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Improving the accuracy of a new viscosity-based method for estimating lubricating oil dilution by diesel oil in an internal combustion engine

Leszek Chybowski[1], Piotr Dąbrowski[2], Przemysław Kowalak[3], Konrad Ćwirko[4], Marcin Szczepanek[5]

[1] https://orcid.org/0000-0003-0245-3946
[2] https://orcid.org/0000-0001-5082-5391
[3] https://orcid.org/0000-0003-1370-2231
[4] https://orcid.org/0000-0003-2231-9533
[5] https://orcid.org/0000-0002-0764-9772

[1,3] Maritime University of Szczecin, Faculty of Marine Engineering
Department of Marine Propulsion Plants
2 Willowa St., 71-650 Szczecin, Poland
[2] Independent Researcher
71-650 Szczecin, Poland
[4] Maritime University of Szczecin, Institute of Mathematics, Physics, and Chemistry,
1-2 Wały Chrobrego St., 70-500 Szczecin, Poland
[5] Maritime University of Szczecin, Faculty of Marine Engineering
Department of Power Engineering,
2 Willowa St., 71-650 Szczecin, Poland
e-mail: {[1]l.chybowski; [3]p.kowalak; [4]k.cwirko; [5]m.szczepanek}@pm.szczecin.pl;
[2]piotr.j.dabrowski@icloud.com
✉ corresponding author

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Abstract

This paper presents the results of a study aimed at improving the accuracy of the recently published SATUFER method for estimating the dilution level of lubricating oil with diesel oil. It used the measured value of oil kinematic viscosity and known reference values of kinematic viscosity at the same temperature for fresh lubricating oil and diesel oil fed to the engine. This method was based on the REFUTAS algorithm for the analytical determination of the viscosity of a mixture with known mass shares and viscosities of the components. The correction factor K used in the formula estimating the concentration of diesel in the lubricating oil was Pareto optimized in the range 0.0–1.0 to minimize the value of the maximum absolute fitting error, $\delta_{\max}$, and maximize the coefficient of determination, R^2, determined for the function estimating the degree of dilution of the lubricating oil with diesel relative to a known reference value. The analysis used a dataset of kinematic viscosity values for blends of SAE 30 or SAE 40 viscosity grade lubricating oil with B7 diesel oil at concentrations of 0, 1, 2, 5, 10, 20, 30, 40, 50, 75, and 100% m/m diesel oil in the blend at temperatures of 40, 50, 60, 70, 80, 90, and 100 °C. For each mixture, an estimated dilution level was calculated using the SATUFER method, and the result was presented with a known reference value. The results of the analysis for the assumptions presented in this article indicated that the initial value of the K-factor for further analysis was $K = 0.53$ instead of the initial value of $K = 0.80$ adopted in the REFUTAS method, which was the basis for the proposed and developed SATUFER method.

Abbreviations

API – American Petroleum Institute
C – reference (accurate) percentage mass concentration of diesel oil in the mixture with lubricating oil
C_{est} – estimated percentage mass concentration of diesel oil in the lubricating oil mixture
C_i – ith reference value of diesel oil concentration in lubricating oil
CD, CF, SJ – API-defined quality classes of lubricating oils
i – the number of the next parameter in the optimization process
ISO – International Organization for Standardization
j – sequence number of the measurement carried out at the set temperature t
K – correction constant
n – number of components of the mixture
REFUTAS – a method for estimating the viscosity of a mixture developed by the British Petroleum Co.
P_i – the ith parameter in the optimization process
R^2 – coefficient of determination
SAE – Society of Automotive Engineers
SAE 30, SAE 40 – lubricating oil viscosity classes according to SAE J300 viscosity classification
SATUFER – method/model for estimating diesel oil concentration in lubricating oil, an acronym for Speedy Analysis of The degree of lUbricating oil with FuEl Rarefaction
t – temperature at which the measurement of liquid viscosity is carried out
w_i – weight of the ith parameter in the optimization process
X – target function
$\delta_{\max}$ – maximum absolute error of estimation of the percentage mass concentration of diesel oil in a mixture with lubricating oil
ν_{DO} – kinematic viscosity of diesel oil
ν_{FLO} – kinematic viscosity of fresh lubricating oil
ν_{ULO} – kinematic viscosity of the lubricating oil used

Introduction

During the operation of a reciprocating internal combustion engine, especially a trunk piston engine, there is a risk of contamination of the lubricating oil in the engine's circulating lubrication system. The causes of this phenomenon are related to oil and fuel leaks due to the deterioration of piston rings during engine use, and malfunctioning engine fuel apparatus and drainage systems.

Dilution of oil with fuel results in a deterioration of the lubrication quality of the engine's tribological pairs, thereby reducing the efficiency and reliability of engine operation. This contributes to accelerated wear of the engine components and, in extreme cases, can be one of the factors leading to explosions in crankcases. To ensure efficient, reliable, and safe engine operation, it is therefore necessary to monitor lubricating oil quality on an ongoing basis to assess the extent of contamination during operation. Lubricating oils in industrial and marine engines are subjected to periodic laboratory tests, which may be ad hoc or detailed.

One alternative for monitoring oil quality is the use of ongoing lubricating oil monitoring systems. Oil parameters directly related to the dilution of lubricating oil with diesel fuel are flash point, density, and viscosity (they decrease with increasing dilution of lubricating oil with distillation diesel fuel). Specialized apparatuses must be used to determine the flash point, which excludes this parameter from easy and safe ongoing monitoring of its value in situ during engine operation. Changes in oil density, on the other hand, are relatively small and depend on many factors.

The most useful parameter for ongoing evaluations remains fuel viscosity, which can depend on a number of factors (contaminants, oil aging, water dilution, bacterial contamination, etc.), but with ongoing monitoring, factors affecting oil viscosity can be significantly reduced. In automotive vehicles, the potential dilution of lubricating oil with fuel is commonly detected by monitoring the crankcase oil level (the amount of oil in the system), which increases under the influence of fuel leaks into the lubricating oil. However, this solution only provides coarse information about the occurrence of leakage. Here, the authors undertake a study on the use of oil viscosity measurement to determine not only the occurrence of oil dilution with fuel, but also to assess the degree of this dilution.

Viscosity characterizes the resistance occurring in the relative movement of adjacent fluid layers and is among the most important functional properties of lubricating oils. A distinction is made between kinematic viscosity, with an SI unit of m^2/s, and dynamic viscosity, with an SI unit of Pa·s. Resistance (internal friction) in liquids decreases with increasing temperature (the opposite effect takes place in the case of gases). In addition, viscosity increases with increasing pressure. Viscosity depends on the chemical composition of the substance, which involves, in the case of lubricating oils, various factors and relationships that enable the use of viscosity measurements and assessment of their changes for diagnostic purposes (AMETEK Spectro Scientific, 2016; Niedermayer et al., 2016).

According to engine manufacturers' recommendations, the kinematic viscosity of the oil used in the engine relative to the viscosity value of fresh oil determined at the reference temperature (40 °C or 100 °C) should not change in a range greater than −10% to +10%, which is considered a warning range (Techenomics, 2014), while a range of −20% to +30% (Krupowies, 2002) is considered an alarm range. According to other recommendations, the kinematic viscosity of circulating lubricating oil at 100 °C should not decrease by more than 3.0 mm^2/s nor increase by more than 3.5 mm^2/s relative to the value for fresh oil (CIMAC, 2017).

The viscosity of the oil changes when the lubricating oil is contaminated with fuel; it may decrease when the lubricating oil is diluted with distillation fuel (diesel, gasoline, etc.) or increase due to dilution of the lubricating oil with residual fuel (i.e., heavy fuel oil). Taking into account the abovementioned changes in oil viscosity in the context of the degree of dilution of lubricating oil with fuel, it is necessary to know what fuel was fed to the engine (Montaud et al., 1998).

Figures 1 and 2 show examples of the relationship between the kinematic viscosity of oil and the degree of dilution of lubricating oil with diesel fuel at 40 °C (ν_{40}) and 100 °C (ν_{100}), respectively. The graphs show selected results obtained by the author (Chybowski, 2022) for Eni/Agip Cladium 120 CD/CF oils of viscosity classes SAE 30 (Oleje-Smary, 2026a) and SAE 40 (Oleje-Smary, 2026b) diluted with Orlen Efecta Diesel Bio (7% FAME) fuel (PKN Orlen S.A., 2021), results for blends of Lotos Marinol CB-30 RG1230 CD/CF oil (LOTOS, 2026) of viscosity class SAE 30 with Orlen Efecta Diesel Bio (7% FAME) (PKN Orlen S.A., 2021), and results obtained by other authors for blends of unspecified mineral oil A SAE 15W/40 SJ/CF with Eurodiesel fuel (compliant with PN-EN 288:2004) (Ljubas, Krpan & Matanović, 2010). In the presented graphs, kinematic viscosity is intentionally presented as an independent variable to show the possibility of using this parameter in lubricating oil diagnostics.

Among the advantages of using viscosity as a measure of the degree of dilution of lubricating oil with diesel fuel is the general availability of both portable and laboratory apparatus for viscosity

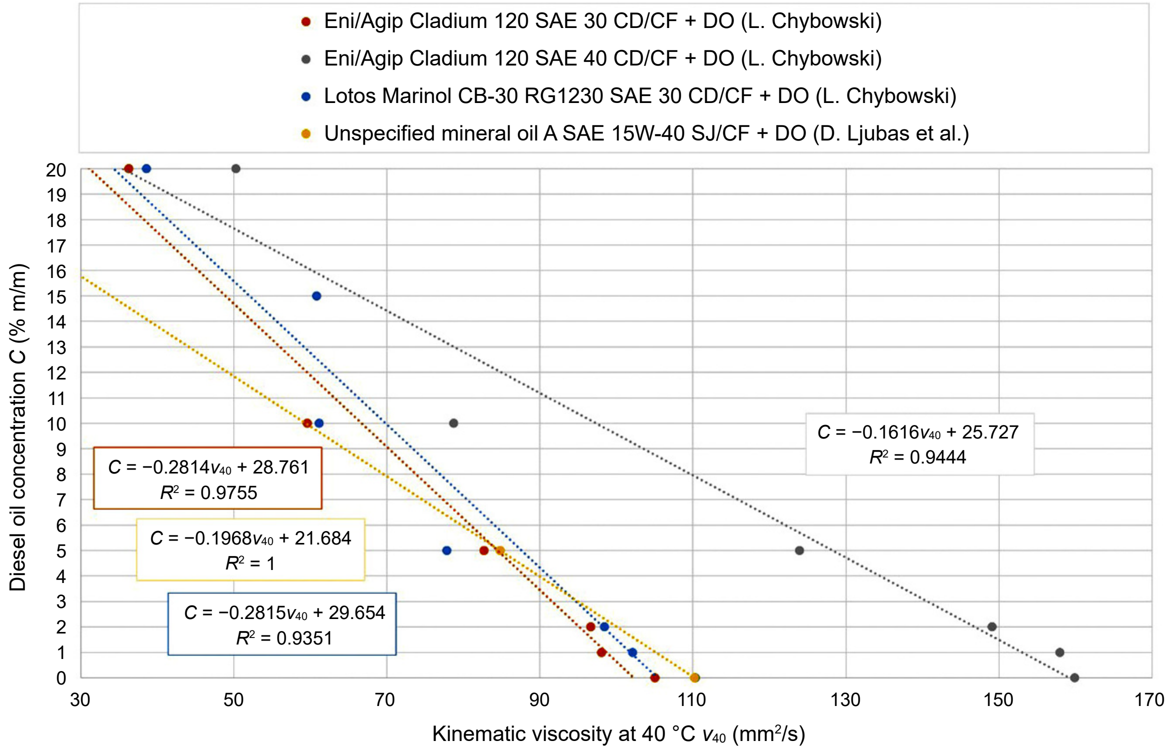

Figure 1. Example curves that are useful in evaluating the level of lubricating oil dilution with fuel as a function of kinematic viscosity at 40 °C (based on sources: Ljubas, Krpan & Matanović, 2010; Chybowski, 2023; Chybowski, Kowalak & Dąbrowski, 2023; Chybowski et al., 2024))

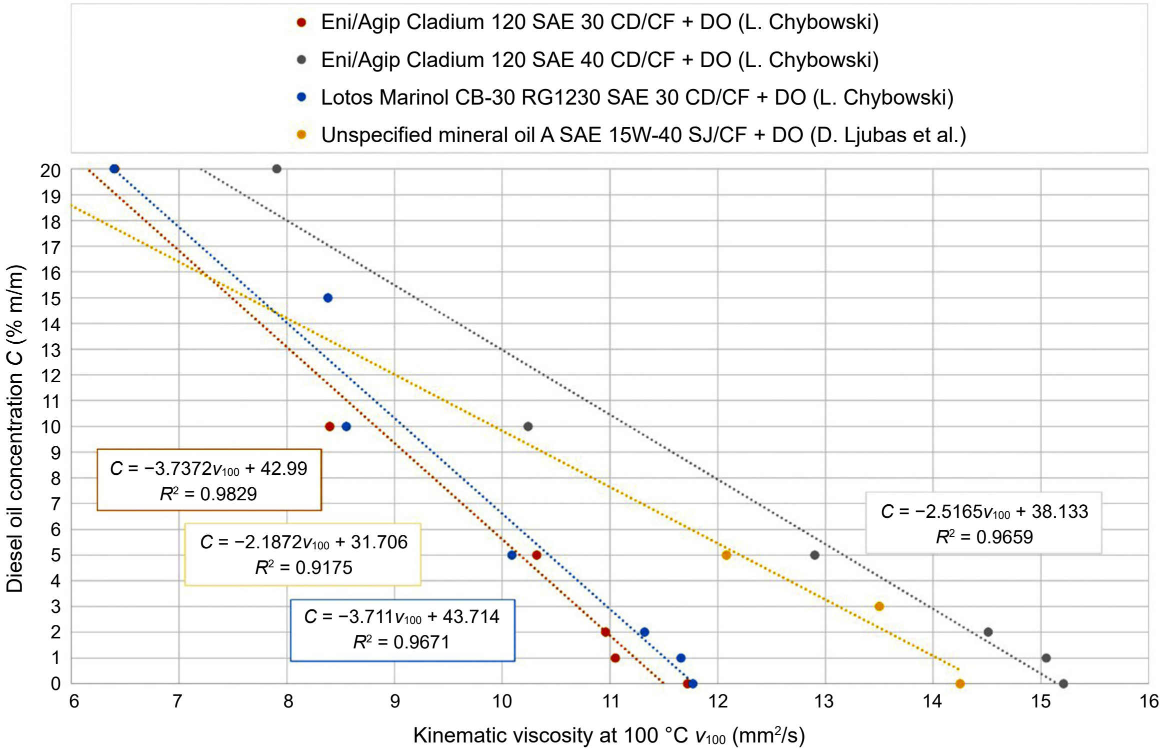

Figure 2. Example curves that are useful in evaluating the level of lubricating oil dilution with fuel as a function of kinematic viscosity at 100 °C (based on sources: Ljubas, Krpan & Matanović, 2010; Chybowski, 2023; Chybowski, Kowalak & Dąbrowski, 2023; Chybowski et al., 2024))

measurements. For this reason, the method is routinely used for the periodic checking of lubricating oils and additionally offers the possibility of detecting ethanol and biodiesel-type biofuels. The disadvantage of assessing the degree of dilution is the possibility that the viscosity of the oil may change under the influence of factors other than fuel contamination of the lubricating oil, such as aging of the oil or infection of the oil with bacteria. Nevertheless, simply estimating the amount of viscosity change corresponding to a hypothetical dilution of lubricating oil with diesel fuel can be used in the ongoing assessment of the quality of lubricating oil used in an engine.

The authors' previous research resulted in the development of the SATUFER method for estimating the degree of dilution of lubricating oil with diesel fuel (Chybowski, Szczepanek & Kowalak, 2026). The method is based on the measured value of the kinematic viscosity of oil in the engine, v_{ULO} (mm^2/s), the known kinematic viscosity of fresh lubricating oil, v_{FLO} (mm^2/s), and the known kinematic viscosity of diesel oil, v_{DO} (mm^2/s), at the same measurement temperature. The estimated mass percentage concentration of diesel oil in the lubricating oil is determined according to the following formula:

$$C_{\mathrm{est}} = \frac{\ln\left[\dfrac{\ln(v_{\mathrm{ULO}}+0.8)}{\ln(v_{\mathrm{FLO}}+0.8)}\right]}{\ln\left[\dfrac{\ln(v_{\mathrm{DO}}+0.8)}{\ln(v_{\mathrm{FLO}}+0.8)}\right]}\cdot 100\% \tag{1}$$

The results presented in the article (Chybowski, Szczepanek, & Kowalak, 2026) refer to a value of the correction coefficient in the logarithmic expressions equal to 0.8 mm^2/s. In the next step, the notation is generalized by introducing a correction constant K, i.e.:

$$C_{\mathrm{est}} = \frac{\ln\left[\dfrac{\ln(v_{\mathrm{ULO}}+K)}{\ln(v_{\mathrm{FLO}}+K)}\right]}{\ln\left[\dfrac{\ln(v_{\mathrm{DO}}+K)}{\ln(v_{\mathrm{FLO}}+K)}\right]}\cdot 100\% \tag{2}$$

Modifying the initial value of the constant ($K = 0.8$ mm^2/s) in the logarithmic expressions makes it possible to increase the accuracy of the model. Simulations carried out by the authors indicate that the values of the correction constant K should be in the range of 0.00–1.00 mm^2/s. The proposed range of the K factor values is based on those commonly used in practice in models describing the viscosity of petrochemical products.

The *K*-correction factor is used in the sublogarithmic expression of many empirical and semi-empirical formulas describing the viscosity of mixtures, the variation of viscosity as a function of temperature, and for determining auxiliary indices based on viscosity. The *K*-factor has been adopted in various applications in the range from $K = 0–1$ (Roegiers, 1951; Ramos–Pallares et al., 2017). The first applications of the coefficient were related, among others, to the determination of viscosity-temperature relationships, and the Walther formula developed for this purpose was first presented in 1930 (Walther, 1930). Walther originally suggested the value of the constant (often taken as $K = 0.6$, $K = 0.7$, or $K = 0.8$), which allows for a correct mathematical representation of viscosity even at low temperatures, where traditional exponential functions lose accuracy. In many European standards, the coefficient takes the value $K = 0.8$, and in American standards, it is often found in the range $K = 0.65–0.75$ (Górska & Górski, 1986). On the other hand, residual fuels are used to determine calculated ignition indexes (CIMAC, 1990), such as the calculated ignition index (CII) developed by BP, where $K = 0.7$, and the calculated carbon aromaticity index (CCAI) developed by Shell, where $K = 0.85$ (Chybowski, 2023). The optimization of the *K*-factor in formula (2) within the range of 0.0–1.0 has been the subject of further, in-depth analyses by the authors, and this article shows the results of this research.

Materials and methods

The experiment used blends of the Agip/Eni Cladium 120 lubricating oil (Oleje-Smary, 2026a; 2026b) with Orlen Efecta Diesel Biodiesel oil B7 (designation CN27102011D) (PKN Orlen S.A., 2019). The employed viscosity classes of lubricating oils were selected due to their widespread use in industrial and marine applications for compression-ignition engines operating in confined spaces. The basic parameters of the lubricating oils and diesel oil used to prepare the test blends are shown in Table 1.

The SATUFER model was applied to blends of each class of lubricating oil with diesel oil at concentrations of 0, 1, 2, 5, 10, 20, 30, 40, 50, 75, and 100% m/m diesel oil in the blend at measurement temperatures of 40, 50, 60, 70, 80, 90, and 100 °C using SAE 30 and SAE 40 viscosity grade oils. Despite the fact that such a high degree of dilution of lubricating oil with diesel oil is not encountered under operating conditions, measurements were performed in the experiment for the mentioned range of diesel oil concentrations in lubricating oil for cognitive purposes and overall evaluation of the SATUFER model. The temperature range, in turn, coincided with the oil temperatures in the engine lubrication system occurring under normal operating conditions of an internal combustion engine.

Table 1. Manufacturers' declared data for the oils used in the experiment (PKN Orlen S.A., 2019; Oleje-Smary, 2026a; 2026b)

Parameter	Lubricating oil		Diesel oil
SAE viscosity class	SAE 30	SAE 40	N/A
API quality class	CD/CF	CD/CF	N/A
Density at 15°C (kg/m^3)	895	900	820–845
Kinematic viscosity at 40 °C	108	160	~2.549
Viscosity index	100	100	N/A
Flashpoint (measured in a closed cup)	225	235	> 56

The kinematic viscosity of the individual samples was determined in accordance with PN-EN ISO 3104:2004 (PKN, 2024) using a Cannon-Fenske Opaque glass capillary viscometer (Paradise Scientific Company Ltd., Dhaka, Bangladesh) and a TV2000 viscometric bath (Labovisco bv, Zoetermeer, the Netherlands). The kinematic viscosities of the SAE 30 grade and SAE 40 grade lubricating oil-based blends used in the experiment are shown in Tables 2 and 3, respectively.

For the data obtained in the experiment, the SATUFER model was applied to verify the accuracy of the estimation of the degree of dilution of lubricating oil with diesel fuel for values of *K* in the range between 0.0 and 1.0. The verification of the results was based on comparing the estimation results with the reference (known) values of the degree of dilution of each mixture at each measurement temperature.

Therefore, the *K* values depended on the type of petroleum substance. The challenge then arose to determine the optimal value of this coefficient for lubricating oils diluted with distillation fuel. The authors examined the possibility of optimizing the value of the constant, *K*, that would maximize the coefficient of determination, R^2, of the model fit to empirical data and minimize the absolute percentage error of estimation, $\delta_{\max}$ (% m/m), for estimating the concentration of diesel oil in lubricating oil at a given measurement temperature, which is described by the following relationship:

$$\delta_{\max} = \max_{j=1,2..m} \left| C_j - C_{\mathrm{est}\,j} \right| \quad (3)$$

Table 2. Kinematic viscosity of SAE 30 oil–diesel oil blends as a function of diesel oil concentration and measurement temperature

Diesel oil concentration C (% m/m)	Measurement temperature t										
	0	1	2	5	10	20	30	40	50	75	100
40	105.010	98.060	96.640	82.700	59.610	36.250	24.200	15.560	11.070	5.260	2.897
50	66.110	59.280	58.720	53.890	39.730	24.970	16.940	11.480	8.461	4.230	2.443
60	41.660	38.070	37.710	33.340	26.310	17.850	12.320	8.340	6.495	3.360	2.064
70	28.620	26.350	26.100	23.290	18.770	13.180	9.420	6.690	5.204	2.860	1.769
80	20.530	19.190	18.970	17.610	13.930	10.070	7.330	5.420	4.250	2.420	1.551
90	14.990	14.300	14.160	13.290	10.670	7.916	5.870	4.430	3.545	2.090	1.376
100	11.720	11.050	10.960	10.320	8.398	6.404	4.820	3.700	3.012	1.860	1.232

Note: Columns indicate diesel oil concentration C (% m/m), rows indicate measurement temperature t (°C), and table values indicate kinematic viscosity v_t (mm²/s).

Table 3. Kinematic viscosity of SAE 40 oil–diesel oil blends as a function of diesel oil concentration and measurement temperature

Diesel oil concentration C (% m/m)	Measurement temperature t										
	0	1	2	5	10	20	30	40	50	75	100
40	159.9	157.95	149.1	123.95	78.71	50.29	29.34	18.91	13.25	5.63	2.897
50	98.09	92.39	87.62	73.92	50.96	34.01	20.74	13.96	10.01	4.56	2.443
60	59.78	57.14	54.5	46.72	34.07	23.71	14.85	10.37	7.605	3.70	2.064
70	39.91	38.44	36.73	32.01	23.91	17.15	11.16	7.97	6.040	3.08	1.769
80	27.95	27.28	26.21	22.88	17.39	12.85	8.63	6.33	4.918	2.61	1.551
90	20.20	19.82	19.08	16.84	13.15	9.979	6.85	5.14	4.095	2.24	1.376
100	15.21	15.05	14.51	12.9	10.24	7.908	5.61	4.27	3.447	1.97	1.232

Note: Columns indicate diesel oil concentration C (% m/m), rows indicate measurement temperature t (°C), and table values indicate kinematic viscosity v_t (mm²/s).

Since, for the proposed model, it was observed that the absolute percentage error of estimation, $\delta_{\max}$, was inversely proportional to the value of the coefficient of determination, R^2, we were dealing with Pareto optimization, where an increase in one of the optimized indicators is associated with a decrease in the other indicator (Bishop, 2004). In terms of a given objective function, X, for n parameters, of which the given ith parameter P_i has a weight w_i, the optimization process minimizing friction X has the form:

$$\min_{i=1,2...n} X(P_1,P_2...P_n) = \min_{i=1,2...n} \sum_{i=1}^{n} P_i w_i \tag{4}$$

A set ($P_{1\text{opt}}$, $P_{2\text{opt}}$ ... $P_{n\text{opt}}$) is optimal in the Pareto sense when there is no other set (P_1, P_2 ... P_n) in the range of acceptable values of individual parameters such that:

$$X(P_1,P_2...P_n) \le X(P_{1\,\text{opt}},P_{2\,\text{opt}}..P_{n\,\text{opt}}) \tag{5}$$

This article analyzes the data obtained from the experiment for determining the optimal values of the K-factor in relation (1) based on the maximized values of R^2 and the minimized values of $\delta_{\max}$ that characterized the fit of the model to the empirical data.

In order to determine the optimal value of the correction factor in the Pareto sense, the objective function X, the minimum value of which was associated with the maximization of the value of $R^2_{\min}$ and the minimization of the value of $\delta_{\max}$ after first normalizing these indices so that they fell within the interval [0, 1] was used. The weighting factor, β, for the coefficient of determination was assumed to be equal to 0.2, which was due to its high value over the entire analyzed range of values of K. Thus, the weight assigned to the maximum relative error parameter $\delta_{\max}$ was $1 - \beta = 0.8$. In addition, for practical purposes, the unit of measurement of both optimized indicators was unified by introducing into the equation of the objective function a multiplier equal to 1 mm²/s. The objective function had the form:

$$X(K)=\beta\cdot\left\{\frac{1-R^2_{\min}(K)}{\max\limits_{K\in\langle 0,1\rangle}\left[1-R^2_{\min}(K)\right]}\cdot 1\,\frac{\mathrm{mm}^2}{\mathrm{s}}\right\}+$$

$$+(1-\beta)\cdot\left\{\frac{\delta_{\max}(K)}{\max\limits_{K\in\langle 0,1\rangle}\left[\delta_{\max}(K)\right]}\right\} \tag{6}$$

As the optimal value of the $K = K_{\mathrm{opt}}$ coefficient, the authors took the value that minimized the objective function:

$$X\left(K_{\mathrm{opt}}\right)=\min_{K\in\langle 0,1\rangle} X(K) \tag{7}$$

Minimization of the objective function, X, was performed by the authors by solving an inequality of the form:

$$\frac{\mathrm{d}\,X\left(K=K_{\mathrm{opt}}\right)}{\mathrm{d}\,K}=0 \tag{8}$$

Equation (8) was used to find the optimal values of the K coefficient for the tested oils and viscosity measurement temperatures.

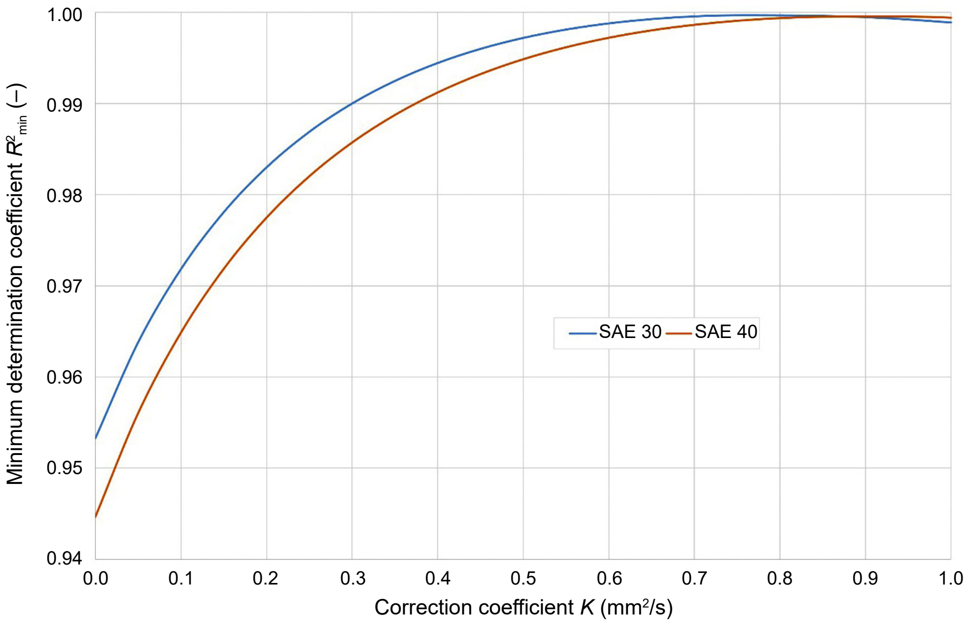

Figure 3. Lowest coefficient of determination obtained over the analyzed measurement temperatures, $R^2_{\min}$, describing the fit of the SATUFER model as a function of the correction factor, K, for the tested lubricating oil-diesel blends

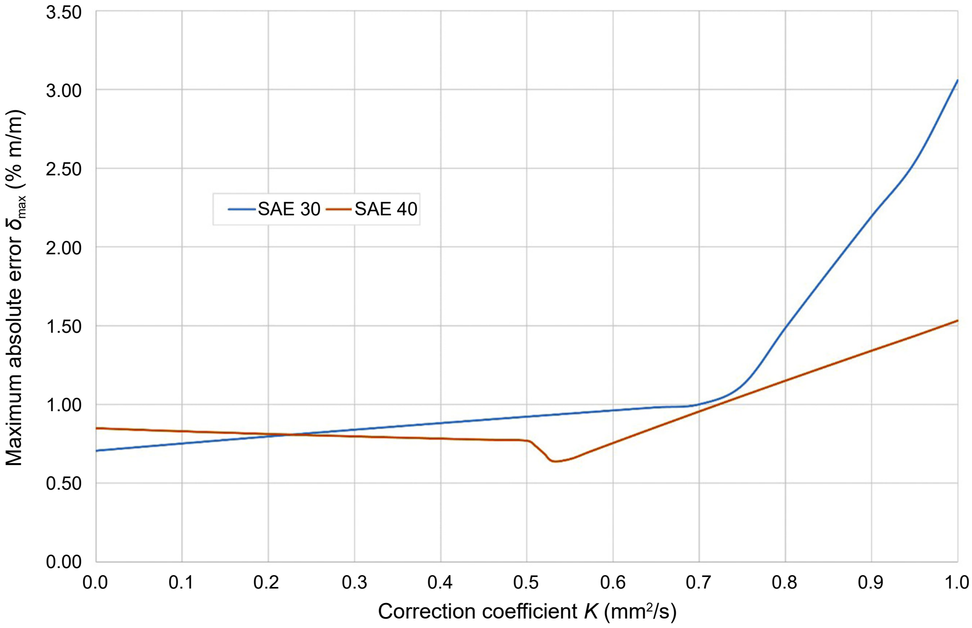

Figure 4. Maximum absolute estimation error, $\delta_{\max}$, of the SATUFER model as a function of the correction factor, K, for the tested lubricating oil-diesel blends

Results and discussion

Initial analysis

For the tested mixtures of SAE 30 and SAE 40 lubricating oils with diesel oil, the lowest coefficient of determination obtained over the analyzed measurement temperatures, denoted as $R^2_{\min}$, and the maximum absolute estimation error, denoted as $\delta_{\max}$, were determined for the SATUFER model. The results are shown in Figures 3 and 4 for each indicator, respectively.

The results shown in Figures 3 and 4 were used to determine the optimal value of the K factor in equation (1). The lowest values of the coefficient of determination obtained over the entire range of tested temperatures, denoted as $R^2_{\min}$, together with the maximum absolute estimation errors, denoted as $\delta_{\max}$, are shown in Figures 5 and 6 for mixtures prepared using SAE 30 and SAE 40 lubricating oils, respectively.

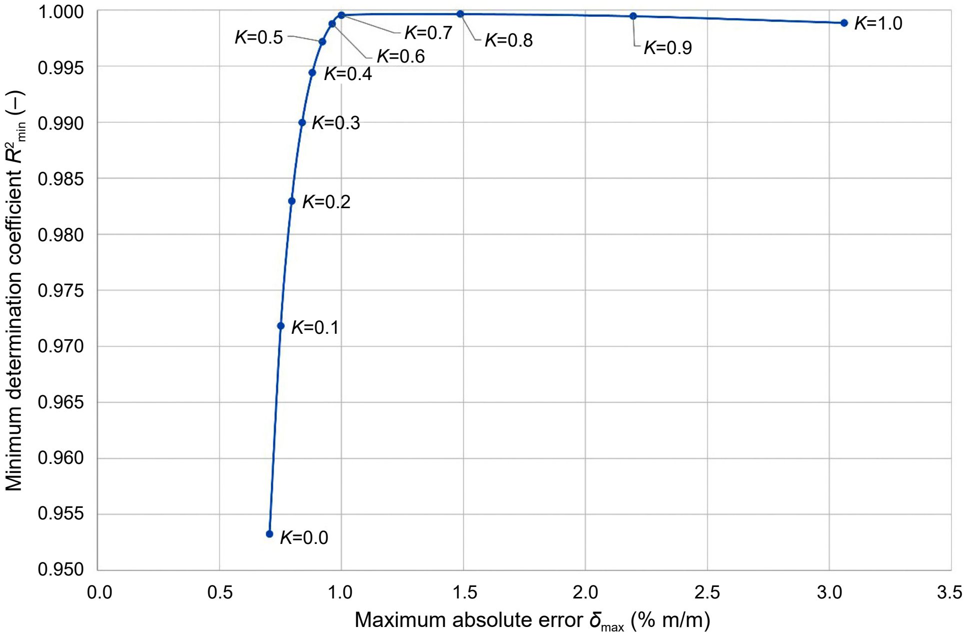

Figure 5. Lowest coefficient of determination obtained over the tested temperature range, $R^2_{\min}$, of the SATUFER model fitting and maximum absolute estimation error, $\delta_{\max}$, for the tested blends of lubricating oil of viscosity class SAE 30 with diesel oil

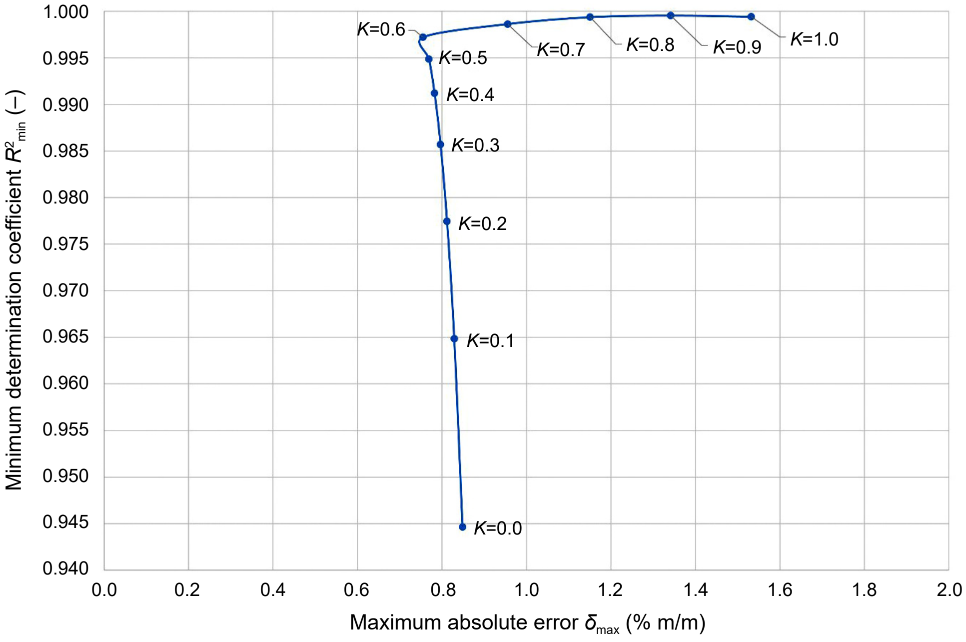

Figure 6. Lowest coefficient of determination obtained over the tested temperature range, $R^2_{\min}$, of the SATUFER model fitting and maximum absolute estimation error, $\delta_{\max}$, for the tested blends of lubricating oil of viscosity grade SAE 40 with diesel oil

Optimization of the coefficient *K*

The dependence of the objective function, *X*, on the value of the correction factor, *K*, for the mixtures of lubricating oils tested is shown in Figure 7.

Equation (8) was differentiated to determine the minimum value. The derivative of the objective function for lubricating oil-diesel blends for both base oils is shown in Figure 8.

The optimal value of the K_{opt} correction factor was found. Formula (4) was satisfied with correction factors $K = 0.45$ and 0.53 for mixtures prepared on the basis of lubricating oil of SAE viscosity classes 30 and 40, respectively.

Conclusions

The results of the analysis showed that the baseline value of the coefficient $K = 0.80$ used in the baseline REFUTAS method did not provide Pareto-optimal results in estimating the degree of dilution for the objective function adopted in the experiment. The analysis presented here shows that it is possible to improve the accuracy of the estimation

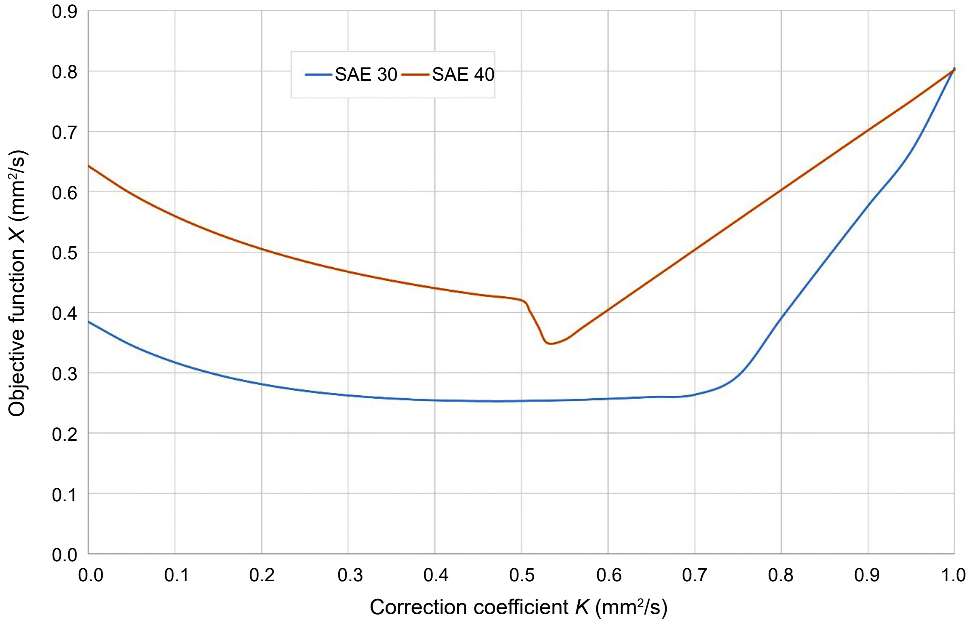

Figure 7. Goal functions, *X*, for determining the optimal value of the correction factor, *K*, in the SATUFER model

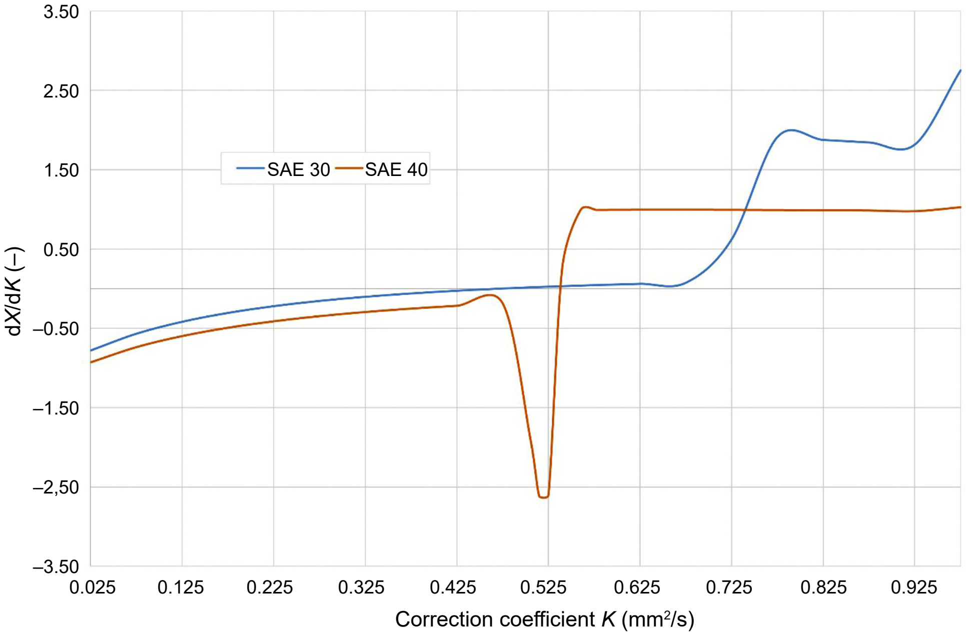

Figure 8. Derivative of the objective function d*X*(*K*)/d*K* as a function of the correction factor *K* in the SATUFER model

of the degree of dilution of lubricating oil with diesel fuel by appropriately selecting the value of the correction factor K for a given oil.

In practical applications, for both SAE 30 and SAE 40 oil mixtures, sufficient accuracy was provided in both cases by $K = 0.53$. Therefore, a value of $K = 0.53$, instead of the baseline value of 0.80 used in the REFUTAS method, is proposed as the starting value for further analysis in additional studies relating to the development of the SATUFER method.

In future research, it is proposed to test the modified SATUFER model with other types of base oils and to build and test a prototype system for measuring the degree of dilution of lubricating oil with diesel oil during the operation of an internal combustion engine.

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