*ISSN 2079-1372 **Problems of Tribology**, V. 31, No 1/119-2026, 48-55*

Problems of Tribology
Website: http://tribology.khnu.km.ua/index.php/ProbTrib
E-mail: tribosenator@gmail.com

DOI: https://doi.org/10.31891/2079-1372-2026-119-1-48-55

Experimental and Analytical Study of Acid Number Variation in Engine Oils Under Operational Contamination

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Received: 05 January 2026: Revised 20 January 2026: Accept: 02 February 2026

Abstract

This paper presents an experimental and analytical study of the variation of the total acid number (TAN) in engine oils under operational contamination. The research is aimed at assessing the correlation between the acidity growth of lubricants and their wear behavior in the four-ball test configuration. Theoretical modeling and experimental testing were performed to identify the parameters of a wear law that incorporates contact pressure, oil viscosity, hardness, and TAN as key variables. The obtained results confirm that the acid number increases significantly during oil operation: from 0.9 to 2.9 mg KOH/g—which leads to an intensified wear rate of the contact surfaces. The proposed model quantitatively describes the relationship between the acidity level and wear intensity and enables prediction of oil performance based on its physicochemical degradation. The developed approach allows for improved evaluation of the residual life of lubricants and optimization of maintenance intervals for internal combustion engines.

Keywords: engine oil degradation; total acid number (TAN); operational contamination; wear model; four-ball test; physicochemical properties; lubrication; tribology; predictive maintenance

Introduction

The efficiency of an internal combustion engine is largely determined by the stability of the physicochemical properties of the engine oil, which performs the functions of lubrication, cooling, cleaning, and protecting parts from corrosion. During operation, the oil is exposed to the combined effects of high temperature, pressure, combustion products, and mechanical impurities, leading to gradual degradation of its composition. One of the most informative indicators of lubricant condition is the acid number (TAN), which characterizes the amount of acidic compounds formed as a result of oxidation of the base oil and decomposition of additives. An increase in the acid number indicates the accumulation of organic and inorganic acids, which in turn enhances the corrosive activity of the medium and reduces the service life of friction components.

Research conducted for different types of engines confirms that the acid number of engine oils increases consistently with longer operating time or vehicle mileage. In the initial stages of operation, a relatively slow increase in acidity is observed due to the consumption of neutralizing additives and stabilization of the chemical composition. Subsequently, as oxidation processes intensify and contamination by combustion products grows, the rise in TAN becomes accelerated. Experimental studies show that in used oils, the acid number can increase by 170–280% compared with the fresh oil, as a result of the accumulation of resinous and oxygen-containing compounds. It has been established that the moment when the acid number reaches or exceeds the base number (TBN) is critical, indicating the depletion of the oil's alkaline reserve and the need for replacement. For gasoline engines, this typically corresponds to a mileage of about 10–13 thousand km, while for diesel engines: 14–16 thousand km.

Thus, the dynamics of acid number variation serve as a sensitive diagnostic parameter that reflects the degree of lubricant aging and contamination level. It enables timely assessment of the remaining service life of the oil, optimization of replacement intervals, and prevention of premature engine wear. The analysis of the influence of engine oil contamination on changes in acidity is therefore an important step toward improving the reliability and durability of internal combustion engines, as well as developing efficient systems for monitoring their technical condition.

Literature Review

The variation of the total acid number (TAN) in engine oils during operation is a key factor in assessing their technical condition and predicting service life. A synthesis of modern studies indicates that the acid number is an integral indicator of oil degradation, reflecting the accumulation of organic and inorganic acids formed as a result of base oil oxidation, additive decomposition, and contamination by combustion products [1]. It has been established that with increasing temperature, operating time, and levels of fuel or soot contamination, the acid number rises consistently, leading to greater corrosive activity and reduced protective properties of the lubricating film [2].

Analytical and experimental investigations show that the dynamics of TAN changes are closely related to degradation processes such as oxidation, nitration, and the formation of varnishes and deposits [3,4]. At the early stages of oil operation, the TAN increase is minor due to the effective action of neutralizing additives; however, after the depletion of the alkaline reserve, a sharp rise in acidity is observed. This point is considered critical for deciding when to replace the oil [5].

The change in the acid number is accompanied by a decrease in the base number (TBN) and variations in viscosity, which allows these parameters to be used together for comprehensive assessment of oil condition [6]. Practical studies demonstrate that as engine mileage increases, TAN steadily grows, particularly under urban driving conditions characterized by frequent start–stop cycles that accelerate oxidation [7]. Analysis of used oil samples also revealed that in different viscosity grades, the rate of TAN increase may vary significantly, reflecting the distinct resistance of oils to thermal and oxidative aging [2, 5].

Recent research increasingly treats TAN as a fundamental parameter for real-time oil condition monitoring systems. The use of electrochemical and dielectric sensors enables continuous tracking of acidity changes during engine operation, forming the basis for adaptive maintenance strategies [8]. In addition, statistical and intelligent models are being developed to predict oil degradation by integrating TAN data with oxidation parameters, viscosity, wear-metal content, and temperature profiles [9].

Special attention has also been given to identifying the chemical nature of the acidic components formed during oil aging. It has been shown that the main degradation products are organic acids—predominantly carboxylic and phenolic—which catalyze further oxidation and sludge formation [8]. These compounds deteriorate antifriction properties and increase temperatures in friction zones, thereby accelerating wear.

In summary, the reviewed studies [1–10] confirm that the acid number is one of the most sensitive diagnostic indicators of engine oil condition. Its growth with increasing operating time signifies the intensification of oxidation processes, depletion of the alkaline reserve, and loss of lubricant stability. Monitoring TAN dynamics, in combination with other physicochemical properties, makes it possible not only to determine the remaining oil life but also to optimize replacement intervals—directly enhancing the reliability and durability of internal combustion engines.

Geometric parameters of the four-ball test scheme

The structural scheme consists of four identical balls of radius R. Three lower balls 1-3 are motionlessly located on the plane and touch each other according to the scheme in Fig. 1.

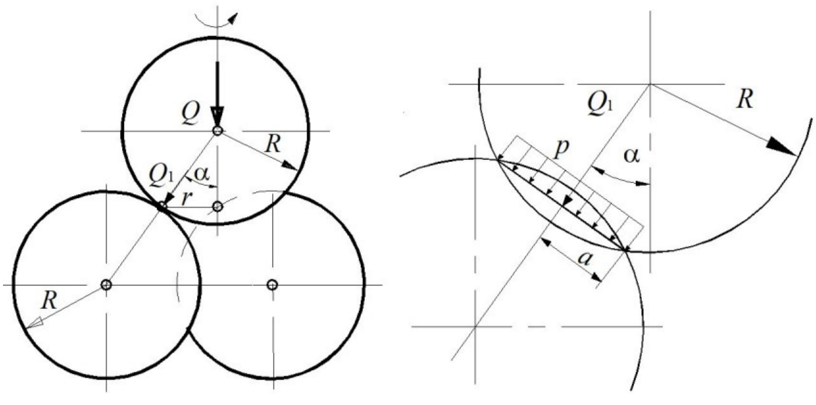


Fig.1. The geometry of the four-ball test scheme.

The upper ball 4 rotates and is pressed in the center to the lower balls with a force Q. In the process of friction of the upper ball on the lower ones, wear areas of a circular shape are formed on them. To determine the normal component of the force Q1 on the lower balls, it is necessary to determine the angle α:

$$Q_1 = \frac{Q}{3\cos\alpha}. \tag{1}$$

From the geometry of the contact (Fig. 1), the angle α is determined:

$$\alpha = \arcsin\frac{r}{R} = \frac{R/\sqrt{3}}{R} = \frac{1}{\sqrt{3}} = 35.26^{\circ}. \tag{2}$$

Taking into account (2), we obtain an expression for the normal force on the lower balls:

$$Q_1 = 0.4082Q. \tag{3}$$

Friction path for the friction pads of the lower balls:

$$L = 2\pi rnt = \frac{2\sqrt{3}}{3}\pi Rnt, \tag{4}$$

where n is the number of revolutions of the upper ball per unit of time; t is the test duration.

Wear model.

Traditionally, the wear model (law) is understood as the functional dependence of the wear rate (intensity) on the determining factors of the wear process: contact pressure, properties of structural and lubricant materials, sliding speed, temperature and other factors in the form:

$$\frac{dW}{dL} = F(p, HB, \mu, \nu, \alpha...).$$

The number of determining factors and their form of presentation depend on the physical formulation of the wear problem with respect to the design of the friction pair and the conditions of testing and operation in practice. It is convenient to represent the level of influence of determining factors on wear in the form of power dependences. In this case, the values of the parameters determine both the quantitative and qualitative effect on wear. For practical calculations based on the wear model, it is rational to represent the determining factors in the form of dimensionless complexes. In our case, to predict the wear of non-conformal joints in the presence of a lubricant and tests using a four-ball scheme, the following form of the wear model (law) is proposed:

$$\frac{dW}{dL} = k_W\left(\frac{\mu p}{HB}\right)^m\left(\frac{\alpha}{\nu}TAN\right)^n, \tag{5}$$

where dW/dL is the were rate;
k_W is the were coefficient;
μ is the friction coefficient;
p is the contact pressure, N/mm^2;
HB is brinell hardness, N/mm^2;
α is the oil temperature conductivity coefficient, m^2/s;
ν is the kinematic oil viscosity, m^2/s;
TAN is the total acidity number, *mg KOH/g*;
m, n are the parametres.

The model is proposed in the form of two dimensionless complexes that determine the influence of contact pressures, properties of structural and lubricant materials. The principle of similarity and dimensions was used as the basis for constructing the model.

The geometric relationship between normal wear and the half-width of the circular area a will be written in the form (Fig. 1):

$$W(L) = \frac{a^2(L)}{2R}. \tag{6}$$

Let us assume that the pressure is uniformly distributed over the contact area. Then the contact pressure through the load and the contact area is determined by the formula:

$$p = \frac{Q_1}{\pi a^2(L)}. \tag{7}$$

Based on the results of wear tests, an approximating power function of the size of the wear area a from the friction path L is determined in the form:

$$a(L) = cL^{\beta}, \tag{8}$$

where c, β are the parameters of the approximating function.

After substituting (3, 6-8) into the wear model (5), we get:

$$\frac{d\left(\frac{(cL^{\beta})^2}{2R}\right)}{dL} = k_W\left(\frac{0.4082Q\mu}{\pi(cL^{\beta})^2 HB}\right)^m\left(\frac{\alpha}{\nu}TAN\right)^n, \tag{9}$$

After integrating and transforming equation (9), we have:

$$c^2L^{2\beta} = 2RK_W\left(\frac{0.4082Q\mu}{c^2\pi HB}\right)^m\left(\frac{\alpha}{\nu}TAN\right)^n\frac{L^{1-2\beta m}}{1-2\beta m}. \tag{10}$$

From the condition of satisfaction of equation (10) for any L it follows:

$$m = \frac{1-2\beta}{2\beta}. \tag{11}$$

To determine the parameter n, a series of tests is carried out at different values of the acidity number. In this case, the corresponding approximating functions of the type (8) are obtained.

Here, the tasks of determining the wear parameters based on the test results of samples with a variable contact area are considered. The exponent m in expression (5) characterizes the rate of change in contact pressures during wear and is related to the exponent β of the experimental function according to (11). The acid number of the oil does not depend on the size of the wear area and therefore does not affect the parameters m and β. The acid number will only affect the dimensional coefficient c, which is confirmed experimentally.

Let two approximating functions be obtained from the test results at two values of the acid number:

$$a = c_1L^{\beta}, a = c_2L^{\beta}. \tag{12}$$

Thus, we get a system of two equations:

$$\left.\begin{aligned}\beta c_1^{\,2m+2} &= RK_W\left(\frac{0.4082Q\mu}{\pi HB}\right)^m\left(\frac{\alpha}{\nu}(TAN)_1\right)^n\\ \beta c_2^{\,2m+2} &= RK_W\left(\frac{0.4082Q\mu}{\pi HB}\right)^m\left(\frac{\alpha}{\nu}(TAN)_2\right)^n\end{aligned}\right\}. \tag{13}$$

Dividing the first equation by the second after taking the logarithm and transformations, we obtain the formula for the parameter n:

$$n = (2m+2)\frac{\ln(c_1/c_2)}{\ln\left[(TAN)_1/(TAN)_2\right]}. \tag{14}$$

The coefficient K_W is determined from one of the equations of system (13):

$$K_W = \frac{\beta c_1^{\,2m+2}}{R}\left(\frac{\pi HB}{0.4082Q\mu}\right)^m\left(\frac{\nu}{\alpha(TAN)_1}\right)^n. \tag{15}$$

An example of identifying the parameters of the wear model (5).

The results of wear tests with a lubricant according to the four-ball scheme are shown in Table 1. The friction path was calculated using the formula (4) at n=1420 rpm.

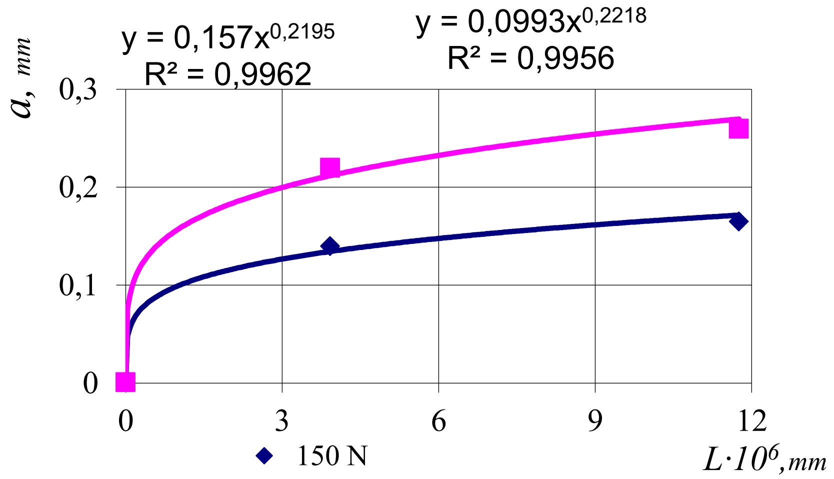
Table 1

Wear test results

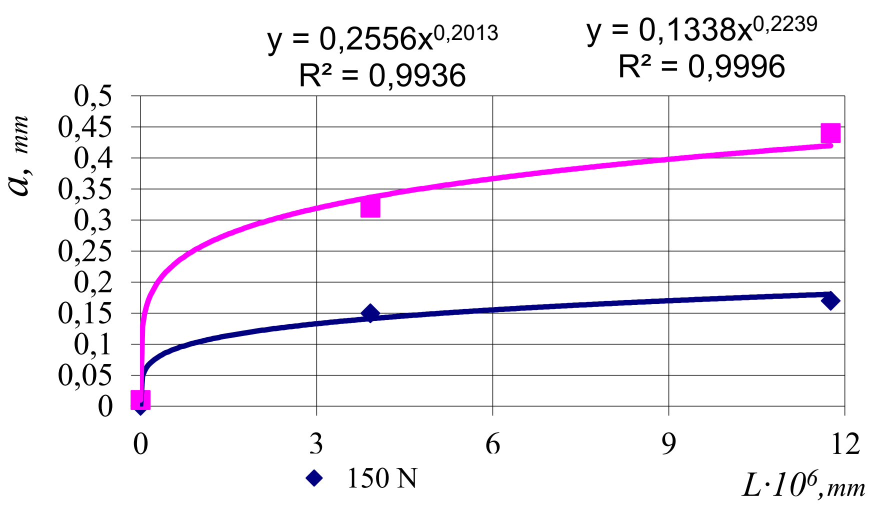
Test oil	TAN, mg KOH/g	Load, N	Test duration, h	WSD/2 (*a*), mm	L, mm·10^6
New oil 10W40 Test 1	0.91	150	60	0.140	3.919
			180	0.165	11.758
		300	60	0.220	3.919
			180	0.260	11.758
After 5000 km Test 2	1.7	150	60	0.150	3.919
			180	0.170	11.758
		300	60	0.320	3.919
			180	0.440	11.758
After 10000 km Test 2	2.9	150	60	0.190	3.919
			180	0.335	11.758
		300	60	0.425	3.919
			180	0.680	11.758

Shown below are approximations (Excel) of the dependence of the wear area on the friction path at different loads and values of the acid number of the lubricant.

Test 1



Test 2



Test 3

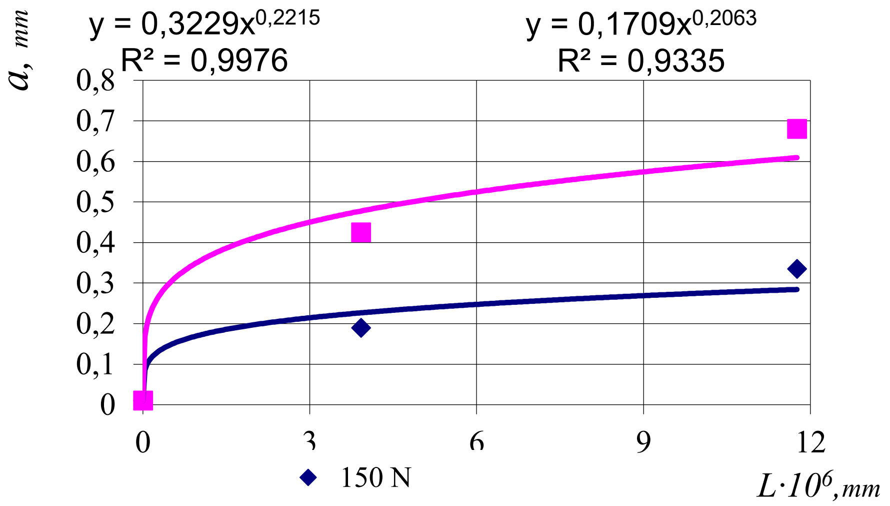


Fig. 2. Determination of the parameters of the approximation function $a(L) = cL^{\beta}$

The parameters of the approximation function (4) are summarized in Table 2.

Table 2

Approximation function parameters (4)

Load		Q=150 N	Q=300 N
Test 1	c	0.0953	0.157
	β	0.2218	0.2195
Test 2	c	0.1338	0.2556
	β	0.2013	0.2239
Test 3	c	0.1709	0.3229
	β	0.2063	0.2215

As expected, the values of the β parameter for a given lubricant are approximately the same. In accordance with the data in Table 2, we take the average value of the β parameter equal to 0.2157.

Then, according to formula (11), the parameter m=1.32. The determination of the parameter n was carried out for tests 2 and 3 according to the formula (14):

$$n(150N) = (2\cdot 1.32 + 2)\frac{\ln(0.1338/0.1709)}{\ln(1.7/2.9)} = 2.1;$$

$$n(300N) = (2\cdot 1.32 + 2)\frac{\ln(0.2556/0.3229)}{\ln(1.7/2.9)} = 2.05.$$

Accepted n=2.075. The coefficient K_W was determined by the formula (15) for the following test parameters: HB=200 MPa, μ=0.05, ν=13.6 N/mm^2, α=6.9 N/mm^2, TAN=1.7 mg KOH/g, R=12.7 mm.

$$K_W = \frac{0.2157\cdot 0.1338^{2\cdot 1.32+2}}{12.7}\left(\frac{\pi\cdot 200}{0.4082\cdot 150\cdot 0.05}\right)^{1.32}\left(\frac{13.6}{6.9\cdot 1.7}\right)^{2.075} = 2.3\cdot 10^{-3}.$$

Thus, the law of wear (5) after identifying the parameters takes the form:

$$\frac{dW}{dL} = 2.3\cdot 10^{-3}\left(\frac{\mu p}{HB}\right)^{1.32}\left(\frac{\alpha}{\nu}TAN\right)^{2.075}.$$

The dimensionless complex for the wear rate allows one to quantitatively take into account the effect of contact pressures, mechanical and frictional properties of materials, and lubrication parameters on wear. This model makes it possible to predict the wear resistance of lubricated friction units of the type: gear drives, rolling bearings, cam mechanisms and others.

Conclusions

1. The study confirms that the total acid number (TAN) of engine oils increases progressively with operating time and contamination, reflecting the accumulation of oxidation and degradation products.
2. The proposed mathematical wear model, which integrates TAN as a parameter along with contact pressure, viscosity, hardness, and friction coefficient, accurately describes the wear behavior of lubricated contacts.
3. Experimental results demonstrate that with an increase of TAN from 0.9 to 2.9 mg KOH/g, the wear scar diameter and wear rate rise proportionally, indicating the strong influence of acidification on surface damage.
4. The model parameters identified from the four-ball test ($m = 1.32$, $n = 2.075$) characterize the dependence of wear on contact pressure and acidity, providing a reliable basis for quantitative wear prediction.
5. The inclusion of TAN in the wear equation allows the use of acidity as a diagnostic indicator for lubricant condition and residual life assessment.
6. The obtained results can be applied to optimize oil change intervals, reduce maintenance costs, and enhance the reliability and durability of friction units in internal combustion engines.

References

1. De Rivas, B. L., Vivancos, J. L., Ordieres-Meré, J., & Capuz-Rizo, S. F. (2017). Determination of the total acid number (TAN) of used motor oils by IR and chemometrics applying a combined strategy for variable selection. Chemometrics and Intelligent Laboratory Systems, 160, 32–39. https://doi.org/10.1016/j.chemolab.2016.02.008
2. Wolak, A. (2018). Changes in lubricant properties of used synthetic oils based on the total acid number. Measurement and Control, 51(3–4), 65–72. https://doi.org/10.1177/0020294018770916
3. Wei, L., Duan, H., Jin, Y., & Li, J. (2021). Motor oil degradation during urban cycle road tests. Friction, 9(5), 1002–1011. https://doi.org/10.1007/s40544-020-0386-z
4. Shinde, H. M., & Bewoor, A. K. (2020). Evaluating petrol engine oil deterioration through oxidation and nitration parameters by low-cost IR sensor. Applied Petrochemical Research, 10(1), 83–94. https://doi.org/10.1007/s13203-020-00248-6
5. Tomita, M. (1995). Study on deterioration of engine oil and its sensing. Wear, 186–187, 286–293. https://doi.org/10.1016/0389-4304(95)00019-4
6. Ramírez Camba, R., García García, C., García Tobar, M., & Fajardo Merchán, J. (2025). An integrated methodological approach for interpreting used oil analysis in diesel engines. Lubricants, 13(4), 169. https://doi.org/10.3390/lubricants13040169
7. Wakiru, J. M., Pintelon, L., Muchiri, P. N., & Chemweno, P. (2019). A review on lubricant condition monitoring information analysis for maintenance decision support. Mechanical Systems and Signal Processing, 118, 108–132. https://doi.org/10.1016/j.ymssp.2018.06.050
8. Harvath, P. V., & Walzer, M. (2016). Identification of organic acids in used engine oil residues. SAE Technical Paper. https://doi.org/10.4271/2016-01-2274
9. Bastiampillai, N. (2023). Statistical analysis and modelling of engine oil degradation. DIVA-Portal Dissertation, 1–150. https://doi.org/10.1017/CBO9781107415324.004
10. Gołębiowski, W., Zając, G., & Wolak, A. (2018). Definition of oil change intervals based on the analysis of selected physicochemical properties of used engine oils. Combustion Engines, 172(1), 44–50. https://doi.org/10.19206/CE-2018-105

Диха М.О., Гетьман М.В., Дитинюк В.О., Маковкін О.М. Експериментальне та аналітичне дослідження зміни кислотного числа моторних олив за умов експлуатаційного забруднення

У цій статті представлено експериментальне та аналітичне дослідження зміни загального кислотного числа (ЗКЧ) моторних олив за умов експлуатаційного забруднення. Метою дослідження є оцінка кореляції між зростанням кислотності мастильних матеріалів та їхньою поведінкою при зносі в конфігурації чотирикулькового випробування. Було проведено теоретичне моделювання та експериментальні випробування для визначення параметрів закону зносу, який включає контактний тиск, в'язкість оливи, твердість та ЗКЧ як ключові змінні. Отримані результати підтверджують, що кислотне число значно зростає під час експлуатації оливи: від 0,9 до 2,9 мг KOH/г, що призводить до посиленої швидкості зносу контактних поверхонь. Запропонована модель кількісно описує зв'язок між рівнем кислотності та інтенсивністю зносу та дозволяє прогнозувати характеристики оливи на основі її фізико-хімічної деградації. Розроблений підхід дозволяє покращити оцінку залишкового ресурсу мастильних матеріалів та оптимізувати інтервали технічного обслуговування двигунів внутрішнього згоряння.

Ключові слова: деградація моторної оливи; загальне кислотне число; експлуатаційне забруднення; модель зносу; чотирикульковий прилад; фізико-хімічні властивості; змащування; трибологія; прогнозне обслуговуванн