its semi-solid structure, and additives improve properties such as anti-wear behaviour, extreme-pressure performance, corrosion protection and friction reduction [1]. Therefore, grease performance cannot be judged only from base-oil viscosity; thickener type, oil bleeding, mechanical stability and surface-film formation are also important.

In gear and bearing contacts, grease does not supply lubricant in the same way as oil. Lugt describes grease lubrication as moving from an initial churning phase, where grease is redistributed, to a later bleeding phase, where lubrication depends more on oil released from the grease reservoir [1]. This is relevant for robot gear reducers because the grease must remain available near repeated rolling/sliding contacts and protect the surfaces under high local pressure.

For this project, the grease must satisfy two main functions: stable friction behaviour and surface protection. A low coefficient of friction (COF) is useful, but it does not automatically prove that the surface is protected. If the film is too thin or weak, material removal can still occur. Therefore, the industrial and food-grade greases are compared using both COF behaviour and post-test surface observations.

2.2 Contact Mechanics in Ball-on-Disc and Gear Contacts

The actual severity of a tribological test depends not only on the applied load, but also on the size and shape of the contact area. In ball-on-disc testing, the contact area is very small, so even a moderate normal load can produce high local contact pressure. Therefore, contact pressure is more meaningful than load alone when comparing laboratory testing with real gear contact [4].

In this project, the Bruker UMT TriboLab creates a ball-on-disc point contact, where a steel ball is pressed against a rotating steel disc. This is different from a real robot gear, where gear teeth experience rolling-sliding motion and a more line-like contact. However, the ball-on-disc method is still useful as a controlled screening test because both greases can be tested under the same load, speed, track radius and grease application condition. Similar simplified tribometer tests are commonly used in grease studies before moving to more application-specific validation [5, 12, 9].

2.2.1 Hertzian Contact Pressure

Hertzian contact theory is used to estimate the contact pressure between curved elastic bodies. In a ball-on-disc test, the apparent point contact becomes a small circular contact area under load. If the same load acts over a smaller area, the local pressure becomes high. Therefore, the applied laboratory load must be interpreted together with material properties, ball radius and contact geometry [4].

For this study, Hertzian pressure is used to understand contact severity. The real robot reducer may operate with much higher force, but the gear tooth contact area is different. The laboratory test uses a lower load, but the small point-contact area can still create high pressure. Therefore, the aim is not to exactly reproduce the real robot load or rpm, but to create a controlled and comparable contact severity for both greases.

2.2.2 Point Contact versus Gear Line Contact

The main limitation of ball-on-disc testing is that it does not fully reproduce real gear contact. A ball-on-disc setup produces a simplified point contact, while real gear teeth normally work under rolling-sliding line contact with changing pressure and sliding speed during meshing.

However, this limitation does not make the test invalid. Ball-on-disc and four-ball tests are commonly used in grease studies to isolate friction and wear behaviour before moving to more application-specific testing [5, 12]. In this project, the ball-on-disc test is therefore treated as a first screening and benchmarking method, not as final gearbox validation.

2.3 Surface Roughness and Real Contact Area

Real engineering surfaces are not perfectly smooth. Even polished steel contains asperities, and the real contact area is much smaller than the apparent contact area. If the lubricant film is thick enough, the surfaces are separated. If the film becomes too thin, asperity contact can occur, increasing friction fluctuation and wear risk.

Surface roughness is important because it affects whether the contact is operating in full-film, mixed or boundary lubrication. Gonçalves et al. showed that grease film thickness and friction should be interpreted together with surface roughness and lubrication regime [8]. Sanchez Garrido et al. also showed that roughness and temperature can change grease friction and wear performance [13]. This supports the need to inspect the ball and disc surfaces after testing, not only the COF curve.

2.4 Lubrication Regimes and Stribeck Interpretation

Lubricated contacts are often described using boundary, mixed, elastohydrodynamic and hydrodynamic lubrication regimes. In general, higher speed and viscosity help increase film formation, while higher load and lower speed push the contact toward mixed or boundary lubrication. For grease, this behaviour is more complex because thickener structure, oil bleeding and replenishment also affect the film [1].

De Laurentis et al. showed that grease friction can behave differently at low and high speeds. At high speed, the base oil may dominate the friction response, while at low speed the thickener and grease structure can have a stronger effect [7]. Therefore, COF changes in this project should not be interpreted only as speed effects. They may also come from grease redistribution, film formation, starvation or surface damage.

2.4.1 Boundary and Mixed Lubrication in Grease Tests

In boundary lubrication, the lubricant film is too thin to fully separate the surfaces, so friction and wear depend strongly on surface films and additives. In mixed lubrication, part of the load is carried by the lubricant film and part by asperity contact. A grease-lubricated contact can enter these regimes when the load is high, speed is low, grease supply is limited or the grease layer is too thin.

Food-grade grease studies show that surface-film formation is important in these regimes. Gong et al. found that nano-PTFE and nano-$CaCO_3$ additives improved COF stability and reduced wear volume in food-grade grease by forming protective films and reducing direct surface contact [5]. Sun et al. also showed that calcium-based chemistry can contribute to protective boundary films containing $CaCO_3$ and CaO on steel surfaces [6]. This is useful for interpreting the calcium-based food-grade grease in the present project.

2.4.2 Run-in, Grease Redistribution and Film Formation

The beginning of a grease test can be unstable because the grease is still redistributing and the surfaces are still running in. During this period, the COF may rise, fall or fluctuate before reaching a more stable condition. This agrees with the general churning and bleeding behaviour of grease described by Lugt [1].

For this reason, the present project does not judge the grease from the first part of the

COF curve. The first 300 s are treated as a run-in period, and the stable part of the curve is used to calculate mean COF, standard deviation, coefficient of variation and drift.

2.5 Wear Mechanisms in Lubricated Steel Contacts

Wear in lubricated steel contacts can occur through adhesive wear, abrasive wear, plastic deformation, fatigue-related damage or material transfer. The exact mechanism cannot be confirmed only from visual images, but visible material removal is still important evidence that the grease did not fully protect the surface.

Literature studies normally combine friction data with wear evidence. For example, Gong et al. used COF, wear morphology and wear volume to judge food-grade grease performance [5]. Acar et al. also used friction and wear measurements together when evaluating biogenic greases [11, 12]. This supports the decision in this project to combine COF stability with post-test visual inspection.

2.5.1 Why Low COF Does Not Always Mean Low Wear

Low COF means low frictional resistance, but it does not always mean low wear. A grease may keep the friction signal low because oil is still present in the contact, while the surface is still damaged if the protective film is not strong enough.

This is why wear evidence is necessary. In the literature, better grease performance is normally confirmed only when low/stable COF is accompanied by lower wear scar size, wear depth or wear volume [5, 12]. Therefore, in this project, a test with low COF but visible material removal is not treated as a full pass.

2.5.2 Quantitative Wear Indicators

Common quantitative wear indicators include wear scar diameter, wear-track width, wear depth and wear volume. These are usually measured using optical microscopy, profilometry, white-light interferometry or SEM. Gong et al. used white-light interferometry to measure wear-track morphology and wear volume after ball-on-disc tests [5]. Acar et al. also used interferometry to evaluate wear marks in steel contacts [12].

In the present project, the current surface evaluation is mainly visual. Therefore, quantitative wear-track measurement is an important future-work step.

2.6 Experimental Methods Used in Grease Studies

The literature uses different test methods depending on the purpose of the study. Ball-on-disc and pin-on-disc tests are useful for controlled friction and wear screening because load, speed, contact geometry and test duration can be controlled. Vafaei et al. used ball-on-disc testing to study grease film thickness and friction for different bio-based thickeners [9]. Gonçalves et al. used film-thickness and friction tests to connect grease behaviour with lubrication regime [8].

Four-ball testing is often used for anti-wear and extreme-pressure behaviour. Gong et al. used four-ball testing to evaluate load-carrying behaviour and ball-on-disc testing to evaluate COF and wear [5]. This supports the future plan of using four-ball testing as a complementary method. It will not replace the ball-on-disc test, but it can provide additional information about load-carrying and anti-wear performance.

2.7 Performance Indicators Used in Literature

The reviewed literature shows that grease performance is judged using several indicators, not one value only. The most common friction indicators are COF versus time, average COF, fluctuation, peaks and stability. Wear indicators include wear scar size, wear depth, wear volume and surface morphology.

This combined approach is important because friction and wear can give different messages. A grease with low COF but high wear is not necessarily better. Similarly, a grease with slightly higher COF but much lower wear may be better for durability. Therefore, the present project uses COF stability together with visual surface condition as the decision basis.

2.8 Main Lessons from Literature for This Project

The literature gives four main lessons for this project. First, grease performance depends on base oil, thickener, additives, oil bleeding and replenishment, so similar viscosity does not guarantee similar performance [1]. Second, contact severity should be interpreted using Hertzian pressure, not only applied force. Third, the early part of the COF curve can include run-in and grease redistribution, so a stable-window analysis is needed. Fourth, COF alone is not enough; surface protection must also be checked using wear or material-removal evidence.

Based on these lessons, the present project uses the industrial grease first to identify a benchmark condition, then tests the food-grade grease near that condition. The decision is based on two criteria: stable COF and no clear visual material removal. The current ball-on-disc work is treated as screening, while future work should include quantitative wear measurement, four-ball testing, improved grease application control and more gear-relevant validation.

3 Materials and Experimental Methodology

This chapter describes the materials, test setup, experimental logic and data-processing method used in the grease benchmarking study. The aim of the methodology was to compare the industrial reference grease and the food-grade candidate grease under the same controlled laboratory conditions. The work was designed as a screening-level ball-on-disc study, not as a full gearbox qualification test.

3.1 Lubricants Used in the Project

Two lubricants were compared in this project. MolyWhite RE No.00 was used as the industrial reference grease, while CIBUM RoboSafe FG was used as the candidate food-grade grease. MolyWhite RE No.00 represents the current industrial-type reduction gear grease used as the benchmark in this project. RoboSafe FG was selected because it is intended for food-related robotic applications where food-grade lubricant approval is important.

Both greases are soft NLGI No.00 greases and have similar base-oil viscosity values around $32\,\mathrm{mm^2\,s^{-1}}$ at $40\,^{\circ}\mathrm{C}$. However, the two greases are not chemically the same. MolyWhite RE No.00 is based on lithium-soap thickener with synthetic hydrocarbon oil and refined mineral oil, while RoboSafe FG is treated in this project as a PAO-based food-grade grease with an anhydrous calcium thickener. Therefore, the comparison should not be made only from viscosity. Thickener chemistry, oil release, additive package and boundary-film behaviour can also affect friction stability and surface protection.

Table 1: Available lubricant information used for the experimental comparison. Values are taken from the supplier/datasheet information available to the project.

Property	MolyWhite RE No.00	CIBUM RoboSafe FG
Role in project	Industrial reference grease used in Nabtesco reduction gear context	Candidate food-grade grease for possible robot gear use
Thickener	Lithium soap	Anhydrous calcium thickener
Base fluid	Synthetic hydrocarbon oil and mineral oil	Fully synthetic PAO base oil
NLGI grade / consistency	No.00; worked penetration reported as 415	NLGI 00; penetration reported as 400–430
Kinematic viscosity at 40 °C	32.1 $\mathrm{mm^2/s}$	32 $\mathrm{mm^2/s}$ reported by supplier; SDS states >20.5 $\mathrm{mm^2/s}$ for base oils
Dropping point	193 °C	>140 °C
Temperature range	-40 to 130 °C	-40 to 120 °C, 130 °C maximum
Food-grade / safety status	Industrial grease, not selected as food-grade reference	NSF H1 food-grade; SDS classifies the mixture as not hazardous under CLP
Additional remark	Contains organic molybdenum compound according to datasheet description	Supplier notes no extra dry lubricant; MoSH/MoAH free

The purpose of including the grease properties was to document the main differences between the two lubricants before comparing their measured tribological response. In the final evaluation, the grease performance was judged from the measured COF behaviour and the post-test surface condition, not from the datasheet values alone.

3.2 Ball and Disc Materials

The experiments were carried out using a 100Cr6 steel ball and a 100Cr6 steel disc. This material pair was selected because it gives a repeatable steel-on-steel contact and is commonly used for laboratory tribology screening. Using the same ball and disc material for all tests also made the comparison between the two greases more consistent.

The main material and elastic properties used for the contact calculation are summarised in Table 2. The same steel material pair was used for both greases, so the difference in measured response can mainly be related to the lubricant and test condition rather than a change in counterface material.

Table 2: Ball and disc material information used in the ball-on-disc screening tests.

Parameter	Ball	Disc
Material	100Cr6 steel	100Cr6 steel
Diameter / geometry	6.5 mm ball diameter	Flat rotating disc
Radius used in Hertzian calculation	3.25 mm	Treated as flat surface
Young's modulus, E	210 GPa	210 GPa
Poisson's ratio, ν	0.30	0.30
Surface role	Loaded upper counterface	Rotating lower counterface

The surface roughness and hardness of the specific test specimens were not measured separately in this project. This is a limitation because roughness and hardness influence asperity contact, boundary-film formation and wear. However, the same 100Cr6 ball–disc material pair was used for all tests, so the grease comparison remains consistent within the present screening study.

The 100Cr6 ball and disc should be understood as experimental counterfaces for screening. They should not be presented as an exact copy of the real Nabtesco reducer gear material. Real reducer gears may have different alloy composition, case-hardening, surface roughness, surface finishing and contact geometry. Therefore, the present material pair was suitable for controlled comparison, but the results must still be validated later using gear-relevant materials and surface finish.

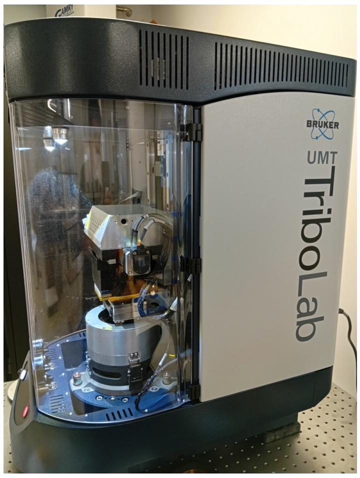
Before each test, the ball and disc were treated as fresh or prepared test surfaces so that the measured response mainly represented the grease and selected test condition, rather than uncontrolled previous surface damage. After testing, the ball and disc were visually inspected to check whether clear material removal or surface concern had occurred.

3.3 Experimental Apparatus

The tests were carried out using a Bruker UMT TriboLab in a rotary ball-on-disc configuration. The instrument allows a normal load to be applied through the ball while the disc rotates at a selected speed. During the test, the system records the normal force, friction force and coefficient of friction. The coefficient of friction was calculated from the ratio between friction force and normal force.

The TriboLab setup was selected because it provides a controlled and repeatable way to compare the two greases under the same load, speed, radius and test duration. This was important because the main aim of the project was comparative benchmarking, not exact gearbox simulation.

(a) Bruker UMT TriboLab setup (Front)



(b) Bruker UMT TriboLab setup (Side)

Figure 1: Experimental ball-on-disc tribology apparatus used for the grease benchmarking tests.

The tests were carried out under laboratory room-temperature conditions. The disc or contact temperature was not logged during the tests. Therefore, the results should be interpreted as room-temperature screening results, and not as elevated-temperature gearbox validation.

3.4 Ball-on-Disc Test Configuration

The experimental configuration was a rotary ball-on-disc point-contact test. In this setup, the steel ball is pressed against the rotating steel disc under a selected normal load. Grease was applied to the disc contact region before the test, and the ball repeatedly passed through the lubricated circular track during rotation.

The main controlled test variables were normal load, rotational speed, track radius and test duration. The test programme included loads of 20, 25, 30, 50 and 70 N. The disc speed ranged from 75 to 367 rpm, and the track radius was between 12.5 and 16.0 mm. Based on the recorded track radius and rpm, the nominal surface speed ranged from approximately 0.118 to 0.500 m/s. Most tests were run for 1800 s, while some early screening trials had different durations or cycle targets.

The high-load region around 70 N was used as the main decision region. Table 3 lists the most important high-load cases and their calculated nominal surface speeds. This table is useful because rpm alone does not fully describe the contact motion; the track radius also affects the surface speed.

Note: The trial names follow the internal labelling system used during data processing. MW refers to MolyWhite RE No.00, RSFG refers to CIBUM RoboSafe FG, and T denotes the overall trial number in the full experimental campaign. In the RoboSafe FG labels, B denotes the food-grade grease test-series case; for example, RSFG-B3-T18 means the third RoboSafe FG food-grade test-series case and overall trial 18.

Table 3: Key high-load test conditions and calculated nominal surface speed.

Trial	Grease	Load (N)	RPM	Track radius (mm)	Speed (m/s)
MW-T14	MolyWhite	70	125	13.6	0.178
MW-T13	MolyWhite	70	150	13.4	0.210
MW-T22	MolyWhite	70	150	14.1	0.221
RSFG-B2-T17	RoboSafe FG	70	125	13.5	0.177
RSFG-B3-T18	RoboSafe FG	70	150	13.7	0.215
RSFG-B4-T19	RoboSafe FG	70	175	13.9	0.255
RSFG-B5-T20	RoboSafe FG	70	200	13.4	0.281
RSFG-B6-T21	RoboSafe FG	70	300	13.6	0.427

The disc track radius was also recorded because rotational speed alone does not fully describe the contact motion. The local sliding speed depends on both rotational speed and track radius. For a circular track, the nominal surface speed can be estimated as

$$v = \frac{2\pi R n}{60}, \tag{1}$$

where v is the surface speed, R is the track radius in metres, and n is the disc rotational speed in revolutions per minute. This is why rpm values from the TriboLab should not be compared directly with robot gear rpm without considering contact radius, contact geometry and sliding/rolling condition.

In the present TriboLab configuration, the disc was driven while the ball was held in the upper holder. Therefore, the contact can be treated as a predominantly sliding ball-on-disc contact rather than a rolling gear contact. Under this simplified assumption, the slide-to-roll ratio is high and the entrainment speed is lower than the disc surface speed. This makes the laboratory contact conservative for screening because the contact is more severe than a fully rolling contact. For this reason, the rpm values in the TriboLab should not be compared directly with the robot gear rpm; the contact pressure, surface speed, sliding condition and total sliding distance are more meaningful for interpretation.

3.5 Contact Severity and Hertzian Pressure Basis

The test severity was interpreted using contact pressure, not only normal load. In a ball-on-disc test, the applied load acts over a very small contact area, so the local pressure can be high even when the laboratory force is much smaller than the force in a real gear system. For this reason, Hertzian contact theory was used as a pressure basis for interpreting the test conditions.

The contact was treated as a 100Cr6 steel sphere-on-flat steel contact. The ball diameter was 6.5 mm, giving a ball radius of 3.25 mm. For the steel–steel contact calculation, both bodies were taken as $E = 210\,\mathrm{GPa}$ and $\nu = 0.30$, giving an equivalent elastic modulus of approximately 115.38 GPa. The calculated values are given in Appendix C.

The 70 N tests were treated as the high-contact-severity region of the experimental matrix. At this load, the calculated contact radius was approximately 113.9 µm, the mean

Hertzian pressure was approximately 1.72 GPa, and the maximum Hertzian pressure was approximately 2.57 GPa. This shows why the simplified laboratory contact can still be severe even though it does not reproduce the full robot gearbox geometry.

This approach is useful for the present project because the real Nabtesco-type gear contact is not identical to the laboratory contact. The real reducer has gear-tooth rolling/sliding contact, while the TriboLab test uses a simplified point contact. Therefore, the aim was not to exactly reproduce the full robot gear motion. Instead, the aim was to create a controlled and repeatable contact severity that allowed both greases to be compared under the same conditions.

A full lambda-ratio calculation was not performed because the surface roughness of the specific ball and disc specimens and the lubricant film thickness were not measured in this project. Therefore, the lubrication regime is interpreted qualitatively from the high contact pressure, low-speed grease-lubricated sliding condition, COF fluctuation and post-test surface observations. The contact is expected to operate mainly in mixed or boundary lubrication, but this should be confirmed in future work by measuring the surface roughness and estimating or measuring the minimum lubricant film thickness. This limitation is important because the film parameter,

$$\Lambda = \frac{h_{\min}}{\sqrt{Rq_1^2 + Rq_2^2}},$$

is normally needed to classify the lubrication regime quantitatively.

Since the surface roughness was not measured, a numerical Λ value was not calculated in the present work. For example, if both steel surfaces had $Rq = 0.05$ μm, the composite roughness would be $\sqrt{0.05^2 + 0.05^2} \approx 0.071$ μm. This shows that even a small uncertainty in surface roughness can strongly affect the lubrication-regime classification. Therefore, the mixed/boundary lubrication interpretation in this report is treated as qualitative and should be confirmed in future work by measuring Rq and estimating $h_{\min}$.

3.6 Test Matrix Development

The test matrix was developed step by step. First, MolyWhite RE No.00 was tested over a wider range of load and speed combinations. This was done because MolyWhite was the industrial reference grease, and it was used to identify a stable benchmark condition and a nearby limit region. After this, RoboSafe FG was tested near the selected benchmark region and then at higher speeds to see whether it could maintain stable friction and acceptable surface condition.

The overall logic was therefore:

1. test the industrial reference grease over a wider range of load and speed conditions;
2. identify a stable industrial benchmark condition from the COF response and visual inspection;
3. test the food-grade grease near the same high-load benchmark region;
4. increase the food-grade speed stepwise to check whether stable COF and acceptable visual condition were maintained;

5. compare the food-grade results with the nearest available industrial reference cases.

The complete processed test matrix is provided in Appendix A. The main high-load comparison cases are later summarised in Chapter 4. This structure was used because the exact same industrial reference condition was not available for every food-grade trial. Therefore, the food-grade grease was compared both against the stable industrial benchmark and against the nearest available industrial reference cases.

The grease layer was applied manually to the test region before testing. The aim was to provide sufficient grease for the ball-on-disc contact while keeping the procedure similar between tests. However, the exact grease film thickness was not measured as a controlled variable in the present work. The exact applied grease mass was also not weighed, so the grease application procedure should be interpreted as consistent by method but not fully quantified by mass or film thickness. This is one reason why improved grease mass and film-thickness control is recommended in the future work.

3.7 Data Processing and Stability Metrics

The raw COF data were processed in the same way for all trials. The first 300 s of each test were treated as the run-in period. This part of the curve was not used for the main statistical comparison because early grease redistribution, surface running-in and local film formation can cause temporary changes in COF. The stable analysis window was then defined from 300 s to the end of the available test duration, usually 1800 s.

The stability statistics were calculated from the processed COF data in the stable analysis window, while the smoothed curves shown in the figures were used mainly for visual interpretation. The same processing approach was applied to all trials to keep the comparison consistent.

For visualisation, the COF curves were smoothed using a centred rolling median with an approximately 8 s window. This smoothing was used only to make the plotted trends easier to read; all mean COF, standard deviation, CV and drift values were calculated from the stable-window data using the same processing approach for every trial.

The following quantities were calculated in the stable window:

$$\bar{\mu} = \frac{1}{N}\sum_{i=1}^{N}\mu_i, \qquad (2)$$

where $\bar{\mu}$ is the stable mean COF and μ_i is each COF value in the stable window. The standard deviation was calculated as

$$\sigma_\mu = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(\mu_i - \bar{\mu})^2}. \qquad (3)$$

The coefficient of variation was then calculated as

$$CV = \frac{\sigma_\mu}{\bar{\mu}} \times 100\%. \qquad (4)$$

The CV was used because it shows the friction fluctuation relative to the mean value. This is useful because two tests can have similar mean COF but very different stability. A lower CV indicates a smoother COF response relative to the average friction level.

Drift was also calculated to describe the long-term change in COF during the stable window. In this project, drift was treated as the difference between the end and beginning of the stable-window trend:

$$\Delta\mu = \mu_{\text{end}} - \mu_{\text{start}}. \tag{5}$$

A positive drift indicates that COF increased over time, while a negative drift indicates that COF decreased over time. The final interpretation used mean COF, standard deviation, CV and drift together, instead of relying on mean COF alone.

3.8 Post-Test Visual Surface Inspection

After each test, the ball and disc surfaces were visually inspected. The purpose of this inspection was to check whether the contact showed clear surface concern, such as visible material removal, wear marks or local damage. This step was important because a low and smooth COF curve does not automatically mean that the surface was protected.

The visual inspection was used as a qualitative surface-protection check. If a test showed stable COF but also clear visible material removal, it was not treated as a fully acceptable condition. In the present work, this inspection was mainly visual and photographic. Quantitative wear-track measurement, such as wear width, wear depth, wear volume and ball scar size, was not yet included. Therefore, the surface inspection should be understood as a first screening step, not as a complete wear analysis.

3.9 Decision Criteria

The final decision was based on both friction stability and surface condition. A test condition was considered acceptable only if it satisfied both of the following criteria:

1. the COF curve became reasonably stable after the run-in period, with low fluctuation and no severe long-term drift;
2. no clear visual material removal or serious surface concern was observed after the test.

This decision rule was used because low mean COF alone is not enough for grease selection. A grease can show a low and smooth COF curve while the surface is still being damaged. Therefore, the most reliable screening conclusion comes from combining COF statistics with post-test surface observations.

Using these criteria, the industrial grease was first used to identify a stable benchmark and a nearby limit region. The food-grade grease was then assessed against this benchmark logic. This allowed RoboSafe FG to be evaluated as a promising candidate while still avoiding an over-strong replacement claim before quantitative wear and application-level validation are completed.

4 Results

4.1 Overall COF Behaviour

The coefficient of friction (COF) results were first compared to understand the general behaviour of both greases before selecting the main benchmark cases. In the main results chapter, the most important benchmark and limit-region curves are shown in Figure 2. The complete set of smoothed COF curves is provided in Appendix B for transparency.

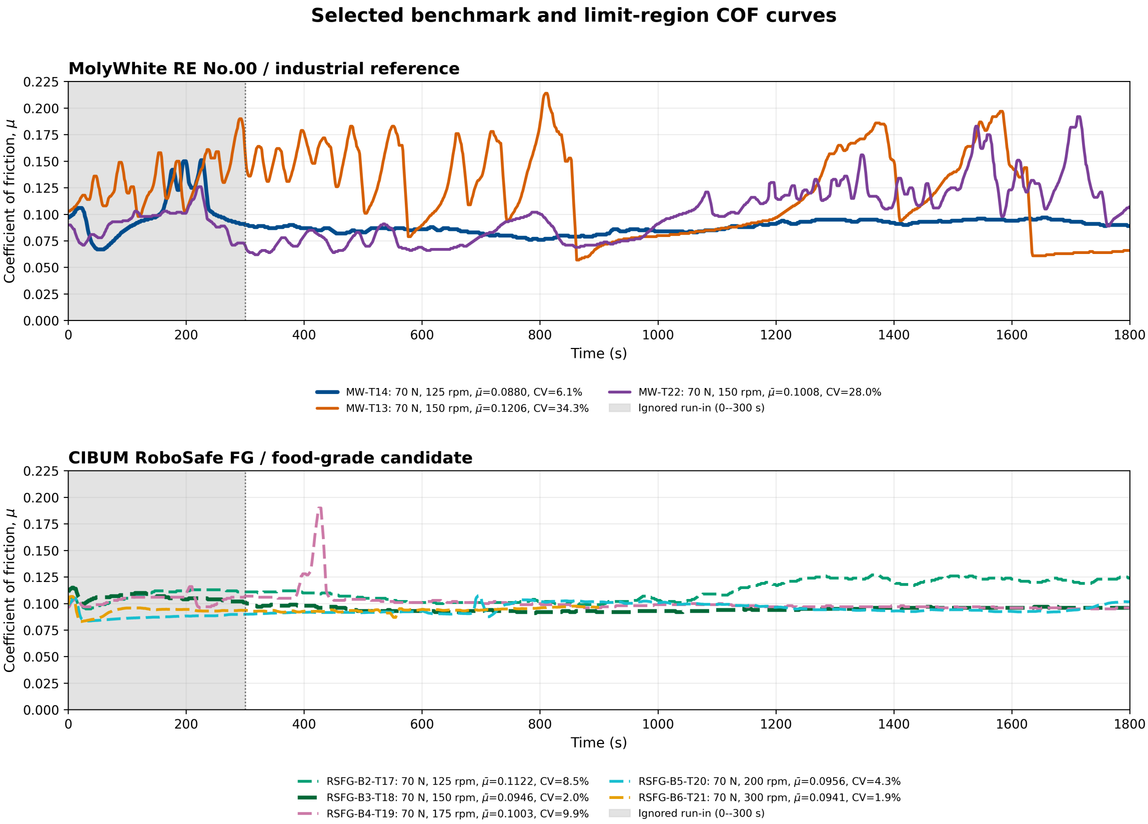


Figure 2: Selected benchmark and limit-region COF curves. The figure focuses on the industrial benchmark, industrial limit-region cases, and the food-grade trials near and above the benchmark region. The grey region marks the ignored 0–300 s run-in period.

The selected curves show the main behaviour clearly. For MolyWhite RE No.00, MW-T14 at 70 N and 125 rpm behaved as the stable industrial benchmark. In contrast, MW-T13 and MW-T22 at 70 N and 150 rpm showed stronger fluctuation, which indicates that this condition was closer to the limit region for the industrial grease in the present ball-on-disc setup.

For RoboSafe FG, the selected curves show generally smoother COF behaviour in the high-load region. RSFG-B3-T18 at 70 N and 150 rpm was especially stable, while the higher-speed food-grade trials also maintained low COF. However, these higher-speed cases still need to be interpreted together with the post-test surface observations, because low and smooth COF alone does not prove that surface protection was acceptable.

4.2 Stable Mean COF and Stability Indicators

The main statistical comparison was made using the stable part of each curve. For most tests, this was the interval from 300 s to 1800 s. The calculated quantities were stable mean COF, standard deviation, coefficient of variation (CV), and drift. The mean COF describes the average friction level, while the standard deviation and CV describe how much the COF fluctuates. The drift was used to indicate whether the COF increased or decreased during the stable analysis window.

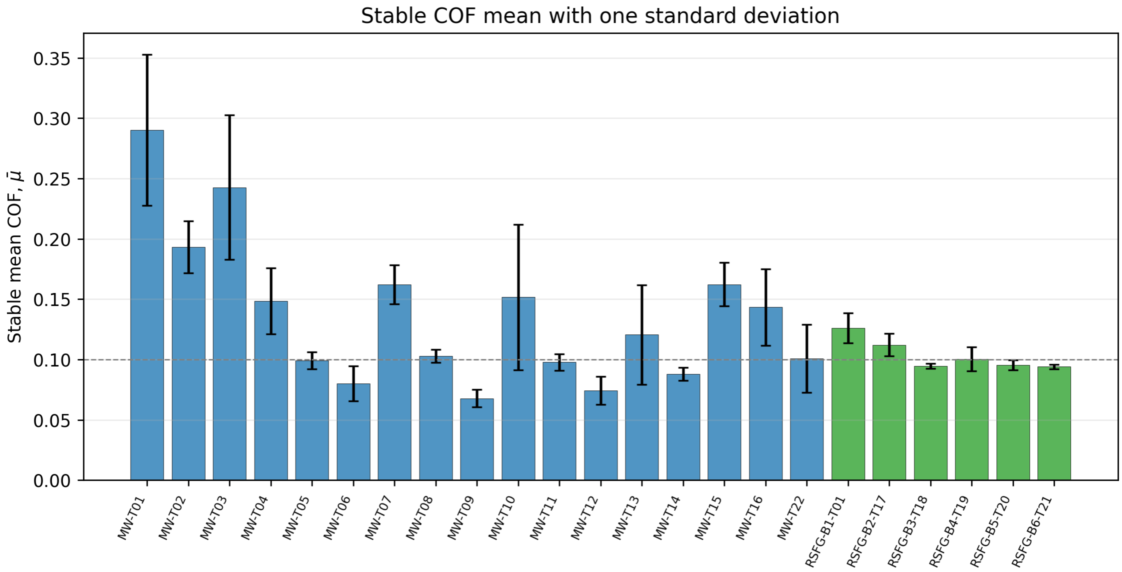


Figure 3: Stable mean COF with one standard deviation for all processed trials.

Figure 3 compares the stable mean COF values with one standard deviation. A low mean COF is useful, but it must be interpreted together with the size of the variation. A small standard deviation indicates that the contact maintained a more consistent friction response, while a large standard deviation indicates stronger fluctuations around the average value.

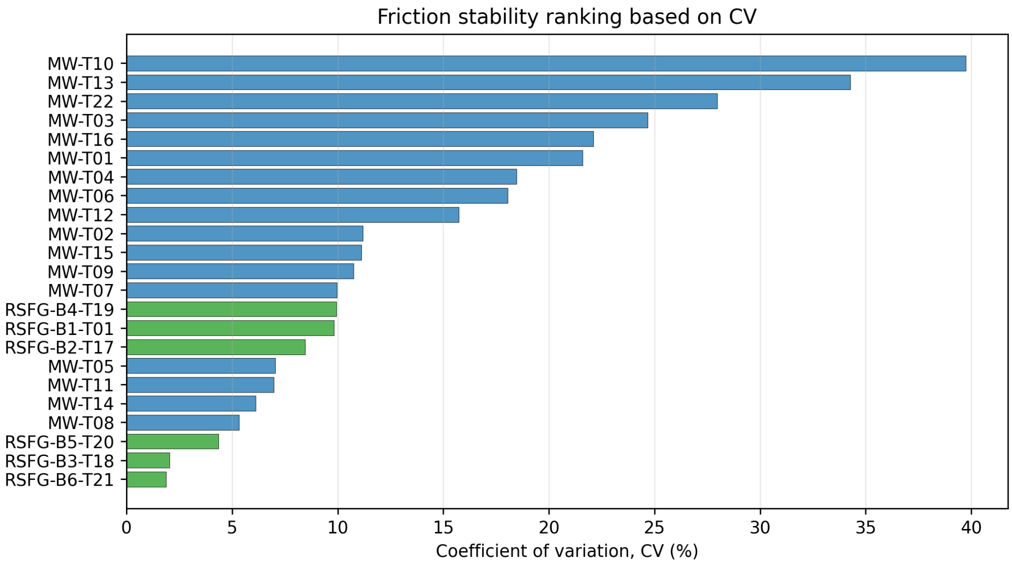


Figure 4: Friction stability ranking based on coefficient of variation. Lower CV means more stable COF relative to the mean.

Figure 4 ranks the tests by CV. This is useful because CV gives the fluctuation relative to the mean COF. For example, two tests can have a similar mean COF around 0.10, but one test can be almost flat while another contains repeated peaks. In that case, CV separates the stable response from the unstable response more clearly than the mean value alone.

The drift values also help interpret the curve behaviour. MW-T22 showed a positive drift, which suggests a gradual increase in friction during the stable window and may indicate progressive starvation, surface change or increasing contact severity. MW-T13 showed a negative drift despite high fluctuation, which may indicate late grease redistribution, local polishing or changing surface interaction during the test. In contrast, RSFG-B3-T18 had almost zero drift, which supports that this trial reached a genuinely stable friction condition after the run-in period.

The CV ranking shows that the most stable COF signals were mainly obtained from the RoboSafe FG high-load tests. RSFG-B3-T18 at 70 N and 150 rpm had a mean COF of 0.0946 and a CV of 2.0%. RSFG-B6-T21 at 70 N and 300 rpm had a similar mean COF of 0.0941 and a CV of 1.9%. RSFG-B5-T20 at 70 N and 200 rpm also had a low CV of 4.3%. These values show that RoboSafe FG was able to give a smooth friction response in the selected test setup.

For MolyWhite, the best high-load benchmark was MW-T14 at 70 N and 125 rpm, with a mean COF of 0.0880 and a CV of 6.1%. This was selected as the stable industrial reference condition. However, when MolyWhite was tested at 70 N and 150 rpm, the response became much more unstable. MW-T13 had a mean COF of 0.1206 and a CV of 34.3%, while MW-T22 had a mean COF of 0.1008 and a CV of 28.0%. This shows that the 70 N and 150 rpm condition was a more critical region for the industrial grease in the present ball-on-disc setup.

4.3 Load-Speed Performance Map

The load-speed matrix was used to understand where stable and unstable regions appeared in the test programme. Figure 5 shows that the MolyWhite trials covered a wider screening range, while the RoboSafe FG trials were concentrated near the high-load benchmark region. This was intentional. The industrial grease was tested first to identify a practical boundary, and the food-grade grease was then tested near and above that boundary.

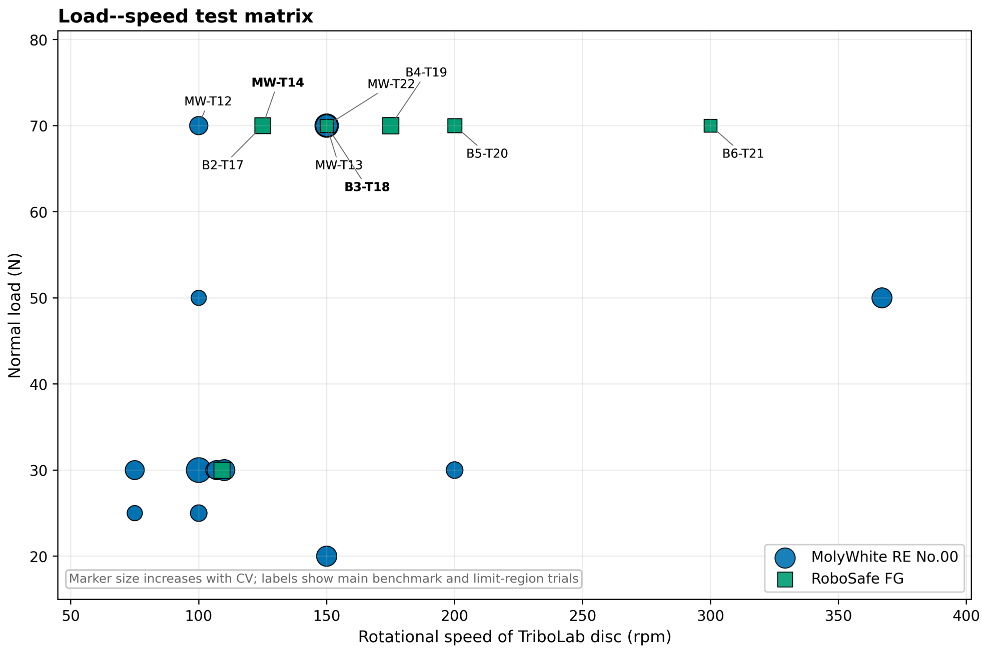


Figure 5: Load-speed test matrix used in the ball-on-disc experiments. Marker size increases with CV, and labels highlight the main benchmark and limit-region trials.

Figure 6 combines the stable mean COF and CV. Points closer to the lower-left part of the plot are preferred because they have both lower friction and lower relative fluctuation. The RoboSafe FG points are mainly located in the lower-CV region, especially RSFG-B3-T18 and RSFG-B6-T21. This means that the food-grade grease produced a smoother COF response than several of the industrial grease tests.

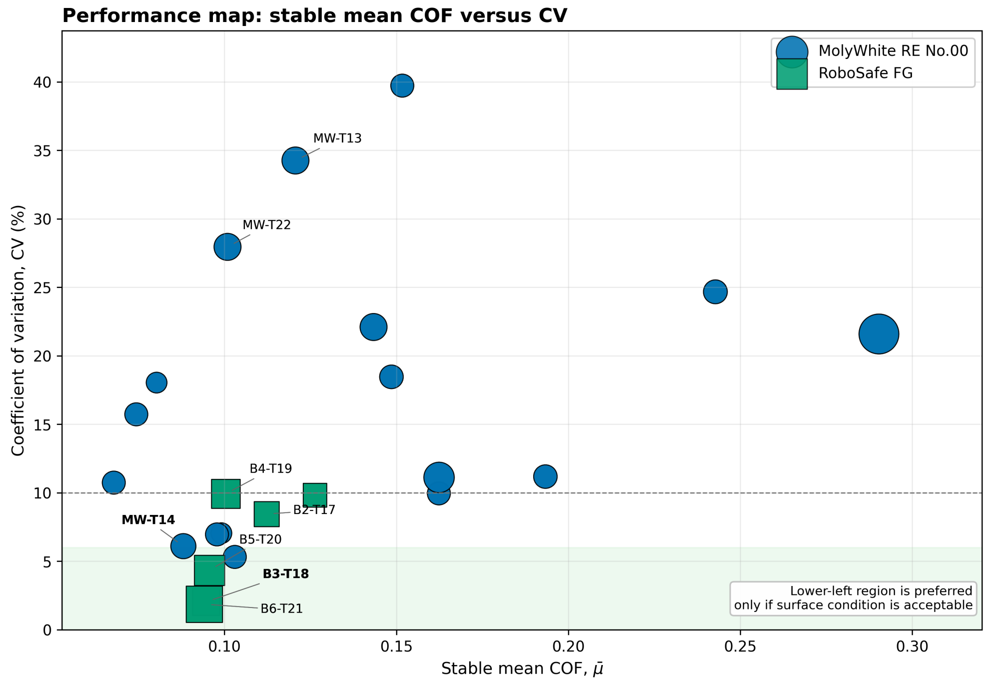


Figure 6: Performance map based on stable mean COF and CV. Lower-left is preferred, but visual surface condition must also be considered.

However, the performance map should not be used as the only decision tool. It only includes COF-based metrics and does not directly include wear or material removal. This is important in the present project because a grease can show a smooth and low COF curve while the surface is still being damaged. Therefore, the lower-left region of the map should be interpreted as friction-promising, not automatically as fully acceptable.

4.4 Industrial Grease Screening and Benchmark Selection

MolyWhite RE No.00 was used as the industrial reference grease and was tested first. The purpose was not only to measure its COF, but also to identify a reasonable benchmark region for comparing the food-grade grease. Table 4 summarises the most important high-load trials from the stable analysis window.

Table 4: Key high-load benchmark trials from the stable analysis window.

Trial	Grease	Load (N)	Speed (rpm)	Mean μ	Std	CV (%)	Drift
MW-T14	MW	70	125	0.0880	0.0054	6.1	+0.0072
MW-T13	MW	70	150	0.1206	0.0413	34.3	-0.0381
MW-T22	MW	70	150	0.1008	0.0282	28.0	+0.0599
RSFG-B2-T17	RSFG	70	125	0.1122	0.0095	8.5	+0.0150
RSFG-B3-T18	RSFG	70	150	0.0946	0.0019	2.0	+0.0003
RSFG-B4-T19	RSFG	70	175	0.1003	0.0100	9.9	-0.0149
RSFG-B5-T20	RSFG	70	200	0.0956	0.0042	4.3	+0.0031
RSFG-B6-T21	RSFG	70	300	0.0941	0.0018	1.9	+0.0038

Among the high-load MolyWhite tests, MW-T14 at 70 N and 125 rpm was selected as the most useful stable industrial benchmark. It had a mean COF of 0.0880, a standard deviation of 0.0054, and a CV of 6.1%. The individual curve also showed a relatively stable response after the run-in period. This means that the test condition was severe enough to be useful for comparison, but still stable enough to act as a reference.

When the speed was increased to 150 rpm at the same 70 N load, the MolyWhite response became less stable. MW-T13 gave a mean COF of 0.1206 and a CV of 34.3%, which indicates large relative fluctuation. MW-T22 was another 70 N and 150 rpm MolyWhite trial, with a slightly different track radius. It had a lower mean COF than MW-T13, but its CV was still high at 28.0%. This means that the instability was not only a single isolated feature of one curve. In the available test matrix, the 70 N and 150 rpm region was generally more critical for MolyWhite.

Based on these observations, MW-T14 was used as the stable industrial benchmark, while MW-T13 and MW-T22 were treated as limit-region cases. This distinction is useful because it allows the food-grade grease to be compared both against a stable reference condition and against a more demanding boundary condition.

4.5 Food-Grade Grease Response near the Benchmark Region

RoboSafe FG was tested near the selected high-load region and then at higher rotational speeds. At 70 N and 125 rpm, RSFG-B2-T17 had a mean COF of 0.1122 and a CV of 8.5%. Compared with MW-T14 at the same load and almost the same speed, the food-grade grease had a higher mean COF. Therefore, at this exact benchmark speed, MolyWhite gave the lower friction level.

The most promising RoboSafe FG result was RSFG-B3-T18 at 70 N and 150 rpm. This trial had a mean COF of 0.0946 and a very low CV of 2.0%. Compared with the MolyWhite 70 N and 150 rpm trials, this was a clear improvement in friction stability. The drift was also very small, which means the curve remained almost constant during the stable window. From the COF point of view, this condition was the strongest food-grade result in the benchmark region.

At higher speeds, RoboSafe FG still showed low mean COF. RSFG-B4-T19 at 70 N and 175 rpm had a mean COF of 0.1003 and a CV of 9.9%. RSFG-B5-T20 at 70 N and 200 rpm had a mean COF of 0.0956 and a CV of 4.3%. RSFG-B6-T21 at 70 N and 300 rpm had a mean COF of 0.0941 and a CV of 1.9%. These values show that the food-grade grease was able to keep the COF signal smooth even when speed was increased.

However, these higher-speed cases cannot be accepted only from the COF values. The visual observations showed surface concern for some of the higher-speed RoboSafe FG tests. Therefore, the food-grade grease response should be described as promising in friction stability, but still uncertain in surface protection at higher speed.

4.6 Representative Individual COF Curves

The individual curves help explain the behaviour behind the summary statistics. Figure 7 shows the selected MolyWhite benchmark and limit-region case. Figure 8 shows the selected RoboSafe FG stable case and high-speed warning case.

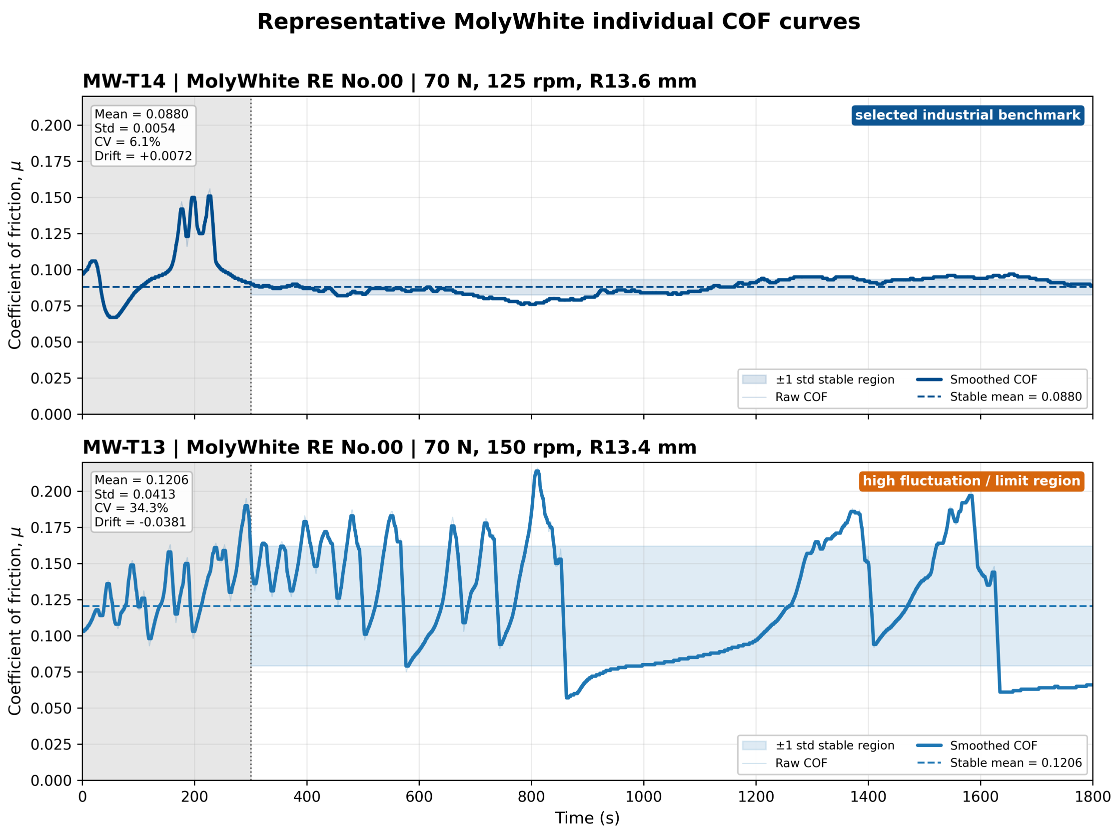


Figure 7: Representative MolyWhite individual COF curves. MW-T14 is the selected industrial benchmark, while MW-T13 shows higher fluctuation at 70 N and 150 rpm.

MW-T14 shows why it was selected as the industrial benchmark. After the run-in period, the COF remained close to its mean value and did not show large repeated peaks. In contrast, MW-T13 shows stronger fluctuations and sudden changes. Even though both tests were carried out at 70 N, the increase from 125 rpm to 150 rpm changed the behaviour significantly. This suggests that the MolyWhite contact became less stable in the higher-speed high-load condition.

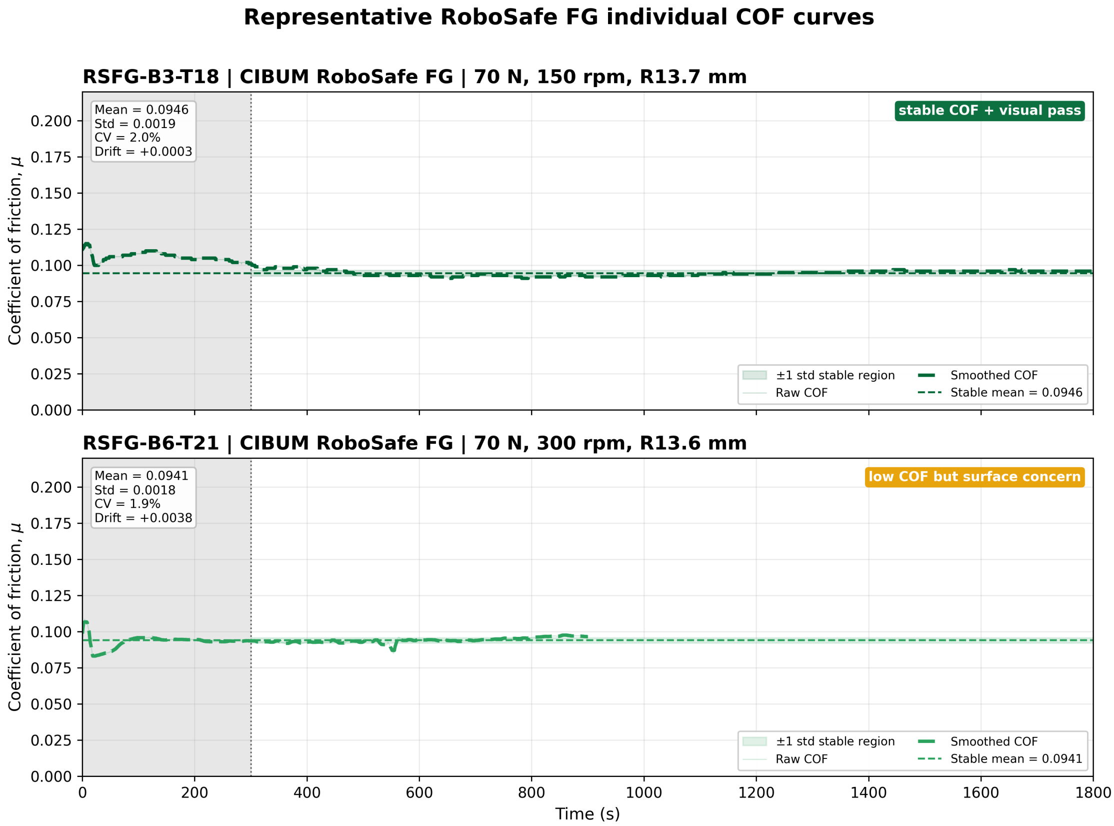


Figure 8: Representative RoboSafe FG individual COF curves. RSFG-B3-T18 shows stable COF and showed no clear visual material removal in the current inspection, while RSFG-B6-T21 shows low COF but must be interpreted together with the post-test surface observation.

RSFG-B3-T18 shows a very stable COF signal at 70 N and 150 rpm. The curve remains close to the stable mean and has only small variation after the run-in period. This supports the idea that RoboSafe FG performed well near the selected benchmark boundary. RSFG-B6-T21 also shows a very smooth COF signal at 70 N and 300 rpm, but this result must be treated carefully. The curve alone suggests excellent friction stability, while the surface condition after testing indicates that low COF does not automatically mean acceptable wear protection.

4.7 Food-Grade Grease Compared with Industrial Reference Cases

Because the exact same MolyWhite reference condition was not available for every RoboSafe FG trial, the food-grade tests were compared with the nearest industrial reference cases in the available matrix. Figure 9 and Table 5 summarise this comparison.

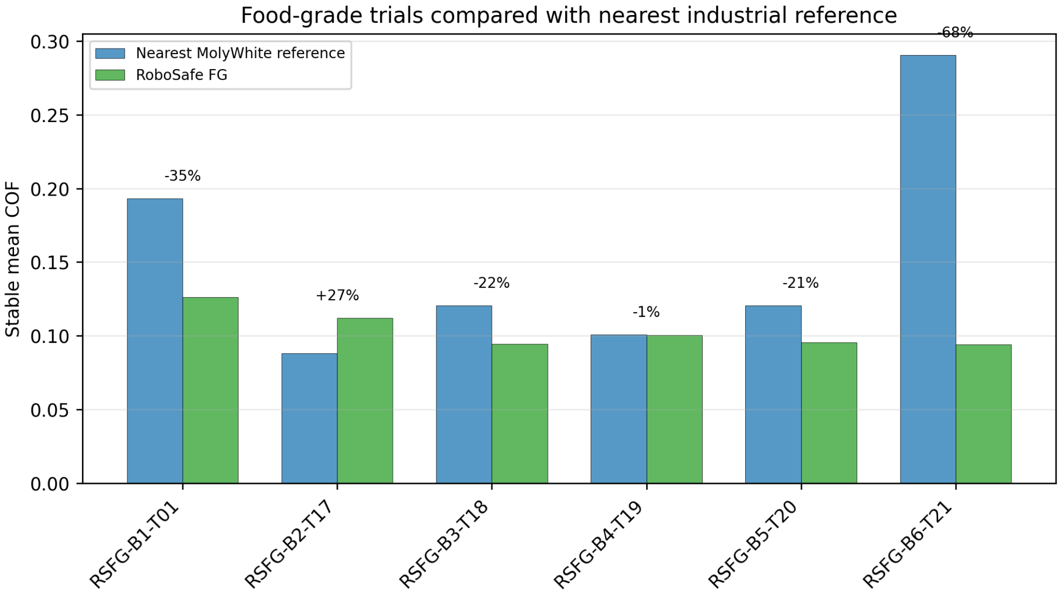


Figure 9: RoboSafe FG trials compared with nearest MolyWhite reference conditions. Negative difference means lower mean COF for RoboSafe FG.

Table 5: Food-grade trials compared with the nearest MolyWhite reference condition in the available test matrix. Negative Δ indicates lower mean COF for the food-grade grease.

RSFG trial	MW reference	RSFG $\bar{\mu}$	MW $\bar{\mu}$	Δ vs MW
RSFG-B1-T01	MW-T02	0.1262	0.1933	-34.7%
RSFG-B2-T17	MW-T14	0.1122	0.0880	+27.5%
RSFG-B3-T18	MW-T13	0.0946	0.1206	-21.6%
RSFG-B4-T19	MW-T22	0.1003	0.1008	-0.5%
RSFG-B5-T20	MW-T13	0.0956	0.1206	-20.8%
RSFG-B6-T21	MW-T01	0.0941	0.2903	-67.6%

At 30 N, RSFG-B1-T01 had a lower mean COF than the nearest MolyWhite reference, MW-T02. At 70 N and 125 rpm, RSFG-B2-T17 had a higher mean COF than MW-T14, so MolyWhite performed better at the selected stable benchmark speed. However, at 70 N and 150 rpm, RSFG-B3-T18 had a lower mean COF than MW-T13 and was also much more stable. This comparison is important because it shows that the food-grade grease did not simply perform worse than the industrial grease. Instead, its performance depended on the test condition.

The comparison at higher speed must be interpreted carefully. RSFG-B5-T20 and RSFG-B6-T21 had lower mean COF than their nearest MolyWhite references, but the nearest references were not exact matches in all cases. Therefore, the comparison is useful for screening, but it should not be presented as final one-to-one replacement validation.

Overall, the direct comparison supports one main result: RoboSafe FG is promising near the high-load benchmark region, especially at 70 N and 150 rpm, but the higher-speed results need additional wear measurement before they can be accepted.

4.8 Post-Test Visual Surface Observations

The post-test surface observations were used together with the COF results because friction alone does not fully describe tribological performance. Figure 10 shows selected surface observations after testing. These images were used to identify whether clear visual material removal occurred.

The post-test images are used as qualitative visual evidence only because no calibrated scale bar or profilometry measurement was available for these photographs.

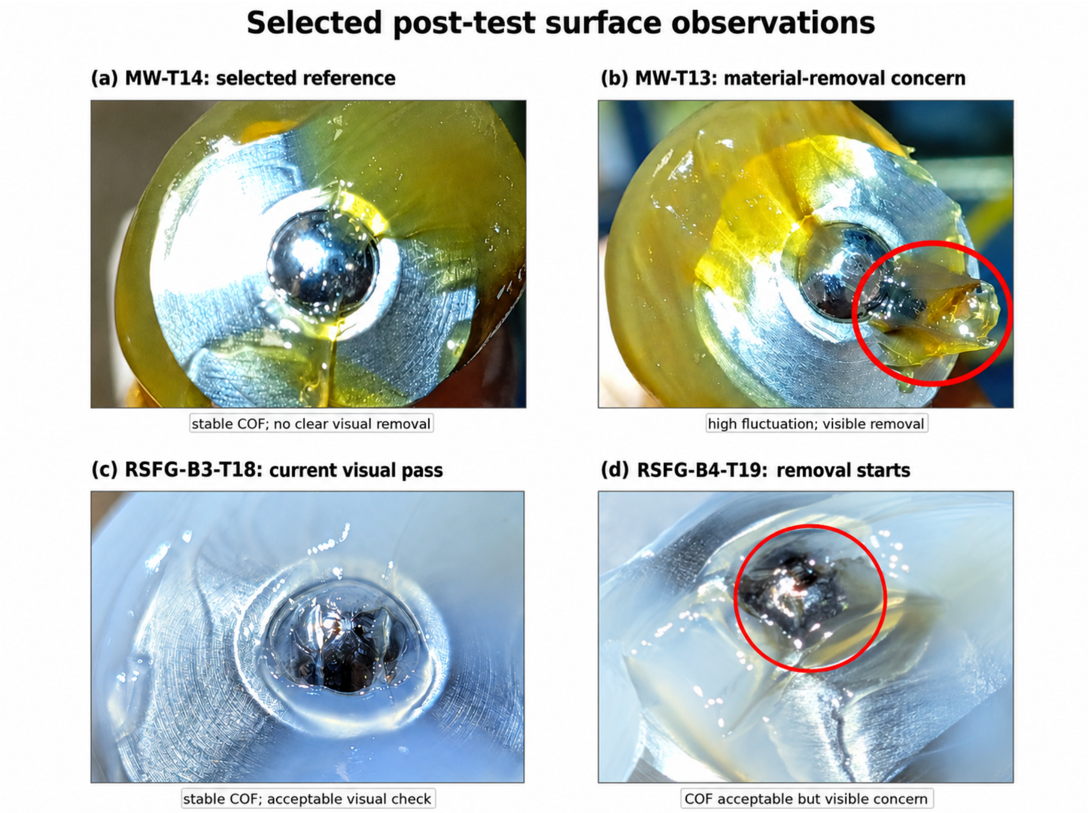


Figure 10: Selected visual observations after testing. The images were used together with COF statistics for decision-making.

The MolyWhite T14 surface was used as the visual reference for an acceptable benchmark condition. This trial had stable COF and did not show the same level of surface concern as the more severe MolyWhite case. In contrast, MolyWhite T13 showed clear visual concern after testing. This supports the interpretation from the COF data that 70 N and 150 rpm was close to, or beyond, the stable operating boundary for MolyWhite in this setup.

For RoboSafe FG, no clear visual material removal was observed for RSFG-B3-T18 in the available post-test photographs, and this trial also had a very stable COF curve. This makes it the strongest food-grade candidate condition in the present study. RSFG-B4-T19 showed the start of visible material removal at 70 N and 175 rpm. This is important because its mean COF and CV were still reasonable, but the surface observation showed that the contact was becoming more severe. Since visible material removal started at the higher-speed conditions despite stable COF curves, the test series was not extended to still higher rotational speeds in the present study. The higher-speed RoboSafe FG tests therefore need quantitative wear-track measurement before any final conclusion can be made. An additional post-test image for RSFG-B6-T21 is included in Appendix D because this case had very low and stable COF at 70 N and 300 rpm, but still requires careful surface interpretation. This behaviour is interpreted as mixed/boundary-dominated lubrication rather than full-film separation: bleed oil or local grease replenishment can keep the friction response smooth, while the high-pressure sliding contact can still allow asperity interaction and material removal. Therefore, low and stable COF does not prove full surface protection; the surface must also be checked by quantitative wear measurement.

4.9 Summary of Key Results

The main results from the present test matrix can be summarised as follows. First, MW-T14 at 70 N and 125 rpm was the best stable industrial benchmark condition, with mean COF 0.0880 and CV 6.1%. Second, increasing MolyWhite to 70 N and 150 rpm led to higher fluctuation and visual surface concern, especially in MW-T13. Third, RoboSafe FG showed its strongest result at 70 N and 150 rpm, where RSFG-B3-T18 had mean COF 0.0946, CV 2.0%, and acceptable visual appearance in the current inspection. Fourth, RoboSafe FG maintained low and smooth COF at higher speeds, but visible material removal started to appear, so these conditions cannot be accepted based on COF alone.

Therefore, the results show that RoboSafe FG is a promising food-grade candidate in the selected benchmark region. However, they also show that the final decision must combine friction stability with surface protection. The next chapter interprets these findings using tribological contact, lubrication, and wear concepts.

5 Discussion: Tribological Interpretation

5.1 Interpretation of the Industrial Benchmark

MolyWhite RE No.00 was used as the industrial reference grease because it represents the current reduction gear grease type used in the project context. Based on the supplier information available to this project, MolyWhite RE No.00 is a lithium-soap grease based on synthetic hydrocarbon oil and refined mineral oil, with a base-oil kinematic viscosity of 32.1 mm^2/s at 40 °C. It is therefore a suitable reference for comparing the candidate food-grade grease under the same laboratory conditions.

In the present ball-on-disc tests, MW-T14 at 70 N and 125 rpm was selected as the stable industrial benchmark. This trial had a stable mean COF of 0.0880 and a CV of 6.1%. The selected key curves in Figure 2 and the individual curve in Figure 7 show that MW-T14 became relatively stable after the run-in period. This behaviour is consistent with the idea that grease lubrication depends on a balance between oil release, replenishment and local film formation in the contact [1, 8, 10].

When the speed was increased to 150 rpm at the same 70 N load, the behaviour changed clearly. MW-T13 had a mean COF of 0.1206 and a CV of 34.3%, while MW-T22 had a mean COF of 0.1008 and a CV of 28.0%. Both cases were much more unstable than MW-T14. The individual curve for MW-T13 shows repeated fluctuations and sudden changes, which indicates that the contact was no longer operating in a stable way. The post-test visual observation also showed surface concern for this condition.

Therefore, the 70 N and 150 rpm condition can be interpreted as a limit region for MolyWhite in the present test setup. This does not mean that MolyWhite is generally a poor grease. It only means that, in this specific ball-on-disc screening configuration, MW-T14 was the best stable industrial reference, while MW-T13 and MW-T22 represented more severe and less stable industrial cases. This interpretation agrees with contact-mechanics theory, where small changes in contact condition can become important when the contact already operates at high local pressure [4].

5.2 Interpretation of the Food-Grade Grease Response

RoboSafe FG was tested as the candidate food-grade grease. The SDS identifies it as a lubricating grease and classifies the mixture as not hazardous under CLP regulation. In the project information, RoboSafe FG is treated as a PAO-based food-grade grease with an anhydrous calcium thickener. This means that its chemistry is different from the lithium-soap MolyWhite grease, and this can influence oil release, boundary film formation and surface protection. Calcium-based grease chemistry and food-grade additive systems have also been shown in the literature to affect friction and surface-film behaviour in lubricated steel contacts [5, 6].

The strongest food-grade result was RSFG-B3-T18 at 70 N and 150 rpm. This trial had a mean COF of 0.0946 and a CV of only 2.0%. It also passed the current visual inspection. This is an important result because it was tested at the same load and speed where MolyWhite showed much stronger fluctuation. From the COF stability point of view, RoboSafe FG therefore performed very well near the selected benchmark boundary.

RoboSafe FG also maintained low and smooth COF at higher speeds. RSFG-B5-T20 at 70 N and 200 rpm had a mean COF of 0.0956 and a CV of 4.3%, while RSFG-B6-T21 at 70 N and 300 rpm had a mean COF of 0.0941 and a CV of 1.9%. At first, these results look very promising because the COF did not increase strongly with speed. However, the post-test surface observations changed the interpretation. Visible surface concern appeared in the higher-speed food-grade tests, especially when the test severity was increased.

This means that RoboSafe FG should be interpreted as promising, but not fully validated. It was able to maintain a smooth friction response, but the surface protection was not always sufficient at higher speed. A reasonable explanation is that the grease continued to supply oil or maintain a low-shear interface, which kept the COF low, while the solid surfaces still experienced local asperity interaction and material removal. This is also visible in Appendix D, where the higher-speed RoboSafe FG cases show clearer post-test surface concern despite stable COF behaviour. Similar separation between friction response and wear response has been reported in grease studies where friction data were interpreted together with wear morphology and wear volume [5, 11, 12].

5.3 Why Stable COF Alone Is Not Sufficient

One of the most important findings of this project is that low and stable COF does not automatically mean good wear protection. COF mainly describes the resistance to sliding or rolling-sliding motion. Wear, on the other hand, describes material loss, material transfer or surface damage. These two responses are related, but they are not the same.

This is why several tribology studies judge lubricant performance using both friction and wear indicators, rather than COF alone [5, 11, 12].

This is especially important for grease-lubricated contacts. Grease can remain near the wear track and release oil into the contact. If the oil supply is stable, the COF curve can look smooth. However, if the lubricant film is too thin to fully separate the asperities, local metal-to-metal interaction can still occur. Under high contact pressure, asperities can plastically deform, adhere, break, or produce wear debris. Therefore, a smooth COF signal can still occur together with surface damage.

The present results show this clearly. RSFG-B6-T21 had a very low CV and a low mean COF, but it cannot be treated as a full pass from COF alone because the higher-speed food-grade region requires careful surface interpretation. The additional B6 surface image in Appendix D supports this caution. Similarly, RSFG-B4-T19 did not look poor from the COF statistics alone, but the visual observation showed that material removal had started. Therefore, the decision rule used in this project is appropriate: a test condition should only be considered acceptable when the COF is stable and no clear visual material removal is observed.

For this reason, quantitative wear measurement is the most important next step. Wear-track width, wear depth, wear volume and ball scar size are needed to confirm whether the visually observed marks represent serious material loss or only superficial surface marking. Similar quantitative wear indicators are commonly used in ball-on-disc and grease-screening studies [5, 12].

5.4 Effect of Load, Speed and Contact Pressure

The results should be interpreted using contact severity, not only load or rpm. In a ball-on-disc test, the applied load is concentrated in a very small point contact. This creates high local Hertzian pressure, even though the laboratory load is much smaller than the real gear load. Therefore, the ball-on-disc test can still be severe and useful for screening grease behaviour. This follows the Hertzian contact concept that contact geometry and elastic properties control the local pressure field, not only the applied normal force [4].

Increasing the normal load increases the contact pressure and the risk of asperity contact, plastic deformation and wear. This is why the high-load region around 70 N was used as the main decision area. Lower-load tests are useful for initial screening, but the high-load tests are more important for judging whether the grease can protect the surface under severe conditions.

Speed also affects the contact, but rpm alone is not enough to describe the tribological condition. The more meaningful quantity is the surface speed or sliding speed at the track radius. Increasing speed increases sliding distance and the number of repeated passes over the same track. It can also increase local heating and make the test more demanding. At the same time, higher speed can sometimes help to maintain a lubricant film. Grease studies also show that film formation, surface roughness and friction can change with speed and contact condition [7, 8, 10].

Therefore, the higher-speed food-grade results should not be interpreted as simple success. They show that the grease can maintain friction stability, but they also show that friction stability alone is not enough to guarantee surface protection.

5.5 Role of Grease Chemistry and Film Formation

The two greases have similar base-oil viscosity values around 32 mm^2/s at 40 °C, but their chemistry is different. MolyWhite uses a lithium-soap thickener with synthetic hydrocarbon and mineral base oils, and the datasheet also mentions an organic molybdenum compound. RoboSafe FG is treated as a PAO-based food-grade grease with an anhydrous calcium thickener.

This is important because grease performance is not controlled by viscosity alone. The thickener structure affects how the grease stays near the contact and how the base oil is released. Additives and thickener chemistry can also influence boundary film formation. In boundary or mixed lubrication, where the surfaces are not fully separated by a fluid film, the chemistry of the surface film becomes very important [1, 7].

MolyWhite performed well at the selected benchmark condition, which suggests that its oil release and boundary protection were sufficient at 70 N and 125 rpm. However, at 70 N and 150 rpm, the COF became much more unstable. This may indicate that the film formation or replenishment process became less stable under the increased contact severity.

RoboSafe FG showed very stable friction at 70 N and 150 rpm. This suggests that its oil release and local film behaviour were favourable at that condition. However, the visible surface concern at higher speed suggests that its friction-reducing behaviour and wear-protecting behaviour did not improve in the same way. The grease may have maintained a low-shear interface, but the protective film was not strong enough to fully prevent surface damage.

The chemistry difference between the two greases is important for interpreting the results. The MolyWhite datasheet mentions an organic molybdenum compound, which may act as a molybdenum-based friction modifier in boundary or mixed lubrication. Such compounds can contribute to low-shear surface films and may help explain why MW-T14 reached a low and stable COF at 70 N and 125 rpm. RoboSafe FG, in contrast, is treated in this project as a food-grade PAO/calcium-thickened grease without an additional dry lubricant. Therefore, the two greases may rely on different surface-protection mechanisms: MolyWhite may benefit from molybdenum-based boundary-film action, while RoboSafe FG depends more on base-oil supply, calcium-thickener behaviour and any food-grade-compatible boundary chemistry. Studies on food-grade or calcium-containing grease systems also show that additive and thickener chemistry can influence the formation of protective surface films [5, 6].

This difference also explains why viscosity alone is not enough for grease selection. Although both greases have similar base-oil viscosity around 32 mm^2/s at 40 °C, their thickener systems and possible boundary-film mechanisms are different. This makes the experimental comparison necessary, because similar viscosity does not guarantee similar friction stability or wear protection.

5.6 Difference between Laboratory Test and Real Robot Gear Operation

The present ball-on-disc test is useful for controlled screening, but it is not a full simulation of a real robot reducer. The real Nabtesco-type reducer contact is closer to a gear rolling-sliding contact, while the laboratory test used a steel ball against a flat steel disc. This changes the contact geometry, lubricant supply and stress distribution. Therefore, the ball-on-disc method should be treated as a comparative screening method, which is also how ball-on-disc and similar tribometer tests are commonly used in lubricant research [5, 9, 12].

The rpm values also cannot be compared directly. The robot gear context includes much higher rotational speed, for example around 2000 rpm at the sun gear. In the TriboLab, the disc rpm was lower. However, the important comparison is not rpm alone. Contact pressure, sliding speed, entrainment speed, slide-to-roll ratio and sliding distance are more meaningful quantities for comparing a gear contact with a ball-on-disc contact [4, 8].

Another difference is grease confinement. In a real reducer, grease is inside a closed gear housing and is redistributed by the gear motion. In the laboratory test, grease was applied on the disc surface and the contact repeatedly passed through the same circular track. This is repeatable and useful for comparison, but it does not fully reproduce the churning, flow and replenishment behaviour inside a gearbox. Grease replenishment and bleeding behaviour are known to be important in concentrated lubricated contacts [1, 2].

The material and surface condition may also be different. The present tests used 100Cr6 steel ball and 100Cr6 steel disc as a repeatable screening pair. Real reducer gears may use different alloy steels, heat treatment, case hardening, hardness, roughness and surface finishing. These differences can strongly affect boundary film formation, asperity contact and wear behaviour. Therefore, the present results should be treated as screening evidence rather than final gearbox approval.

5.7 Limitations of the Present Study

The main limitation of the present study is that the ball-on-disc setup does not fully reproduce the real robot gear contact. It gives a repeatable and useful comparison between the two greases, but it cannot capture the full gearbox geometry, lubrication flow, grease confinement and thermal behaviour. This is a common limitation of simplified tribometer screening tests, which are useful for comparison but still need application-level validation [9, 12].

A second limitation is that the wear evaluation was mainly visual. The surface photos were useful for identifying clear material removal, but they do not provide wear depth, wear width, wear volume or ball scar size. This limits the strength of the final decision, especially for cases where the COF curve was smooth but the surface looked damaged. Literature studies normally strengthen this type of interpretation using profilometry, interferometry or other quantitative wear measurements [5, 12].

A third limitation is the grease application method. The exact grease layer thickness and local grease distribution were not controlled as strictly as in a fully standardised tribology test. Grease amount and film thickness can influence oil availability, churning, replenishment and repeatability [1, 8]. Future work should therefore use a controlled mass or thickness protocol.

A fourth limitation is that most tests were carried out at room temperature. Real robot gearboxes can operate at higher temperatures, and temperature affects grease consistency, oil bleeding, oxidation, viscosity and film formation. The effect of temperature and surface roughness on grease tribological behaviour has been shown in previous grease studies [13].

A grease that performs well at room temperature may behave differently at elevated temperature.

Finally, the number of repeated tests was limited. Some conclusions are based on single trials at each condition. This is acceptable for screening, but not enough for final validation. Repeated tests are needed to separate real grease behaviour from scatter caused by surface preparation, grease placement, alignment and local contact variation.

Overall, these limitations do not make the results invalid. They define the level of conclusion that can be made. The correct conclusion is that RoboSafe FG is promising under the present screening conditions, especially at 70 N and 150 rpm, but it cannot yet be approved as a direct replacement for MolyWhite without quantitative wear measurement and application-level validation.

The results are based mainly on single trials for each condition. Therefore, the reported mean COF, CV and drift values should be interpreted as indicative screening results rather than statistically validated grease performance values. Repeated tests are required before confidence intervals or final replacement decisions can be made.

6 Future Work

6.1 Quantitative Wear-Track Measurement

The most important next step is to measure wear quantitatively. In the present work, the surface condition was evaluated mainly from visual observations. This was useful for identifying clear material removal, but it was not enough to calculate the actual amount of wear.

Future tests should measure wear-track width, wear depth and wear volume on the disc. The ball scar should also be measured. Optical microscopy can be used for wear scar diameter and surface marks, while 3D profilometry or white-light interferometry would be better for wear depth and volume. These methods are commonly used in grease and ball-on-disc studies to connect friction behaviour with actual wear morphology and wear volume [5, 12]. These measurements would make the decision much stronger, especially for cases such as RSFG-B6-T21, where the COF was low and stable but the surface condition raised concern.

6.2 Four-Ball Anti-Wear and Extreme-Pressure Testing

A four-ball test should be added to compare the anti-wear and extreme-pressure behaviour of the two greases. This test is commonly used for grease screening and can provide values such as wear scar diameter, weld load or load-wear index depending on the selected standard. Previous food-grade grease research has also combined four-ball testing with ball-on-disc testing to evaluate both load-carrying behaviour and friction/wear response [5].

The advantage of four-ball testing is that it can give a more standardised comparison of load-carrying capacity and anti-wear performance. It can also run at higher standardised rotational speed than the present ball-on-disc tests. However, the four-ball result should not replace the ball-on-disc result. The contact geometry is different from a robot gear, so it should be used as an additional screening test rather than final validation.

6.3 Elevated Temperature Testing

The present tests were mainly carried out at room temperature. Future work should include elevated-temperature testing because grease behaviour depends strongly on temperature. Temperature affects base-oil viscosity, grease consistency, oil bleeding, oxidation and boundary film formation. Previous grease studies have shown that temperature and surface roughness can change both friction and wear behaviour [13]. Grease composition can also influence friction in rolling/sliding contacts under different operating conditions [7].

This is relevant for robot gear applications because repeated gear contact, sliding and grease churning can increase the lubricant and contact temperature during operation. Therefore, testing only at room temperature may not fully show how the greases will behave under more realistic reducer conditions.

A practical next step would be to repeat the most important benchmark conditions at controlled elevated temperatures. For example, MW-T14 and RSFG-B3-T18 could be repeated first, followed by one higher-speed RoboSafe FG condition such as RSFG-B4-T19 or RSFG-B6-T21. This would show whether the food-grade grease remains stable when the operating condition becomes closer to a real gearbox environment.

6.4 Gear-Relevant Materials and Surface Finish

Future tests should use material and surface conditions closer to the real Nabtesco reducer gear. The present tests used 100Cr6 steel ball and disc because this pair gives a repeatable screening contact. However, real reducer gears may have different alloy composition, heat treatment, hardness, surface roughness and finishing. Surface roughness is especially important because it affects film formation, asperity contact and friction in grease-lubricated contacts [8, 13].

Using gear-relevant material would reduce the gap between the laboratory contact and the real application. If the exact gear material is not available, the selected material should at least be justified by hardness, elastic modulus, roughness and availability. The final material choice should also be interpreted together with Hertzian contact theory because geometry and elastic properties affect local pressure [4].

6.5 Improved Lubricant Supply and Submerged Testing Protocol

The lubricant supply should be made more controlled in the next test campaign. In the present ball-on-disc tests, the grease was manually applied to the disc surface before testing. This was acceptable for a first screening study, but the exact grease amount, layer thickness and local replenishment during sliding were not fully controlled. Since grease lubrication depends strongly on oil bleeding, redistribution and replenishment, the applied grease condition can affect both COF stability and surface protection [1, 2].

A useful next step would be to use a four-ball test where the contact can be fully surrounded by grease during testing. This would give a more repeatable lubricant-supply condition than manual spreading on an open disc, and it is closer to an enclosed greaserich gear environment where grease remains around the contact. Previous grease studies have also used four-ball testing to evaluate anti-wear and extreme-pressure behaviour, while ball-on-disc testing is useful for friction and wear comparison [5].

However, this should still be treated as a complementary screening test, not as direct gearbox validation. The main benefit is that it would help separate the effect of lubricant supply from the actual anti-wear and load-carrying performance of the grease. Therefore, future submerged or four-ball tests should clearly define the grease amount, load, speed, temperature and test duration before comparing MolyWhite and RoboSafe FG.

6.6 Replicates and Uncertainty

More repeated tests are needed for the main benchmark conditions. In the present screening study, several conclusions are based on single trials. This is acceptable for identifying trends, but it is not enough for final validation.

At least three repeated tests should be performed for MW-T14, RSFG-B3-T18 and one higher-speed RoboSafe FG condition. This would allow the mean and standard deviation between repeated tests to be reported and would make the comparison more reliable. It would also help separate real grease behaviour from scatter caused by surface preparation, grease placement or small alignment differences. Previous grease studies commonly combine friction and wear measurements to support lubricant-performance conclusions [5, 12].

6.7 Application-Level Validation

The final stage should move closer to the actual robot reducer application. Possible options include a gear-relevant rig, a rolling-sliding contact with controlled slide-to-roll ratio, or a longer-duration endurance test. These tests should combine friction, wear, temperature, grease condition and post-test surface analysis. This step is necessary because the present ball-on-disc contact is a simplified screening contact, not a full representation of the Nabtesco-type gear reducer application [4, 5, 9, 12].

Only after this type of validation can RoboSafe FG be considered for replacement of the industrial reference grease. Based on the present work, it should be treated as a promising candidate for further testing, not as a fully approved replacement.

6.8 Surface Roughness, Film Parameter and Tribofilm Characterisation

Future work should include surface roughness measurement of the ball and disc before testing. This would make it possible to calculate the film parameter Λ and classify the lubrication regime more quantitatively. The minimum film thickness could be estimated from an elastohydrodynamic film-thickness model or measured using a suitable optical method. The connection between grease film thickness, roughness and friction has been highlighted in previous grease-lubrication studies [8, 10].

Surface chemical analysis would also strengthen the interpretation. Techniques such as Raman spectroscopy or X-ray photoelectron spectroscopy could be used to check whether molybdenum-containing films form on the MolyWhite-tested surfaces and whether calcium-based or other boundary films form on the RoboSafe FG-tested surfaces. This would connect the measured COF behaviour more directly to the grease chemistry. This type of surface-film interpretation is relevant because previous studies have shown that additives and calcium-based chemistry can affect protective film formation and wear response in lubricated contacts [5, 6].

7 Conclusion

This project compared MolyWhite RE No.00 and CIBUM RoboSafe FG using controlled ball-on-disc tribology tests. The aim was to benchmark the candidate food-grade grease against the industrial reference grease under the same laboratory conditions and to evaluate both friction stability and surface protection.

The most useful industrial benchmark from the current test matrix was MolyWhite MW-T14 at 70 N and 125 rpm. This condition showed stable COF behaviour and was therefore used as the reference point. When MolyWhite was tested at 70 N and 150 rpm, the COF became more unstable and visual surface concern was observed. This condition was therefore interpreted as a limit region for the industrial grease in the present screening setup.

RoboSafe FG showed its strongest result at 70 N and 150 rpm. At this condition, RSFG-B3-T18 had a low mean COF, very low CV and acceptable visual appearance in the current inspection. This suggests that RoboSafe FG has real potential as a food-grade candidate in the selected benchmark region.

However, RoboSafe FG cannot yet be approved as a direct replacement. At higher speed conditions, visible material removal or surface concern appeared even when the COF curve remained low and smooth. This is the most important conclusion of the project: low COF alone is not enough. A reliable grease decision must combine friction stability with surface protection.

Based on the present screening work, RoboSafe FG should be considered promising, but further testing is required. The next stage should include quantitative wear measurement, four-ball anti-wear and extreme-pressure testing, elevated-temperature testing, improved grease application control, repeated trials and gear-relevant validation. Therefore, the present conclusion should be understood as a screening-level recommendation based on COF stability, calculated contact severity and visual surface inspection, not as a final gearbox approval.

8 Appendix

The raw COF files, processed summary CSV files, plotting notebook and selected post-test images were submitted as appendix material to support data traceability and reproducibility.

A Complete Processed Test Matrix

The complete processed test matrix used for the COF analysis is provided below. The stable-window statistics were calculated after removing the 0–300 s run-in period.

Table 6: Complete processed test matrix and stable-window statistics.

Trial	Grease	Load N	rpm	R mm	Duration s	Mean μ	Std	CV %	Drift
MW-T01	MW	50	367	13.0	516	0.2903	0.0627	21.6	-0.0070
MW-T02	MW	30	106	13.5	565	0.1933	0.0216	11.2	+0.0504
MW-T03	MW	30	110	13.0	1800	0.2427	0.0599	24.7	-0.1398
MW-T04	MW	30	107	12.5	2800	0.1485	0.0274	18.5	+0.0428
MW-T05	MW	25	75	15.0	1800	0.0991	0.0070	7.1	-0.0010
MW-T06	MW	30	75	15.2	1800	0.0802	0.0145	18.0	-0.0371
MW-T07	MW	25	100	15.4	1800	0.1623	0.0162	10.0	+0.0222
MW-T08	MW	30	100	15.6	1800	0.1030	0.0055	5.3	-0.0081
MW-T09	MW	25	100	15.8	1800	0.0678	0.0073	10.7	-0.0162
MW-T10	MW	30	100	16.0	1800	0.1517	0.0603	39.7	-0.1252
MW-T11	MW	50	100	13.0	1800	0.0978	0.0068	7.0	-0.0080
MW-T12	MW	70	100	13.2	1800	0.0743	0.0117	15.7	-0.0179
MW-T13	MW	70	150	13.4	1800	0.1206	0.0413	34.3	-0.0381
MW-T14	MW	70	125	13.6	1800	0.0880	0.0054	6.1	+0.0072
MW-T15	MW	30	200	13.1	1800	0.1624	0.0181	11.1	+0.0096
MW-T16	MW	20	150	13.3	1800	0.1433	0.0317	22.1	+0.0133
MW-T22	MW	70	150	14.1	1800	0.1008	0.0282	28.0	+0.0599
RSFG-B1-T01	RSFG	30	109	14.0	2800	0.1262	0.0124	9.8	-0.0243
RSFG-B2-T17	RSFG	70	125	13.5	1800	0.1122	0.0095	8.5	+0.0150
RSFG-B3-T18	RSFG	70	150	13.7	1800	0.0946	0.0019	2.0	+0.0003
RSFG-B4-T19	RSFG	70	175	13.9	1800	0.1003	0.0100	9.9	-0.0149
RSFG-B5-T20	RSFG	70	200	13.4	1800	0.0956	0.0042	4.3	+0.0031
RSFG-B6-T21	RSFG	70	300	13.6	900	0.0941	0.0018	1.9	+0.0038

B Additional COF Curves

Figure 11 shows the complete set of smoothed COF curves grouped by grease type. In Chapter 4, only selected benchmark and limit-region curves were shown to make the main comparison easier to read. This appendix figure is included to show the full curve overview and avoid hiding any processed trials.

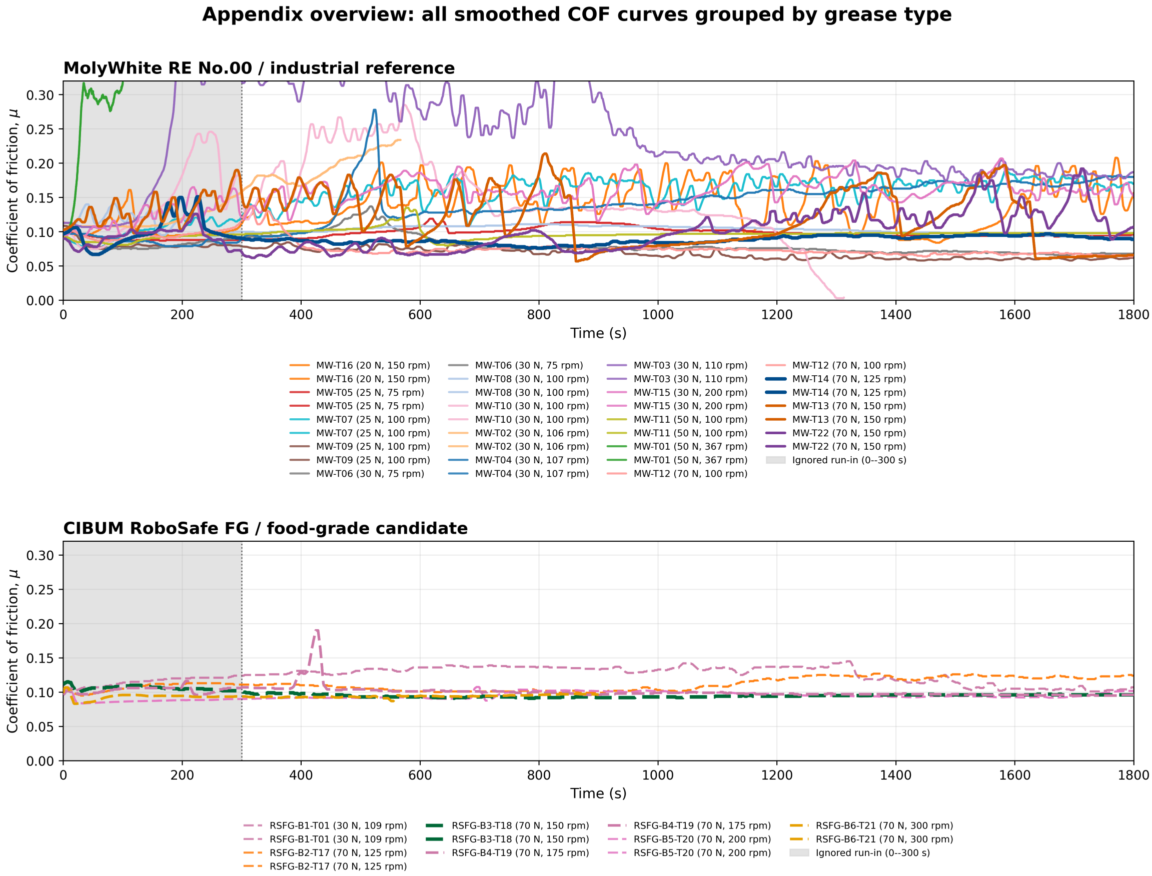


Figure 11: Appendix overview of all smoothed COF curves grouped by grease type. The grey region marks the ignored 0–300 s run-in period.

C Hertzian Contact Calculation

The Hertzian contact calculation is used to document the pressure basis for interpreting the ball-on-disc tests. The calculation was made for a 100Cr6 steel ball against a flat 100Cr6 steel disc. The ball diameter was 6.5 mm, so the ball radius used in the calculation was 3.25 mm. Both contacting bodies were treated as steel with $E = 210\,\text{GPa}$ and $\nu = 0.30$.

For two elastic bodies, the equivalent elastic modulus is

$$\frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}, \tag{6}$$

where E_1, E_2, ν_1, and ν_2 are the elastic moduli and Poisson's ratios of the two contacting bodies. For the 100Cr6 steel–steel contact used here, the equivalent modulus is

$$E^* \approx 115.38\,\text{GPa}. \tag{7}$$

For a sphere-on-flat contact, the reduced radius is approximately the ball radius. The Hertzian contact radius is

$$a = \left(\frac{3FR^*}{4E^*}\right)^{1/3}, \tag{8}$$

where F is the normal load and R^* is the reduced radius. The mean contact pressure and maximum Hertzian pressure are calculated as

$$p_m = \frac{F}{\pi a^2}, \qquad p_0 = \frac{3F}{2\pi a^2}. \tag{9}$$

The calculated values for the load levels used in the test matrix are shown in Table 7. The 70 N case was the main high-load comparison condition used for the benchmark interpretation.

Table 7: Calculated Hertzian contact values for the ball-on-disc load levels.

Load F **(N)**	**Contact radius** a **(**μ**m)**	**Mean pressure** p_m **(GPa)**	**Max. pressure** p_0 **(GPa)**	**Use**
20	75.0	1.13	1.70	Low-load screening
25	80.8	1.22	1.83	Low-load screening
30	85.9	1.29	1.94	Screening / comparison
50	101.8	1.53	2.30	Intermediate severity
70	113.9	1.72	2.57	Main high-load region

These values show why the local pressure in a ball-on-disc test can be severe even when the applied laboratory load is much smaller than the real gear force. The pressure is concentrated over a small circular contact area, which makes the test useful for screening lubricant behaviour. However, the contact is still a simplified point contact, so these values should be used for comparative interpretation rather than final gearbox validation.

D Additional Surface Images

Additional post-test ball and disc images can be included here to support the visual interpretation in Chapter 4. The main visual surface observations are shown in Figure 10. Figure 12 adds the RSFG-B6-T21 post-test image because this trial had very low and stable COF at 70 N and 300 rpm, but it should not be accepted based on friction data alone.

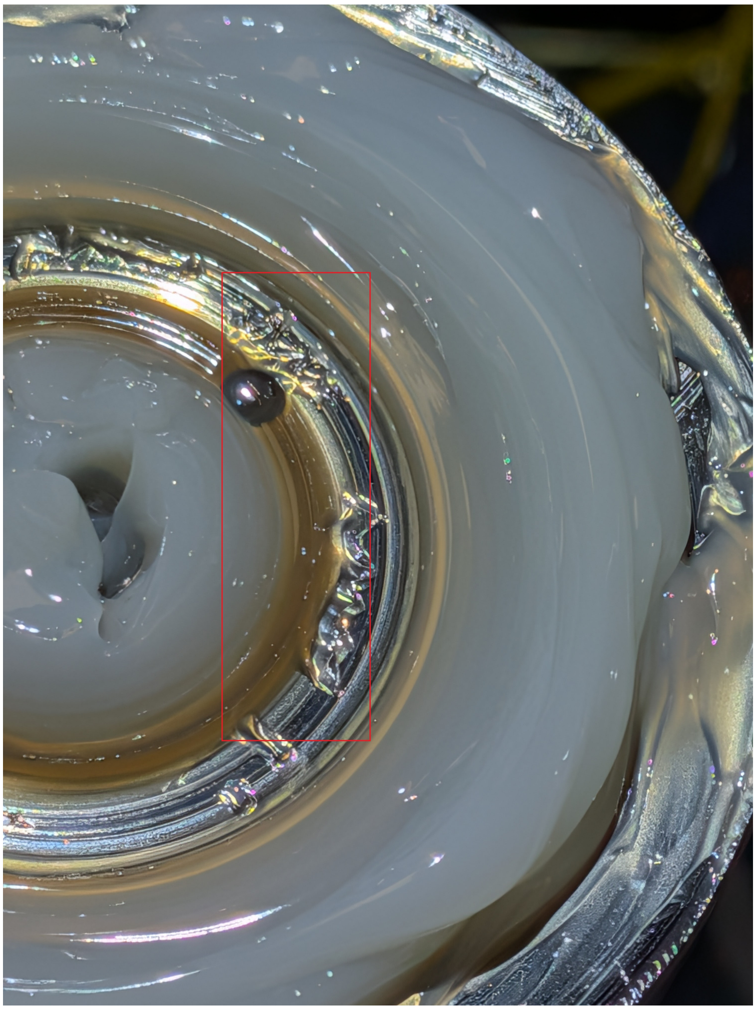


Figure 12: Additional post-test surface observation for RSFG-B6-T21 at 70 N and 300 rpm. This trial showed low and stable COF, but the surface condition should be checked quantitatively before treating the condition as acceptable.

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