On the Estimation of the Useful Lifespan of Lubrication Oil under Constrained Functioning Conditions an ANN / Fuzzy Logic Approach

M. Hamed[1], J. Khalil[2], M. Atia[3]

[1] Renault Group EIM Co, Egypt
[2]Jost Institute for Tribotechnology, University of Central Lancashire, Preston PR1 2HE, UK
[3] Arab Academy for Science Technology and Maritime Transport, Egypt

KEYWORDS
Lubrication, Maintenance management, Diagnosis and prognosis, End user application

ABSTRACT

Lubrication oil in automotives is a multi-billion-pound business but the non-optimization of its lifespan entails colossal harm to societies, global resources and the environment. Losses are caused by premature oil change or by machinery wearing due to deteriorated oil. The actual practice in the automotive field follows a predetermined routine-replacement policy that does not consider the wide spectrum of operating conditions. In this paper a decision support model is developed for the determination of the optimum life span of oil under specific working conditions. A data gathering scheme is set to capture the most relevant oils' characteristics from real samples over specific ranges of operation. The relationship between the causal factors and the resulting condition of oil is programmed in an ANN which is complemented with a fuzzy-logic approach in order to predict the optimum lifespan of oil under any set of causal factors. The approach is applied on a case study in Egypt; the model is tested, validated and is believed to fulfil its objectives satisfactorily.

1 INTRODUCTION

ICE engines, like many other machinery applications, depend on oil for crucial functions namely; lubrication, cooling, cleaning and coating of the heated friction surfaces. These four functions extend the useful lifetime of engines, prevent major failures and improve their reliability and smoothness while running.

1.1 The Oil lifespan dilemma

The oil quality degrades with usage, but the rate of deterioration is not linear, the degrading aspects are not equally important and the working conditions are a key factor in the definition of this degradation. Therefore, there has always been an unresolved issue about the optimum change interval of oil. In Massive applications, degradation models may be used [1] and [2] where samples are routinely tested and analysed, therefore decisions are made. This process is highly costly and complicated, consequently is not adopted within the automotive field, particularly within passengers and light trucks vehicles. The common practice is to rely on a combination between the recommendations of the manufacturers of engines and those of oils. In [3], it is explained that manufacturers' recommendations only reflect a single view of preferences combined with a single set of operation characteristics omitting the crucial variability in operating conditions; therefore, the following dilemma results.
Mere routine oil change is far from cost optimum [4]. Changing oil too early has become a serious waste of money, especially that synthetic oils are getting more expensive on an exponential manner. On the other hand, leaving the oil too long beyond its healthy lifetime will entail serious damage to engines; what may lead to very costly repairs. From a different perspective, the state of oil is a key descriptor for the reliability of critical applications like helicopters-gearboxes; of which the failure may entail human losses [5]. Furthermore, the proper preventive maintenance plan of machinery including lubrication would lead to the extension of the life expectancy on machinery [6]; what is considered a principal purpose of any maintenance system.

1.2 Degradation Parameters

Researchers worked on the measurement and/or the calculation of the degradation level of oils. In literature, different methodologies were implemented aiming at the achievement of this goal [7]. [8] tested the degradation and the remaining useful life of oil by measuring and recording the formation of polyaromatic hydrocarbons (PAHs) which is linked to oil degradation in room temperature. [9] studied the rheological and tribological behaviors of oils in 10 commercial vehicle-engines especially: viscosity and pressure; the study performed measurement and evaluation of the oil film thickness in engines in conjunction with their relevant parameters. The research proved a sharp increase in viscosity according to the addition of viscosity modifier additives and showed its effects on pressure and temperature.
[11] discussed the oil degradation effects on the emissions of heavy duty diesel engines, by taking and analyzing samples of used oils after 40 hours of aging to evaluated their physical properties namely: Viscosity, Total Acid, Density, Ash content, Soot, Particle Count and Metal Content. The study showed that the physical properties of oil changed over the aging time; specifically, the TBN (total base number) decreased because of the decrease in basic additives, while the soot and the

metal contamination levels increased in degraded oil. [12] studied the alkalinity of oils and their ability to neutralize the sulfuric acids in marine engines and passenger vehicle engines, by detecting the sulfur component in emissions; the research highlighted the attributed harmful effect on catalytic converters, the environment and the overall state of oil degradation.
[13] studied anti-extreme pressure, anti-wear and friction reduction in order to evaluate the degradation of recycled oils, their durability, their effects and the feasibility of re-using the treated oil proving that the recycled oil may be used to flush engines rather than being used as oil for actual engine running. [14] studied the tribological performance and sources of degradation of diesel engines' oils through the evaluation of their molecular weight distribution, the count of the kinetic growth of larger molecular weight, and by the finding of tentative chemical markers in base stock oil therefore comparing these to those of the degraded oils.
Based on the reviewed literature and on the science of Tribology, it is deduced that the relevant parameters that describe oils degradation are: Viscosity and pressure viscosity coefficient, density, water content, oxidation level, nitration level, chemical formation particles, soot, total acidity, ash content, foreign Particles count, metal content, extreme pressure and anti-wear additives performance.

1.3 Parameters Measurements Methods

A good bulk of research discussed the scientific tests, machines and protocols that measure and monitor the characteristics of lubrication oils and the state of their deterioration such as, [9] used falling body viscometer and Houillon viscometer to measure the viscosity in different circumstances. Also, Thermo-Gravimetric Analysis TGA), Differential Scanning Calorimeter (DSC), Gel Permeation Chromatography (GPC) and X-ray diffraction (XRD) were all used in order to get the different characteristics of polymer in the lubrication oils. It is believed that the most widely used is, Fourier Transform Infrared Spectrometer (FTIR) which identifies the composition of the lubricant. [8] performed calibration, background subtraction, cosmic ray removal, smoothing, and plots spectra on lubrication oils to perform a clearance study of oils degradation, by using Ultraviolet Raman Microscopy. [10] studied the degradation of different mineral and synthetic lubricants in different operations of diesel engines by measuring the soot characteristics and levels through the implementation of the ICP- AES (Inductively coupled plasma atomic emission spectroscopy), Raman spectroscopy, X- Ray diffraction spectra, XANES Spectroscopy and High Resolution Transmission Electron Microscope (HRTEM). [11] tested the lubrication oil degradation physical properties by using (ASTM D445) for the viscosity test, (ASTM D664) for total acid test, (ASTM D1298) for density test, (ASTM D482) for ash content, and (ASTM D5185) for Metal Content. [12] studied the degradation of lubrication oils by identifying their alkalinity and the changes in the formation of the lubrication oils through capillary video microscopy. [15] studied the chemical compounds formed from the degraded antiwear. [17] measured anti wear performance and studied the results of the chemical reactions between anti wear additives and antioxidant additives, viscosity, total acid number and oxidation levels through the implementation of four methods: FTIR, X-Ray near-edge absorption spectroscopy and ASTM D-445 at 40° C and at 100° C. [18] worked on the oil degradation state; through the conductance of bench tests on used oils, namely microscopy imaging, viscosity Interfacial tension (IFT) and soot particle size analysis. [13] tested the tribological properties of the recycled lubrication oil by using four-ball friction wear tester.

From what preceded, it is deduced that the most acknowledged scientific methods that measure the parameters of lubrication oil degradation may be briefed as follows:

Viscosity: Falling body viscometer and Houillon viscometer.

Oil composition: Fourier Transform Infrared Spectrometer (FTIR), Ultraviolet Raman Microscopy, capillary video microscopy, Phosphorus L-edge, (XPEEM), microscopy imaging, viscosity and (IFT), LC-MS method and DART-MS analysis.

Oxidation level: Chromatographic method, Ultraviolet Spectrophotometry, Vibration techniques and Nuclear Magnetic resonance to measure.

Soot level: ICP- AES, Raman spectroscopy, X-Ray diffraction spectra, XANES Spectroscopy, (HRTEM) and (NTA).

Antiwear performance: Ball on cylinder test, Nano-scale scanning wear and Nano-scratch test, four-ball friction wear tester.

An interesting finding of the review is that researchers worked on defining the degradation of oils in terms of either single variable [10] and [12] or multiple variables [11]and [19].

1.4 Computational and simulation modelling

Researchers developed full simulations of lubrication systems in order to better understand the process, to acquire the knowledge and to manipulate it. [20] used a finite element solver and ANSYS Mechanical with ANSYS CFX to develop a numerical model and to simulate the function of oil on the surfaces they lubricate; the study considered oils performance in a turboprop, and focused on the relation between the oil film temperature, its pressure and the load carrying capacity. It also considered the relation between fluid viscosity, oil film temperature and rotational speed. [8] developed a mathematical model using MATLAB/Simulink program to capture the degradation mechanism of the lubrication oil. [21] used a finite elements simulation and a Baqus program to model the wear tracks of a cup-on-disk sliding wear contact. A user subroutine simulated the sliding contact for the axi-symmetric model. The experiments were analyzed by Arcahard's model where the variables are: cup wear, disk wear, total wear, pressure, cup von Mises stress, disk von Mises stress and delta node temperature making a comparison between thermal and isothermal conditions. In a different approach [22] performed friction measurement experiments to model dynamic friction forces between different surfaces. The study used Lu Gre model of triboindenter parameters to simulate the experiments and to compare between the results of the triboindenter and tribo-rheometer with surface force apparatus (SFA), leading to the validation of the triboindenter accuracy.

Even though, modelling is believed to be cost and time effective; it may turn out to be extremely complicated and/or lacking satisfactory accuracy; therefore, the complexity of the developed solution altogether with its validity must be simultaneously considered for the realization of the aim without overshooting.

1.5 Problem Definition and suggested solution

Within the automotive field, there is a need to develop a user-friendly approach that predicts the state of oil given different combinations of causal parameters, under a set of constraining operating conditions. To realise that aim, samples are taken from engines that comply with the conditions under consideration; then the relevant characteristics of the oil samples are measured with regards to the causal parameters that entail its degradation. The results are fed into a programed prediction tool to be trained through a Matlab Simulink program which relies on ANN and Fuzzy-Logic. Next, the trained model undergoes testing and validation, and consequently becomes able to predict the optimum oil change interval for new cases with different causal parameters; given that they operate at near-similar same conditions. The developed model can be re-fed with new data from samples that functioned in any set of operation conditions making it a universal tool for the solution of the problem.

2 THE APPROACH

The suggested approach starts with two steps:

1- To define the relevant parameters which describe the quality state of oil.
2- To define the relevant causal parameters that entail oil degradation.

2.1 The relevant parameters that describe the quality state of oil

Given a thorough study of the field; the following list is identified; and for each one, the corresponding test methods are recited:
1- **Viscosity**: describes the viscosity of oil at two temperatures 40° C and 100° C; it may be by using mechanical or electrical instruments like U-tube, falling sphere, falling ball, falling piston, oscillating piston, vibration, rotational, electromagnetically spinning sphere (EMS), stabinger, rectangular-slit and capillary tube.
2- **Acidity** level also called base number: describes the acidity of oil (Its PH); it may be measured by using chemical solutions or through electronic instruments.
3- **Chemical composition**: The foreign chemical elements and compounds that exist in the oil; may be identified by the Fourier transform infrared spectroscopy test (FTIR).

4- **Metallic content**: the concentration of metal contaminations in oil, may be detected by the Elemental Analysis Test using a rotating disc electrode test (RDE) or inductively coupled plasma test (ICP).
5- **Carbon content**: (FTIR) is believed to be the most efficient way of particles detection in oils. It measures the number of particles of each contaminant by using an infrared ray with a pre-determined specific wave length.
Water content: The moisture analysis describes the water concentrations in its three phases within the oil; it may be measured by Karl Fisher titration test or the crackle test.
7- **Overall oil cleanliness**: The Particles count describes the cleanliness of the lubricant by optical microscopy test, automatic optical particle counting test or pore blockage particle counting test.

2.2 The Relevant Causal Parameters that Entail Oil Degradation

While maintaining the same working conditions for the whole population, the relevant characteristics of oil goodness are measured in all oil samples, given the believed-to-be the most significant parameters that contribute to oil degradation, namely: Overall engine oldness in kilometer and Oil lifespan, both in kilometer.

2.3 The Oil State Assessment Tool

The first stage of modelling consists of an Artificial Neural Network which predicts the oil characteristics based on the input parameters, namely the engine oldness and the oil lifespan, under the given operating conditions. The output of this stage is the computed characteristics of the oil, specifically its: 1- Viscosity at 40° C. 2- Viscosity at 100° C. 3- PH. 4-Cleanliness code for4μm. 5- Cleanliness code for 14μm.
The second stage is a Fuzzy logic that considers the five outputs of the first stage and processes them through a set of rules, calculates an overall degradation coefficient. The rules that are embedded in the second stage are:

- The PH of the oil must remain between 4 to 9 [23].
- The variation of viscosity at any of the nominal temperatures must not exceed 10% from the reference value according to ISO 3448.
- As per the Renard code which is also the ISO4407 cleanliness code; the two digits separated by a slash represent a coded figure that reflects the amount of existent particles which surpass in size 4μm and 14μm respectively. If the cleanliness code reaches 23/20 then the oil is faulty in terms of cleanliness [24].

Figure 1 shows flow chart that describes the logic of the prediction tool as per the following blocks:

1- X1: the input of the first stage is a two parameters vector namely: engine oldness and oil lifespan.
2- Neural Network Function: The processing of the trained and validated Neural Network.
3- Y1, the output of the first stage being a five values vector namely:

- PH: Potential of Hydrogen also known as acidity or basicity level of the lubrication oil.
- Vis40: Viscosity of oil at 40° C.
- Vis100: Viscosity of oil at 100° C.
- CCode1: Cleanliness code of contaminates over the size of 4 μm.
- CCode2: Cleanliness code of contaminates over the size of 14 μm.

4- The Demux function: splits the output of the first stage from one vector of five parameters to five single vectors therefore allows their individual processing.
5- Mux: multiplexes the values of the oils characteristics again into one vector of five parameters becoming the input of the second stage of the system.
6- The Fuzzy logic controller: processes the second stage linking the output of the first stage to the result which appears in the form of a coefficient between 0 and 1.
7- Coefficient Display: shows the coefficient of goodness of the oil.

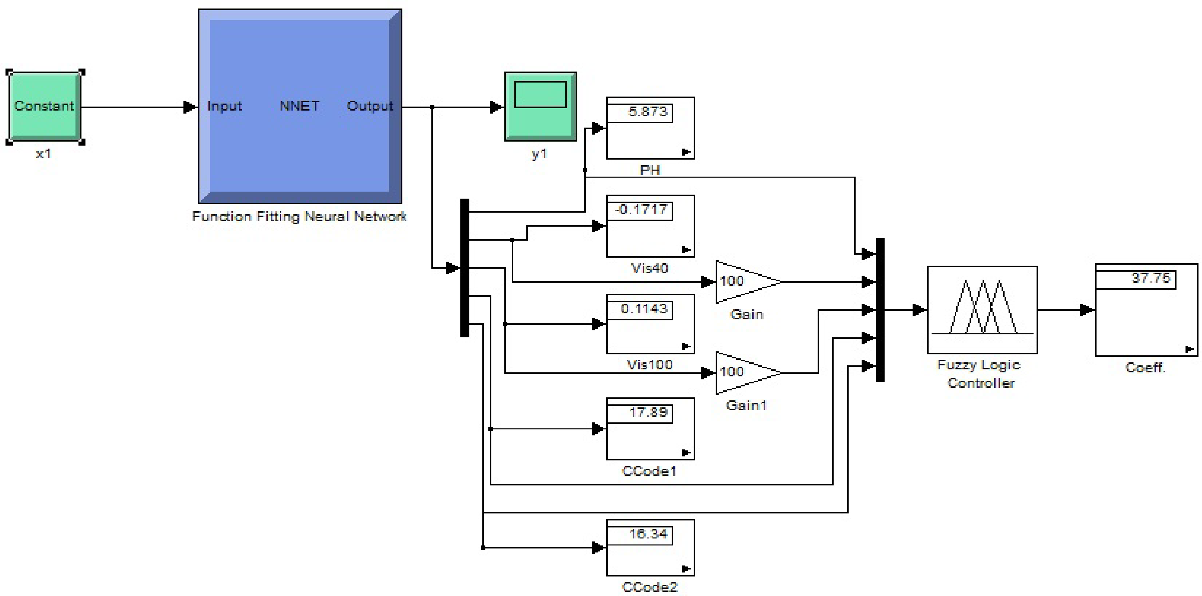

Figure 1. The logic block diagram of the prediction

The neural network builds embedded relations between inputs and outputs through its training with tested samples. Neural Networks are called black boxes for they do not exhibit the relations that they built between the input variables and the fed-in outputs.
Fuzzy logic in the second stage relates inputs and outputs via programed rules given membership functions. Set rules connect the inputs to a degree of membership to the outputs; therefore, a resultant output is calculated. The final output is a single logic value that belongs to the group [Oil is new, remaining useful life, Degraded].

3 TESTS AND MEASUREMENTS

For the training the above described expert system, a system of constraints is set for the collection of 84 oil samples that vary only within the relevant causal parameters namely:

1- The overall engine age in Kilometers
2- The oil lifespan in Kilometers.

The prediction tool software is programmed on Matlab/Simulink. the measured values are fed to the software for training, testing and validation with regard to the neural network and the fuzzy-logic.

3.1 Results

The results of the relevant parameters are tabulated plotted and studied, these are

- Acidity level
- Oil viscosity at 40° C
- Oil viscosity at 100° C
- Particle count as per Renard's series table (Cleanliness code)

It is inferred that:
Engines that are nearly new, e.g. of 1000 KM mileage, had a severe oil viscosity failure at 40℃ and a marginal one at 100℃. Otherwise the general trend of data suggests that over the useful lifetime of engines, viscosity failures at both temperatures occur after 9000Km.
The particle-count test results of all sample involve 2 cases of cleanliness failure, these are usually attributed to engines with high wear out which is a common result of long life.

3.2 VALIDATION AND VERIFICATION OF THE RESULTS:

70 % of the data was fed into the developed model for training. The remaining 30% was divided equally into 2 groups: one for testing and the other for validation. Results of the validation tests could not be included in this paper because of limitation of size, but the overall conclusion confirms the validity of the model.

4 DISCUSSION:

For this work to be widely implemented and to accommodate different types of applications; it is recommended to use more developed measurement techniques of oil samples characteristics. These are costly in modelling but the extra accuracy will pay back in application. For instance, (FTIR) will help identify the cause of failure in viscosity and in particles contamination, given that, viscosity

deteriorates according to degraded viscosity index improvers, oil oxidation, fuel influence and solvent contamination; all being detectable by FTIR.
Moreover, the following tests are suggested for improved accuracy:

- Viscosity; at temperatures, 40° C and 100° C, through (EMS).
- PH level; through, a developed electrical instrument, such as 780 PH Meter by Metrohm Co.
- Cleanliness; through the Pore Blockage Particle Counting Technique.

The model may be expanded to include more engines, vehicle types, road conditions, environmental conditions and fuel types. Furthermore, the prediction tool can be programed with a different logic that reflects the interest of the user.

5 CONCLUSION

Within the scope of the study and the domain of the collected samples it is concluded that:
The acidity level of oil does not reach a failure point; this may be because of the advanced antioxidant additives.
The lubrication oils in new vehicles fail with respect to viscosity and/or particles content after one thousand kilometers of function. For that reason, the manufacturer recommends the first oil replacement after 1000 kilometers, even though its visual inspection appears to be perfect.
The average optimum oil change interval under the constraining working conditions of the study is 9000 km and the earliest parametrical failure is found to be in viscosity at both temperatures, 40° C and 100° C. In that respect it is highlighted that one of the important findings of this study is that, a substantial deterioration will occur in viscosity before any other potential failure aspect. This entails that, a simple and cheap viscosity test is enough to condition monitor the oil.
With respect to oil filters and based on the particles content; it is deduced that the filters never failed before the oil within the samples collected from engines oldness below 150 000 KM. Having said so; it is also important to mention that the price of the filter is minute if compared to the price of the oil and negligible with respect to the potential harm of the engine; therefore, the change of the filter with the oil is not considered a waste of resources. Also; the function of the filter is crucial in preventing harmful particles from reaching the critical surfaces of the engines. At the event of filter failure; the consequences are catastrophic. It is therefore recommended to change the oil filter with the oil, irrespective of its condition since an extra caution in preventive maintenance is welcomed when its financial burden is trivial.

REFERENCES

[1] Y. Wen, J. Wu, D. Das and T.-L. Tseng, "Degradation modeling and RUL prediction using Wiener process subject to multiple change points and unit heterogeneity," Reliability Engineering and System Safety, pp. 113-124, 2018.
[2] V. David, Z. Libor, P. Ondrej and L. Petr, "Perspective analysis outcomes of selected tribodiagnostic data," Reliabiliity Engineering and System Safety, pp. 231-242, 2016.
[3] J. Khalil, S. Saad and N. Gindy, "A Cost Optimisation Decision Support Model for Preventive and Corrective Maintenance Actions," in Flexible Automation and Intelligent Manufacturing (FAIM), 2003.
[4] B. De Jonge, R. Teunter and T. Tinga, "The influence of practical factors on the benefits of condition-based maintenance over time-based maintenance," Reliability Engineering and System Safety, pp. 21-30, 2017.
[5] H. Rashid, C. Place, D. Mba, R. Keong, A. Healey, W. Kleine-Beek and M. Romano, "Reliability model for helicopter main gearbox lubrication system using influence diagrams," Reliability Engineering and System Safety, pp. 50-57, 2015.
[6] J. Andrews and C. Fecarotti, "System design and maintenance modelling for safety in extended life," Reliability Engineering and System Safety, pp. 95-108, 2017.
[7] B. Fitch, "Anatomy of an Oil Analysis Report," Noria, 2013.
[8] E. Y. Su, "Design of and Initial Results from an Instrument for In Situ Tribological Measurements of Lubricant Degradation with Ultraviolet Raman Microscopy," 2011.
[9] B. Lotfizadeh Dehkordi, "Rheology and Tribology of Lubricants with Polymeric Viscosity Modifiers," ProQuest LLC., 2015.
[10] O. A. Adeniran, "Role of Engine Age and Lubricant Chemistry on The Characteristics of EGR soot," ProQuest LLC, Texas, 2013.
[11] M. Dam, "Heavy-Duty Diesel Engine Oil Aging Effects on Emissions," ProQuest LLC., 2010.
[12] M. E. G. Bermudes, "Study on the Neutralization Mechanism of Overbased Detergetns and their Formulates," ProQuest LLC, 2013.
[13] X. L. Wang, G. N. Zhang, J. Y. Zhang, Y. L. Yin and Y. Xu, "Failure Analysis and Regeneration Performances Evaluation on Engine Lubricating Oil," Physics Procedia, no. 50, pp. 473-479, 2013.
[14] A. R. Ruddy, "Development of Multiple Analytical Techniques for the Characterization of Degraded Engine Oil," ProQuest, 2013.
[15] G. Pereira, "Nanoscale Characterization of Antiwear Films Relevant to Automobile Lubrication," ProQuest, London, Ontario, 2006.
[16] R. Mourhatch, "Tribological and Antiwear Mechanisms of Fluorinated Zinc Dialkyl Dithiophosphate in Comparison to Zinc Dialkyl Dithiophosphate in Engine Oils," ProQuest, 2008.
[17] A. Somayaji, "A Study of the Antiwear Behavior and Oxidation Stability of Fluorinated Zinc Dialkyl Dithio Phosphate in the Presence of Antioxidants," ProQuest, 2008.
[18] X. FU, "Enhanced Oil Recovery of Viscous oil by Injection of Water-in-Oil Emulsion Made With Used Engine Oil," ProQuest LLC., Texas, 2012.
[19] M. L. Basinger, "Plant Oil Fueled MFPs as a Development Mechanism:Engine Modification Kit Design, Endurance Testing, and Agroforestry Crop Adoption Implications," ProQuest LLC, 2010.
[20] C. Laukiavich, "The Fluid-Solid Interction and Thermoelastic Behavior (With Rotordynamic Considerations) of The "Oil Transfer Sleeve" in a Turboprop Engine: A Numerical and Experimental Investigation," ProQuest LLC, 2015.
[21] N. C. Stenz, "Finite Element Model of Wear for a Cup-on-Disk Sliding Contact," 2008.
[22] A. Srivastava, "Dynamic Friction Measurement and Modeling at the Micro/Nano Scale," 2006.
[23] P. G. Ball, "New pH Test Offers Benefits over TAN/TBN," Practicing Oil Analysis, 1998.
[24] Noria, "Why You Should Sample and Test New Oil," 2013. [Online]. Available: https://www.machinerylubrication.com/Read/29525/sample-new-oil. [Accessed 2018].