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INTERDISCIPLINARY ADVANCES IN TRIBOTESTING: FROM LUBRICATION STRATEGIES TO ENGINE WEAR ASSESSMENT

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Graphical abstract

Engine Tribotester

Abstract

Engine tribotesters were developed using a variety of tribological analysis approaches, and this article gives a thorough description of these approaches. Improving the efficiency and longevity of engines relies heavily on lubrication, friction, and the study of wear and friction. In order to correctly replicate real-world engine conditions, this study takes a look at the many analytical methodologies used to build and evaluate tribotesters. The article discusses several methods for simulating engine tribological phenomena, including pin-on-disk, reciprocating, fourball and journal bearing, and outlines their benefits and drawbacks. To further assess wear processes and material characteristics subjected to tribological stress, we investigate recent developments in oil modification methods such as applying an alternative lubricant and the use of additives in lubricant. In order to increase engine performance and lifetime, this paper highlights the significance of using approaches from interdisciplinary tribological investigations to promote the development of engine tribotesters.

Keywords: Tribotester, friction, wear, automotive engine, test rig

Abstrak

Penguji tribologi enjin dibangunkan menggunakan pelbagai pendekatan analisis tribologi, dan artikel ini memberikan penerangan menyeluruh tentang pendekatan ini. Meningkatkan kecekapan dan jangka hayat enjin sangat bergantung pada pelinciran, geseran, dan kajian kehausan dan geseran. Untuk meniru keadaan enjin dunia sebenar dengan betul, kajian ini melihat pada banyak metodologi analisis yang digunakan untuk membina dan menilai penguji tribo. Artikel ini membincangkan beberapa kaedah untuk mensimulasikan fenomena tribologi enjin, termasuk pin-on-disk, reciprocating, fourball dan jurnal bearing, dan menggariskan faedah dan kelemahannya. Untuk menilai lebih lanjut proses haus dan ciri bahan yang tertakluk kepada tekanan tribologi, kami menyiasat perkembangan terkini dalam kaedah pengubahsuaian minyak seperti menggunakan pelincir alternatif dan penggunaan bahan tambahan dalam pelincir. Untuk meningkatkan prestasi enjin dan jangka hayat, kertas kerja ini menyerlahkan kepentingan menggunakan pendekatan daripada penyiasatan tribologi antara disiplin untuk mempromosikan pembangunan tribotester enjin.

Kata kunci: Tribotester, geseran, haus, enjin automotif, pelantar ujian

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INTRODUCTION

A tribometer is a tool for determining a material's lubrication, wear, and friction characteristics. A number of sectors rely on them heavily, including the transportation, aerospace, manufacturing, and materials research sectors. Technological and methodological developments in tribometers over the last few decades have greatly enhanced their capacity to reliably and accurately measure tribological qualities. These days, people usually bring up the four industrial revolutions. This basically came up after the term "industry 4.0" was defined so that it would be consistent with that term. Industry 1.0, Industry 2.0, and Industry 3.0—the three preceding industrial revolutions that are briefly outlined. The precise times of these revolutions are a matter of substantial debate in the literature [1]. Assuming that the rise of mechanization marked the beginning of the (first) industrial revolution in the second part of the 18th century, various time intervals, typically ranging from four to ten decades, have been typically indicated as the duration of each revolution. Just as Xu *et al*. [2] and Ciulli, [1] point out, the author isn't attempting to provide a whole history of the industrial revolutions; rather trying to provide a framework for tribological studies that focus on industrial advancement.

Better designs of machine parts were a hallmark of the period between 1750 and 1850. It was the age of William Tell's steam engine. Novel lubricants, including mineral oils, lubricant formulations, and solid lubricants, as well as journal bearings (especially for railways), roller bearings, and gears, were created. Coulomb [3] verified the theories proposed by Leonardo da Vinci and Amontons via his groundbreaking research on friction. It was Navier who first used the term "viscosity" while defining the famous equations with Stokes. The movement of fluids via pipes was the subject of Poiseuille's research.

Following the preceding time, technological advancements continued for around a century, from 1850 to 1940, with several further advancements in lubrication and bearings. Lubrication, wear, and friction were all studied in connection to one another. Among them, Tower found the hydrodynamic pressure development in journal bearings, Hirn studied hydrodynamic friction, and Hertz studied rolling friction. Reynolds [4] established the foundation for bearing calculation with his famous equation for the hydrodynamic pressure. The link between friction, load, speed, and viscosity was established by Stribeck's curve; the Sommerfeld number and an analytical solution to Reynolds' equation were presented by Sommerfeld. The inventor of rolling bearings, Wingquist, was also the founder of SKF. Oils were the first media to receive additives. At the turn of the twentieth century, several engineers and scientists, including Michell, Stribeck, Kingsbury, Rayleigh, and Gümbel, worked on the theoretical elements of journal and thrust hydrodynamic bearings. Not only that, but hydrostatic lubrication and certain kinds of bearings like the tilting pad (Michell, Kingsbury) and the step (Rayleigh) bearings were also developed. In the 1930s, Swift, Stieber, and Kingsbury all put out different analytical and approximate solutions to the Reynolds equation. As Blok pointed out, the flash temperature is part of the overall transient temperature, which also includes scuffing.

Elastohydrodynamic lubrication (EHL) theory, the foundational kind of lubrication for rolling bearings and gears, takes into consideration not only the hydrodynamic effect but also the effects of elastic deformation of the contacting bodies and the dependence of the lubricant viscosity on pressure. This theory can be traced back to the 1940s and 1960s. Beginning with what is more appropriately referred to as the Ertel-Grubin formula [5], [6], which was published in 1949 as Grubin's formula for evaluating the minimum film thickness, numerical solutions were obtained in the late 1950s by Dowson and Higginson [7]. Other areas of tribology also saw further advancements. Additionally, Ocvirk and Du Bois presented the approximation for brief journal bearings. The first numerical answers were put out by Cameron and Wood in the 1950s, followed by Pinkus, Raymondi, and Boyd. As ideas of adhesion evolved, friction investigations advanced. The friction coefficient was introduced by Bowden and Tabor as a simple ratio of shear stress to hardness of the asperity connections. Archard studied wear issues, leading to the development of the traditional formula for worn material volume.

From the late 1960s to the late 1990s, "official" tribology emerged, with the Jost Report [8] highlighting its economic value in improving mechanical system reliability and efficiency by reducing friction and wear. Significant advances in tribology knowledge and industrial applications are presented here. New powerful computers enabled numerical extension of elastohydrodynamic research to point contacts [9]. Non-Newtonian rheological models, such as Bair and Winer's, provide more accurate friction and power loss evaluations. Recent advances in computational and experimental methods, such as optical interferometry for film thickness evaluation, enable research on mixed and boundary lubrication conditions, including micro-EHL, very thin film lubrication, and non-steady state conditions (e.g. Spikes and Kaneta). Recent advancements in low friction bearings include air-lubricated, magnetic, and hydrostatic lubrication [10]. Further research on surface engineering includes Greenwood's contact mechanics studies, friction studies at the atomic scale, and experiments with the surface force apparatus (SFA) and atomic force microscope (AFM). Tribology developed for magnetic storage systems [11]. Blok, Greenwood, Johnson, Dowson, Higginson, Hamrock, and Moes created nondimensional groups for lubrication and contact-mechanics investigations. Several research on wear were conducted, including Kimura, Ludema, and Kato. New materials and coatings, such as diamond-like carbon (DLC) coatings, have assisted in decreasing wear, especially by physical or chemical vapour deposition (PVD or CVD).

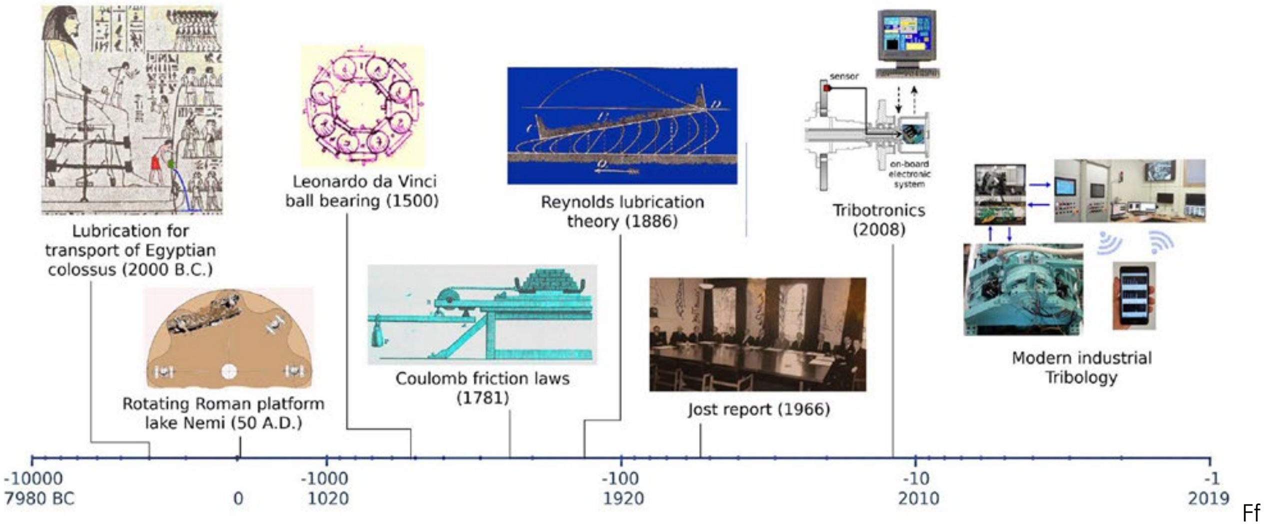

Figure 1 The tribology evolutions [1]

From 2000 until now is tribology's era. Further advancements occur in all previously listed domains. Tribology increasingly encompasses scientific, environmental, and economical factors. Tribological studies cover various transport aspects, including road, rail, engine, machine component, machining, cold/hot forming, atomic scale investigations, micro/nano mechanics applications, information systems, bio-technology, ceramics, surface texturing, coatings, lubricants, and additives. In 2001, Zhang created the term "Green Tribology" to describe the growing field of eco-friendly tribology. Klein introduces superlubricity and hydration lubrication principles. Space tribology is also developed for aeronautical purposes [1]. The name "Tribotronics," combining tribology and electronics, was introduced at Luleå University of Technology (2008). To enhance industrial equipment performance, smart tribological systems, comprising models, sensors, and actuators, must be created. Figure 1 is a schematic representation of the evolutions in tribology.

FACTORS OF ONGOING TRIBOLOGY DEVELOPMENT

The study and analysis of lubrication have seen a notable upsurge in modern engineering and scientific research, indicating a paradigm change in the comprehension and optimization of mechanical systems [12]. The critical role that lubrication plays in a wide range of industrial applications from manufacturing machinery to automobile engines has encouraged researchers and engineers to investigate the complex dynamics of this basic tribological conditions in more detail [13], [14]. It has long been known that improving the lubrication the science and technique of using a lubricant to reduce wear and friction between moving surfaces is essential to increasing the effectiveness, durability, and dependability of mechanical components [15].

The ongoing development and sophistication of mechanical systems is a major factor contributing to the increased attention being paid to lubrication studies [16]. Accurate lubrication solutions are becoming more and more important as engineering designs get more complex and function in harsher environments [17]. The high speeds, temperatures, and loads that modern machinery runs at need a sophisticated knowledge of lubricant behavior in these harsh environments [18], [19]. In order to customize lubricating strategies to the unique requirements of cutting-edge technology, researchers are therefore forced to investigate innovative formulations, additives, and application procedures [20][21]. Figure 2 shows list of the typical parameters, input, and outputs of an ideal experiment s bench [16].

Another factor contributing to the growing interest in lubrication analysis is the unwavering quest of sustainability and energy efficiency [22], [23]. One practical way to accomplish the worldwide emphasis on lowering energy usage and environmental effect is by optimizing lubrication [24]. Effective lubrication not only minimizes frictional losses, which enhances energy efficiency, but it also increases machinery longevity, reducing the environmental impact of premature component wear and replacement [25], [26]. In their 2012 study, Holmberg *et al.* [27] highlighted the substantial impact of friction on fuel efficiency, revealing that 33% of the fuel energy is consumed as a result of friction (refer to Figure 3). This underscores the critical need for effective friction reduction strategies in pursuit of enhanced overall energy efficiency. The depth of lubrication analysis has expanded due to utilization modelling approach that integrates physics,-chemistry, and engineering [28]. It has also promoted a collaborative atmosphere that fosters cross-disciplinary ideas [29].

The creation of engine tribotesters is now a crucial component of tribology research, with the aim of simulating and comprehending the intricate relationships found in internal combustion engines. This review attempts to examines the several approaches used to develop and improve engine tribotesters, providing insight into the developments, difficulties, and potential future directions in this rapidly developing sector.

CURRENT TRIBOTESTER DESIGN AND METHODOLOGY

Tribotesters are one of the most important instruments in the field of tribology, which is the study of friction, wear, and lubrication. Within a secure environment, they make it feasible to replicate and analyze a wide variety of situations that may occur in the actual world. According to Syahrullail *et al*. [30], [31], the strategies and procedures used by tribotesters may vary significantly depending on the specific requirements of the research project. Tribotesters for engines are essential devices that are used to investigate the tribological behavior of engine components in conditions that are controlled and reproducible. It is crucial to have a thorough understanding of the complexity of friction, wear, and lubrication in an engine in order to maximize efficiency, reduce the amount of energy that is wasted, and extend the life of key components [32].

A tribotester is a device that is used for the purpose of quantifying and analyzing the wear, lubrication, and friction characteristics that are present between materials that come into contact with one another [33]. It does this by assessing the quantity of material that is worn away when rubbing or sliding, measuring the amount of effort that is required to overcome friction, and estimating the effectiveness of lubricants. According to Mujtaba *et al*. [34], tribotesters are used for the purposes of improving industrial quality control, developing novel materials, and characterizing existing materials. According to Gul *et al*. [35] research from 2020, these instruments are able to provide light on wear resistance and frictional behavior, which enables companies to make more informed decisions about the materials they use, extend the lifespan of components, and improve operating efficiency.

One sort of tribotester that is often used is called the pin-on-disk tester. This tester involves pressing a pin against a revolving disk. According to Lin *et al*. [36], this apparatus is often used for the purpose of analyzing sliding wear and friction under a variety of loads and speeds. In order to investigate the effects of lubricants, the pin and disk may be constructed from a variety of materials, and lubricants can be injected into the system [37]. The test is comprised of a rotating-disc that is in touch with a stationary pin (or specimen), and the interactions that occur between these two parts are investigated in order to determine various parameters, such as wear rates, lubrication effectiveness, and friction coefficient [38].

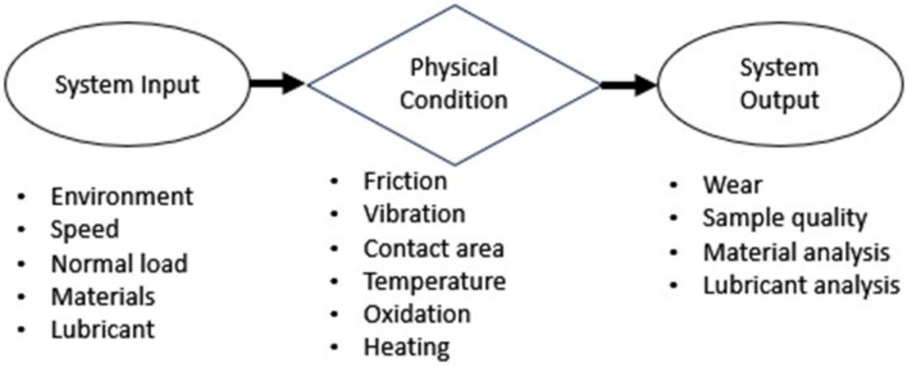

Figure 2 Typical parameters description on a tribotester [16]

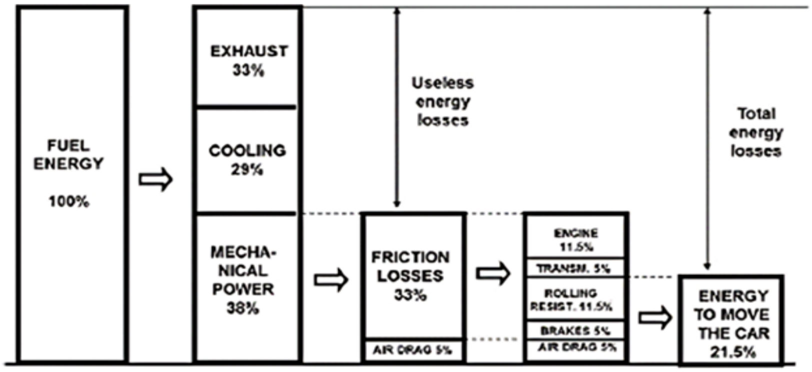

Figure 3 Fuel energy loss in an internal combustion engine [27]

See Figure 4 for a visual representation of this setup, which replicates the rubbing or sliding conditions that materials could experience in real-world applications. Due to the fact that it provides valuable information for understanding material behavior, improving surface treatments, and developing lubrication methods, the pin-on-disk tribotester is an essential instrument in the field of tribological research as well as the assessment of materials for a wide range of technical applications [39].

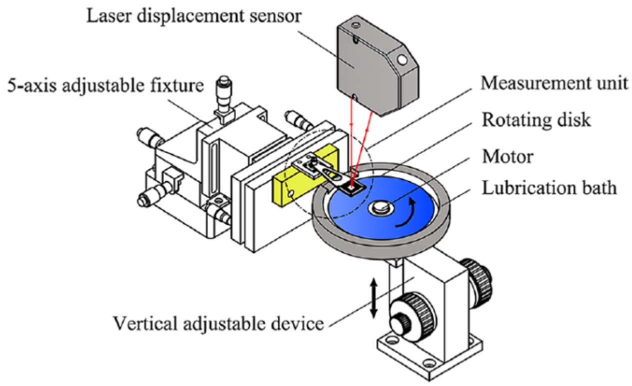

Figure 4 The assembly drawing of the tribometer [38]

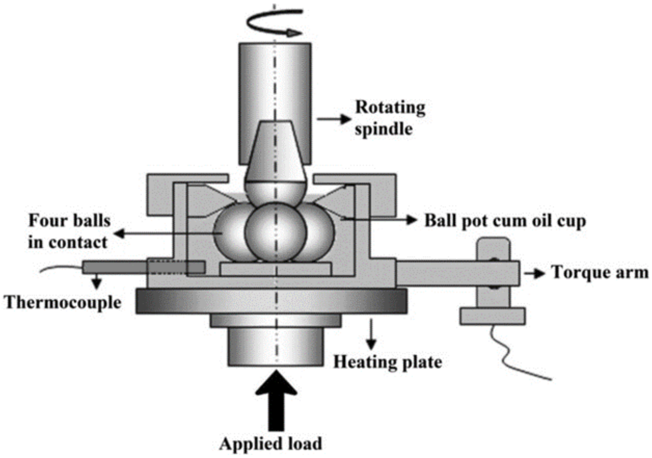

Figure 5 Schematic diagram of Fourball-tribotester [40]

An additional sort of tribotester is the four-ball tester, which is commonly used for the purpose of assessing the lubricants' ability to withstand severe pressure and to promote wear. According to Sharma *et al.*'s research from [40], the test consists of positioning three steel balls in a triangle arrangement while a fourth ball, which is often made of a different material, is forced against the three balls and spun (See Figure 5). Significant information, such as the coefficient of friction and the width of the wear scar, is obtained by the examination of the friction and wear behavior of the materials when they are subjected to the applied load and sliding motion [41]. According to Aiman & Syahrullail [42], this specific species of tribotester is very helpful for determining the efficacy of lubricants in terms of avoiding wear and lowering friction under settings of severe pressure. For the purpose of enhancing the performance and durability of machinery components in a variety of industrial applications, the data produced from a four-ball test are beneficial for the creation of lubricants, quality control, and the optimization of formulations [43].

According to Ayerdi *et al.* [44], a linear reciprocating tribometer is a relatively another specialized testing instrument that has been used in the field of tribology for the purpose of evaluating the wear, lubrication, and friction properties of materials that are brought into contact with linear reciprocating motion. The specimen, which is often a pin or a flat surface, is moved back and forth against another surface, which is typically a reciprocating sledge or a counter face (See Figure 6). This configuration is referred to as the sliding arrangement. It is possible to control the conditions under which the test is conducted, which enables the examination of a number of characteristics, such as the load, the speed, and the stroke length [45]. This particular tribometer is of great assistance when it comes to modeling the conditions that materials run into in applications that include linear reciprocating motion. Some examples of such applications are mechanical systems, automotive components, and biomedical devices. In order to shed light on wear processes, friction behavior, and lubricant effectiveness, the information that is acquired from a linear reciprocating tribometer is helpful in the process of creating and improving materials for specific technological applications [46].

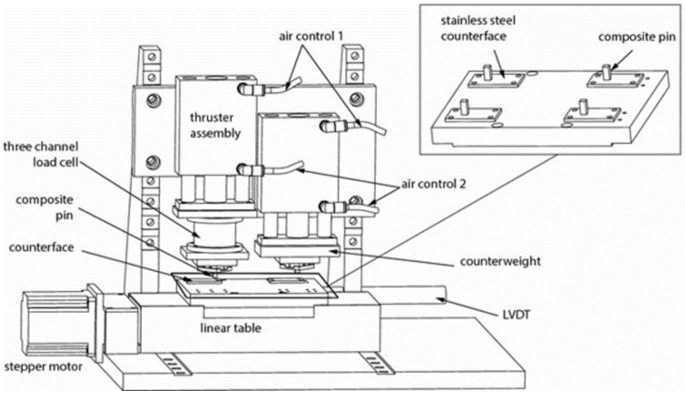

Figure 6 Schematic diagram of linear reciprocation tribotester [47]

In order to analyze the performance of journal bearings under controlled conditions, a specialized testing instrument known as a journal bearing tribometer is used. This instrument simulates the operation of a near-to-journal bearing in automotive applications [21]. Journal bearings are vital components that are used in rotating equipment such as turbines and engines. They are responsible for maintaining the revolving shaft. In a journal bearing tribometer, a test shaft, which serves as a substitute for the journal, is brought into contact with a bearing that is stationary [48]. The tribometer makes it possible to monitor and study the characteristics of lubrication, wear, and friction, which provides valuable insights on the bearing's ability to work effectively (See Figure 6). According to Zulhanafi *et al*. [49] research from 2020, it is possible to control parameters like load, rotational speed, and lubricant properties in order to replicate a wide range of operating circumstances. It is vital to gather data from a journal bearing tribometer in order to optimize bearing designs, choose suitable materials, and improve lubrication procedures, which will eventually result in an improvement in the efficiency and dependability of rotating equipment used in engineering applications [50].

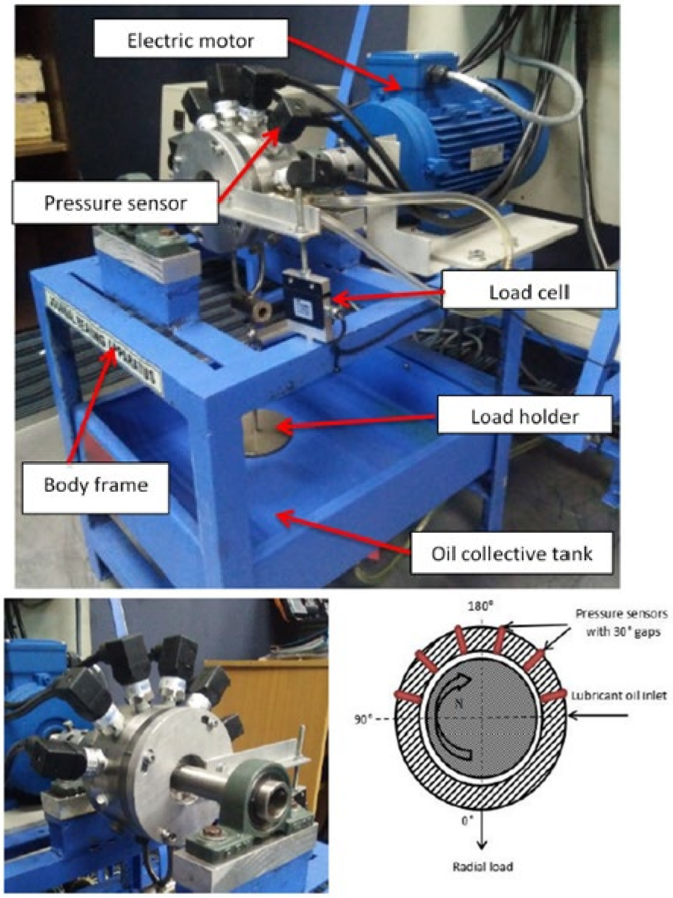

Figure 7 Journal bearing tribotester set up [49]

Tribotester design encompasses a wide array of experimental settings, which is reflective of the wide diversity of circumstances and phenomena that are investigated in the field of tribology. Each configuration comes with its own set of benefits and drawbacks, and the selection of a configuration is contingent upon the particular research subject that is being investigated. There will be an increase in the complexity and diversity of tribotester designs as our knowledge of tribological processes continues to improve.

CAPACITY OF CURRENT TRIBOTESTER APPLICATION AND PARAMETERS

When it comes to applications using tribotesters, capacity is defined as the extent to which they are able to detect and assess lubrication, wear, and friction between materials that are in touch with one another at the same time. These qualities may be assessed whenever they are employed in a tribotester application: wear rate, temperature rise during sliding or rolling contact, and friction coefficient [51]. Other characteristics that can be examined include friction coefficient. According to Marian and Tremmel [52], researchers have the ability to quantify the resistance to motion between two surfaces by using the friction coefficient. Additionally, they can learn about the material loss that occurs as a result of abrasion and friction by using the wear rate. According to Shafi *et al*. [53], the rise in temperature is a significant measure that indicates the likelihood of thermal damage or degradation occurring in materials that are in touch with one another. Typical characteristics of contemporary applications for tribotesters include the ability to exercise fine-grained control over experimental parameters such as speed, temperature, and load measurements. Engineers and researchers are able to examine the behavior of materials in simulated environments that are similar to those seen in the real world. It is possible for some tribotesters to operate in a number of environments in order to imitate the conditions that are seen in a wide range of industrial settings [16].

When it comes to the design and production of micro-tribotesters, accurate in-situ wear measurements are absolutely necessary. According to Penkov *et al*. [54], the transition from sticky to abrasive wear is an essential component of the wear process that must be accurately documented. An integrated load sensor that is based on a strain gauge is often used by a tribotester in order to enable the detection of the friction coefficient that is brought about by the sliding motion of two items that are linked to contact. In order to conduct an accurate analysis, it is required to take measurements of both the normal and friction forces [55]. When it comes to constructing a tribotester that makes use of non-contact displacement measurements, there are complications that are particular to this process. The measurement of the friction coefficient using a fiberoptic sensor requires calibration of the tip displacement due to normal and friction forces. This is important in order to corroborate the measurement. Additionally, it is vital to describe manufactured surfaces both before and after the wear test in order to get an understanding of the fundamental processes that are responsible for friction and wear [56]. We will have a better understanding of the transitional wear behavior that led to the final condition as a consequence of this development. Table 1 provided a summary of the operational characteristics and capacity of the most common kind of tribotester.

Table 1 List of capacity and parameters of the most typical tribotester

Parameters	Speed	Normal Load (N)	Temp (˚C)	Wear	Friction	Surface analysis	References
Pin on Disk	0-2000 rpm	0-60N (Low Load)	25-150	Wear on disc	Coefficient of friction	Surface roughness	[57][58]
Fourball	0-1760 rpm	0- 10k (Medium Load)	30-100	Wear scar diameter	Coefficient of friction	Surface roughness	[59][60][61]
Linear reciprocating	0.1-100 mm/s	0-30k (High Load)	-	Wear rate	Coefficient of friction	Surface roughness	[62][44]
Journal bearing	0-2000 rpm	0-100 (Low Load)	35	None	Based on pressure distribution	None	[63][48]

CURRENT LUBRICATION OIL DEVELOPMENT

Cecilia *et al*. [64] research from 2020 indicates that the recent movement in lubricant formulations towards more environmentally friendly solutions is a significant step forward in the field of sustainable engineering and manufacturing processes. Lubricants have been associated with environmental problems for a very long time [65]. This is because lubricants are dependent on oils and additives that are sourced from petroleum. However, via ongoing research and development, attempts are being made to modify the compositions of lubricants in order to lessen the impact that they have on the environment [66]. One of the most essential aspects of the transformation is the transition to base oils that are renewable and biodegradable. The use of plant-based oils, such as those derived from vegetables, is now being investigated by scientists as a potential replacement for traditional mineral oils [67]. According to Yahaya *et al*. [26], the higher biodegradability of these bio-based lubricants leads to a reduction in the environmental effect of lubricant disposal. This is in addition to the fact that these lubricants reduce dependency on fossil fuels.

The use of environmentally friendly chemicals is also becoming an increasingly important consideration. On a progressive basis, conventional lubricant additives, which often consist of heavy metals and other hazardous compounds, are being gradually replaced with alternatives that are less harmful to the environment [68]. According to Singh *et al*. [69] research, scientists are investigating nanomaterials and additives that are derived from natural sources in order to maintain a high level of lubricant performance while simultaneously lowering their effect on the environment. In the quest for environmentally friendly lubricants, one of the goals is to optimize lubricant formulae in order to extend the life of equipment and reduce the amount of energy that is used. According to Aiman *et al*. [25], lubricants that are more effective in reducing friction allow machines to operate more effectively, which in turn decreases the amount of energy that is used and the emissions of greenhouse gases to the atmosphere. Another facet of lubricant modification is the development of formulae that have longer service intervals. This results in fewer lubricant changes occurring more often, which in turn reduces the amount of waste produced. This strategy is compatible with the concepts of sustainability since it promotes the effective use of resources and reduces the adverse impact that waste lubricant has on the environment. Table 2 shows some of current development of oil modification, and utilize bio-lubricant, modifying viscosity, using additives, improve pour point, improve oxidation stability and using nano material.

ENGINE TRIBO-TEST MAIN ANALYSIS AND COMPONENT

The three primary components of an engine—the piston assembly, the valve train system, and the bearings—have been the subject of lubrication models developed by several institutions, including GM, Ford, Shell, The University of Nissan, Toyota, and Leeds [70]. Estimates of friction (and wear) at various engine speeds, loads, and temperatures may be produced using these models. The models' strength is in the speed and accuracy with which they can estimate the performance of various engines under a broad range of operating situations [56]. A major drawback of this method is the massive quantity of data needed to simulate every part of the engine. What's more, some of this data, like temperatures and pressures in the combustion chamber, may be rather challenging to obtain [71]. The researcher took a different tack by measuring the viscometric properties of lubricants typical of hydrodynamic, mixed, and boundary lubrication; then, they empirically fitted the data from fuel economy engine tests to the Effective Fuel Economy Increase [72]. The method's simplicity and speed are its main selling points. In order to make accurate forecasts, it is need to wait for the results of engine tests to be available. This is to guarantee that the viscometric measurements taken in a lab accurately reflect the engine's working conditions [73].

Table 2 Current development of oil modification

References	Topic highlighted	Types of oil	Findings and conclusion
Cecilia *et al.*, [64]; Uppar *et al.*, [65]	Biodegradable lubricant	Vegetable oil	• When compared to petroleum-based oils, these alternatives offer several benefits, including better lubrication, anti-wear characteristics, viscosity, ignition temperature, elevated viscosity index, equipment service life, load-carrying capacity, low evaporation rates, coefficient of friction, and rapid biodegradability. • Confirming the tribological qualities of various bio lubricant blends requires a rigorous investigation. Sustainable non-edible oil-driven bio-lubricants might be the next major development, according to this study.
Martini *et al.*, [74]	Review of viscosity modifier (VM) lubricant additives	Mineral and vegetable	• The article discusses the three key features of VM function: thickening efficiency, viscosity–temperature relationship, and shear stability. It also explains how these features are measured and affected by polymer chemistry, molecular weight, and concentration. • The article reviews the mechanisms by which VMs change the viscosity of a solution, such as coil expansion, association/entanglement, self-entanglement, and solvent disturbance. It also discusses how these mechanisms are influenced by temperature, concentration, and polymer structure.
Zhang wei *et al.*, [75]	Modification and synthesis of low pour point plant-based lubricants with ionic liquid catalysis	Vegetable oil	• The articles evaluate the lubrication properties of the products, such as viscosity, viscosity index, pour point, flash point, thermal stability, and tribological behavior. They find that the products have excellent viscosity index and low pour point, especially the ones derived from octanoic acid and capric acid. They also have good flash point, thermal stability, and friction coefficient. The authors conclude that the products are promising bio lubricants with high performance and environmental benefits.
Murru *et al.*, [76]	Oxidative stability of vegetal oil-based lubricants	Vegetable oil	• The article reviews the factors and mechanisms that influence the oxidation of vegetal oils and fatty acids, which is the main drawback of their use as lubricants. The article also describes the physical and chemical methods to improve the oxidative and thermal stability of vegetal oils, such as antioxidants, additives, hydrogenation, epoxidation, and esterification. • The article also discusses the interaction mechanisms of fatty acids with metal surfaces and the formation of self-assembled monolayers and tribofilms that affect the friction and wear behavior of the lubricated contacts.
Sun and Du, [77]	Application of graphene derivatives and their nanocomposites in tribology and lubrication: a review	Vegetable oil	• The articles describe four types of graphene derivatives: graphene oxide, doped graphene, graphene-based films, and graphene-based fibers. They discuss their preparation methods, properties, and advantages in tribology and lubrication. • The articles classify the nanocomposites into three categories based on the functional modifiers: graphene-inorganic nanocomposites, graphene-organic nanocomposites, and graphene-polymer nanocomposites. They summarize their synthesis methods, mechanisms, and applications in different tribological and lubrication scenarios.

Some researchers developed a technique in modeling the friction in engines, such as researched by Liu *et al.*, [78], who analyze waste heat recovery (WHR) of internal combustion (IC) engines, based on in-cylinder steam-air expansion where They say that their methodology has a simpler design, more practicality, and better fuel economy than earlier approaches. Under the suggested WHR setup, the steam expansion cylinder (SEC) runs in its own natural aspirated mode and is not reliant on any other firing cylinders. It is well-known that the intake pressure has a significant role in the performance of the IC engine cycle. The next logical inquiry is how the SEC's intake pressure affects the cylinder steam-air expansion (CSAE) cycle's efficiency. This issue was addressed by running the numerical model at various SEC intake pressures. They adjusted the steam temperature to the highest permissible at each engine speed to illustrate the maximal recovery potential of waste heat. The effects of intake pressure on engine performance with CSAE cycle are shown in Figure 8(a)-(d).

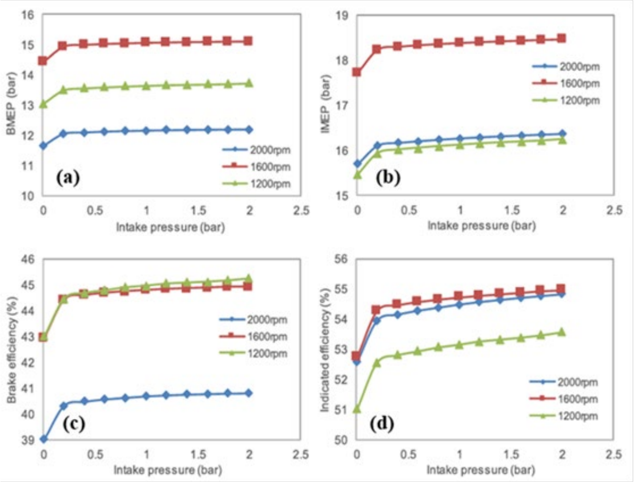

Figure 8 Effects of intake pressure on the performance of engine with CSAE cycle (a) brake mean effective pressure, (b) indicated mean effective pressure, (c) Brake efficiency and (d) Indicated efficiency [78]

As illustrated in Figure 8, the mechanical losses obtained in the four-stroke engine are distributed simulated in this study. Assuming no change in engine speed, the ratio of friction between the journal bearings and the valve train drops as engine load rises. It is mostly due to the effect of the in-cylinder pressure that is achieved in the combustion chamber. As the load increases, the pressure behind the ring's increases, causing friction losses at the piston ring assembly to be larger than at the journal bearing and valve train. The auxiliary losses also increase as the load grows. Rising pressures in the oil circuit and injectors are the main factors. The auxiliary losses also rise in conjunction with the engine speed.

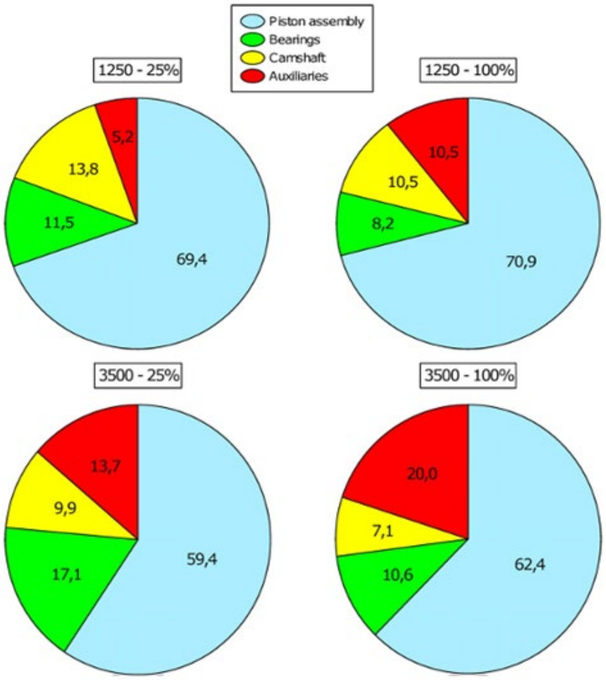

Figure 9 Mechanical losses distribution speed of 1250 rpm and 3000rpm [79]

Another study by Tormos *et al*., [79] that research on one-dimensional model of the distribution of mechanical and friction losses in a four-stroke internal combustion engine, where the objective is to increase the engine's mechanical efficiency so that it uses less fuel and produces less carbon dioxide (see Figure 9). According to them, it is possible to reduce mechanical losses in the piston rings by 75%, friction in the bearings by 20%, in the valve train by 20%, and auxiliary losses by 25%.

Zoldy [80] conducted a further investigation that evaluated previous engine efficiency testing and suggested a new method using a cutting-edge engine with a common rail diesel system to measure engine oils' fuel consumption. Three engine oils with varied viscosities and additives are examined in this study, along with the test parameters, oil wear check tests, and fuel consumption assessments. In comparison to traditional multi-grade oils, synthetic engine oils with reduced viscosity and friction modifiers may enhance fuel economy, according to the test findings reported in the article (See Figure 10). The new approach can distinguish between various classes of oil.

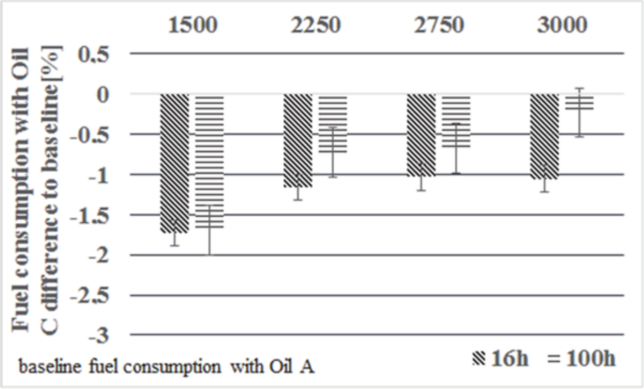

Figure 10 Oil C fuel economy effect [80]

Another tribological analysis research that done by Wan Nik, [96] that investigates the performance of hydraulic systems using refined palm oil as a substitute for traditional mineral-based hydraulic fluids. Conducted on a Yuken vane pump test rig, the experiments evaluated flow, pressure, and efficiency under varying operating conditions, including oil aging. Results indicated that volumetric efficiency increased with oil viscosity, which also rose with aging. The slip coefficient decreased with pump speed due to improved vane sealing. While palm oil demonstrated environmental advantages and compatibility, it aged faster than mineral oils, influencing performance. This research supports the potential of palm oil as an eco-friendly hydraulic fluid alternative.

ENGINE PISTON RING IN DETERMINE THE COEFFICIENT OF FRICTION AND WEAR EVALUATION

The alteration and replacement of materials and coatings, together with newly developed lubricants and novel surface morphologies through innovative machining techniques employed in large-scale manufacturing, include an unknown interference with the wear and friction characteristics of a well-understood tribosystem [81]. These days, development timeframes are cut in half, necessitating even faster defect clarification [82]. Additionally, the components are getting lighter and more compact, which puts additional stress on tribo-materials and prolongs maintenance intervals [83]. In short, the purpose of test rig runs is to provide information that is difficult to collect from engine testing, such as the degree of wear rate, coefficient of friction, wear mechanisms, and effect of process factors [84]. These data are not intended to replace engine testing. Time and cost reductions will only be possible if test results from tribometers can be converted to the functional behavior in the application. The purpose of this contribution is to elucidate the differences between the testing procedures and tribometers of the past and present with regard to the mixed/boundary tribology of cylinder liners and piston rings [85].

The study of the lubrication, wear, and friction of the cylinder liner and piston rings in internal combustion engines is known as piston ring tribology. Essential parts, piston rings serve a number of purposes, including sealing the combustion chamber, transmitting heat from the piston to the cylinder wall, and regulating oil consumption [86]. Piston ring tribology as shown in Figure 11 is a complex and challenging field that involves many factors, such as the design and materials of the piston rings and cylinder liner, the mechanical and thermal loads on the rings, the contact pressure and deformation of the surfaces, the lubrication conditions and oil film thickness, the influence of combustion products and additives on the lubricant properties, the coefficient of friction and friction force, the wear mechanisms and wear rate, and the emission of blow-by gases and particulates [87].

Full-scale engine testing, miniature experimental work, and modeling are a few recent research on piston ring tribology [88]. in order to replicate the mixed lubrication of piston rings under realistic engine settings, Zhang *et al*. [89], for instance, created a computational model. Oil supply, oil evaporation, oil transport, ring dynamics, elastic deformation, and thermal distortion were all taken into account by the model. The model considered the effects of surface roughness, elastic deformation, thermal distortion, ring dynamics, oil supply, oil evaporation, and oil transport. The model was validated by comparing with experimental data from a single-cylinder diesel engine. The results showed that the model could capture the main features of piston ring lubrication and provide insights into the factors affecting friction and oil consumption [90].

Another research by Wang *et al*. [82] that study tribological properties of several surface-modified piston rings under extreme conditions. In particular, the study examines how various commercial piston rings perform in high-power density diesel engines when paired with a cast iron cylinder liner made of the boron-phosphorus (BP) alloy.

Figure 11 Characteristics to be improved in the compression ring performance [87]

The cylinder liner and piston rings' wear, scuffing, and friction properties are the main topics of this article. The findings demonstrate that DLC coatings exhibit superior tribological properties, displaying low friction coefficients and wear loss at temperatures of 150 °C and 240 °C. In contrast, GDC coatings demonstrate relatively poor performance. Additionally, the DLC coating demonstrates excellent scuffing resistance, as no material transfer was observed for up to 77 min, even without lubrication. The article also explains the formation of a tribo-chemical layer of carbides on the DLC surface, which effectively prevents scuffing.

In addition, several researchers considered the application of bio lubrication to investigate the tribological impact on the piston ring. Shahabuddin *et al*. [91] used conventional SAE 15W40 lubricant in various quantities with non-edible jatropha oil to create a bio-lubricant. In order to test the bio-lubricant's tribological qualities, they employed cast iron and stainless steel, which are frequently found in piston ring-cylinder liner pairings for internal combustion engines. The wear and friction of the materials were measured by the authors using a high-frequency reciprocating rig (HFRR) under various lubrication conditions. In comparison to other blends and pure commercial lubricant, they discovered that the addition of 7.5% jatropha oil-based bio-lubricant to the commercial lubricant had the lowest wear rate, coefficient of wear, and viscosity change. Additionally, they saw less metal transfer and surface degradation on the cast iron plate that had 7.5% bio-lubricant applied. The authors concluded that jatropha oil-based bio-lubricant has the potential to partially substitute mineral oil-based lubricants and reduce the environmental impact of lubricant waste. These results are consistent with those of Amiril *et al*., [92], who examined the tribological performance of metals while using jatropha oil as a bio lubricant. The experiment demonstrates that friction coefficients drop when jatropha oil is used as lubricant. The fatty acid, esters, and jatropha oil polar structures all contributed to the reduction of the friction coefficient. The tribological performance of the metal was evaluated by Ruggiero *et al*, [93] with a lubricant derived from jatropha oil. In the experiment, they found that the coefficient of friction decreases at greater velocities when a thin oil lubrication is added.

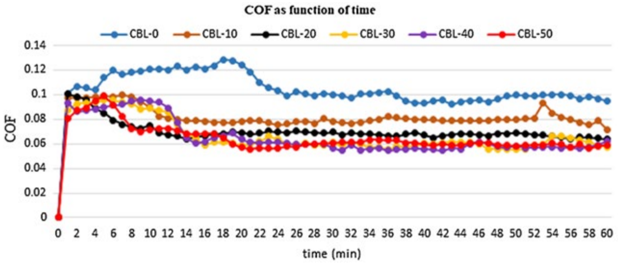

Figure 12 COF during the run-in period and steady-state period by HFRR [35]

A further investigation on creating a bio lubricant for piston rings was conducted by Gul *et al*. [35], who created a cotton bio lubricant using a two-step transesterification process utilizing cottonseed oil and trimethylolpropane (TMP). They examined the physicochemical and tribological characteristics of the commercial SAE 40 lubricant and the cotton bio lubricant in various ratio blends. The authors measured the wear and friction of the lubricant blends on steel and cast-iron materials, which are often used in engine components, using a four-ball tribo-tester and a high-frequency reciprocating rig (HFRR). They also used profilometry, energy-dispersive X-ray spectroscopy (EDX), and scanning electron microscopy (SEM) to analyze the surface. The researchers discovered that in the HFRR and four-ball tests, the commercial lubricant with 10% cotton bio lubricant added had the lowest friction (see Figure 12), wear, and surface roughness. This was explained by the fatty acids and esters of the cotton bio lubricant forming a protective coating on the metal surfaces. Due to reduced viscosity, oxidative degradation, and corrosive effects, higher concentrations of cotton bio lubricant increased wear and friction [94]. According to the authors, cotton biolubricant has the ability to lessen the environmental impact of lubricant waste and partially replace mineral oil-based lubricants. Additionally, they emphasized the advantages of adding cotton bio lubricant to enhance the durability and tribological performance of engine parts [95].

Research on piston ring tribology is crucial for enhancing engine longevity, performance, and emissions. Researchers can create better designs and materials for the cylinder liner and piston rings by comprehending the intricate interplay between these two components. Additionally crucial to maximizing engine efficiency, lowering fuel consumption, and lessening environmental effect is piston ring tribology.

CONCLUSION

In conclusion, this review consolidates current tribological analysis methodologies that underpin the rational development of engine tribotesters, emphasizing the necessity of replicating realistic contact mechanics, lubrication regimes, and thermo-mechanical loading conditions. Engine tribology involves complex interactions among friction, wear, surface fatigue, and tribochemical film formation under transient and multi-scale operating environments. Through critical evaluation of conceptual frameworks and experimental platforms including reciprocating tribometers and pin-on-disk systems the study highlights that appropriate test configuration, kinematic fidelity, and load control are fundamental to reproducing engine-relevant tribological phenomena. Advances in surface characterization techniques have further strengthened mechanistic interpretation by enabling precise assessment of wear mechanisms, material transfer, and tribofilm evolution under controlled laboratory conditions.

The findings demonstrate that optimized tribotester design must integrate structural robustness, modular adaptability, and high-resolution sensing capabilities to ensure experimental reliability and analytical depth. A carefully engineered configuration, combined with rigorous testing protocols, enhances repeatability and measurement accuracy while providing comprehensive insight into frictional response, wear progression, and lubrication performance. The flexibility of modern tribotester systems allows systematic investigation across diverse materials, coatings, and lubricant formulations under variable operational parameters. Such adaptability supports both fundamental tribological research and applied engineering development, bridging laboratory-scale experimentation with engine-representative conditions.

Moreover, the evolution of sustainable and high-performance lubricants including extended-drain formulations and nano-enhanced systems reinforces the importance of advanced tribo-testing methodologies. Contemporary engine tribo-tests rely on integrated instrumentation, real-time data acquisition, and analytical software to quantify lubrication efficiency, durability, and energy-loss mechanisms with high precision. These capabilities are essential for correlating laboratory tribological indicators with engine performance, service life, and environmental impact. Overall, the interdisciplinary advancement of tribological analysis and tribotester technology provides a critical pathway toward enhancing engine efficiency, operational longevity, and sustainability across automotive and industrial sectors."

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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