

MODELING THE DEGRADATION OF VISCOSITY OF ENGINE OILS WITH A STOCHASTIC METHOD

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ABSTRACT. *In this paper, we present an analytical study to describe the monitoring and change in the condition of viscosity of lubricating oil used in combustion engines, and exploited under very severe conditions. The objective is to determine the remaining lifetime of this oil. Stochastic methods in general are statistical methods that can be employed in predictive analysis, and they highly depend on probability theory. Markov models in particular, make it possible to predict the degradation of the oil viscosity after a determined operating time. In these, degradation can be described by transition probabilities from one state to another. Knowing that Markov models are used to describe the transition probability to a new state (i) at time (t) based directly on probability of the previous state (j) at time ($t-1$). In this context, we propose a Markov model to study the degradation law for the SAE 40 oil. The latter is designed for the lubrication of locomotives engines under the working conditions of a steel plant in Algeria. We have demonstrated that the proposed model gives detailed results describing the different conditions/states of the analyzed oil.*

Keywords: Lubrication, Engine oil, Viscosity, Service time, Markov chain

1. Introduction. Lubrication is generally an important operation for maintaining moving parts in good condition. Combustion engines are machines in which the lubrication of the various components requires daily monitoring.

The quality of the lubricating oil used in engines plays a crucial role in lengthening the engine's lifetime and improving its performance [1,2].

Viscosity is one of the major physicochemical factors determining the quality and efficiency of a lubricant [3,4]; it provides the basic function for creating an effective film between mechanical surfaces moving relative to one another to prevent severe wear and engine failure [5-7].

Markov chain is a powerful mathematical tool that is extensively used to capture the stochastic process of transitioning systems among different states, where the past has no influence on the future if the present is known.

The viscosity of motors oils goes through the following states: good, acceptable, degraded, and highly degraded. Hence, we propose to associate a Markov chain describing the transition of viscosity from one state (i) to another (j) for each studied oil.

Markov chains have also been applied to other problems that are similar in nature but in different areas such as the bearings [8], students behavior [9], forecasting a stores credit plan [10], and preventive maintenance [11], reliability of system design [12].

This article aims to model the change of viscosity state of the lubricating oil using a Markov model, which allows us to follow the degradation of the quality of the oil by calculating the probability so that the viscosity will be degraded throughout its lifetime on one side and give an estimate of the remaining life on the other side.

The paper is organized as follows. Section 2 presents the engine type, the lubricating oil and the viscosity measuring method. Section 3 gives a brief introduction of Markov chain, as well as the mathematical formulation of the model. Results and discussion are presented in Section 4. Section 5 concludes the paper.

2. Material and Methods. The experimental study was carried out on nine engines of “POYAUD-DIESEL” type. The latter equip rail locomotives operating inside the steel plant under severe conditions. After a very specific operating time, oil samples were taken from the target engines to perform viscosity analysis. Then, a stochastic study was conducted using Markov models to estimate the real condition/state of the lubricants.

- The equipment used in our study is a diesel type engine – POYAUD DIESEL – direct injection V-12 cylinder.
- The oil is CHELLIA SAE 40, which is petroleum derivative oil, manufactured by NAFTEC-SONATRACH and recommended for the lubrication of fast and super-charged diesel engines operating under the most severe conditions.
- Viscosity measurement ASTD445: This method specifies a procedure for determining the kinematic viscosity of lubrication by measuring the flow time under gravity through a calibrated glass capillary viscometer [13,14].

Measurements were taken using an AVS 370 (Schott) viscometer at 40°C.

3. Markov Chain. A Markov chain is a sequence of random variables $(X_n, n \in N)$ that allows modeling the dynamic evolution of a random system; X_n represents the state of the system at time n [15].

The probability of moving to the next state depends only on the state that immediately precedes it. Putting this is mathematical probabilistic formula:

$$P_{ij} = P(X_n = j / X_{n-1} = i) \quad (1)$$

For each studied oil, we propose to associate a Markov chain reflecting the change in its viscosity from one condition to another.

The viscosity of engine oils goes through four states: good, acceptable, degraded, and highly degraded.

The graphical model shows the probability of the viscosity moving from one state to another.

From Figure 1, we deduce the transition probability matrix M :

$$M = \begin{bmatrix} P_{aa} & P_{ab} & P_{ac} & P_{ad} \\ P_{ba} & P_{bb} & P_{bc} & P_{bd} \\ P_{ca} & P_{cb} & P_{cc} & P_{cd} \\ P_{da} & P_{db} & P_{dc} & P_{dd} \end{bmatrix} \quad (2)$$

The transition matrix must be a stochastic matrix; a matrix whose entries in each row must add up to exactly 1. This makes sense, since each line represents its own probability distribution [16].

According to Markov model, the probability of change in viscosity condition takes the following form:

$$X_{(n)} = X_{(n-1)}M \quad (3)$$

$X_{(n)}$ is the row matrix that gives the probabilities of the different states of the viscosity at the age class (n) . $X_{(n-1)}$ is the row matrix that gives the probabilities of the different states of the viscosity at age class $(n - 1)$. M is Markov transition matrix.

Or:

$$X_{(n)} = X_{(0)} M^n \quad (4)$$

$X_{(0)}$ is the row matrix that gives the initials probabilities (starting condition).

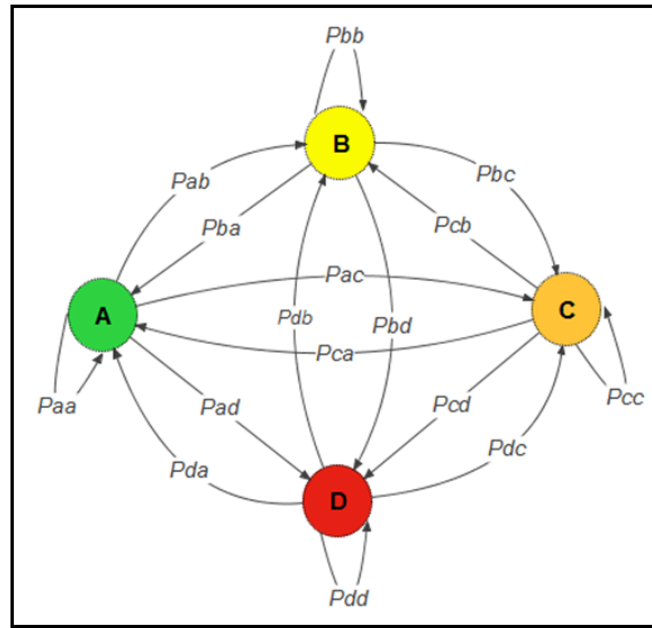


FIGURE 1. Graphical model

4. **Results and Discussion.** The analysis results are shown in the following Table 1.

TABLE 1. The viscosity values obtained from the nine oils after 50 hours of service

Oils N°	1	2	3	4	5	6	7	8	9
η (cSt)	87.65	138.6	139.4	139.5	90.5	138.2	103	137.5	83.6

Analysis of new CHELLIA SAE 40 oil gives a viscosity value of 143.5 cSt (at $t = 0$ h). From Table 1, the viscosity degradation function of each engine oil can be deduced:

$$\eta = a(t) + b \quad (5)$$

The equations are represented in Figure 2.

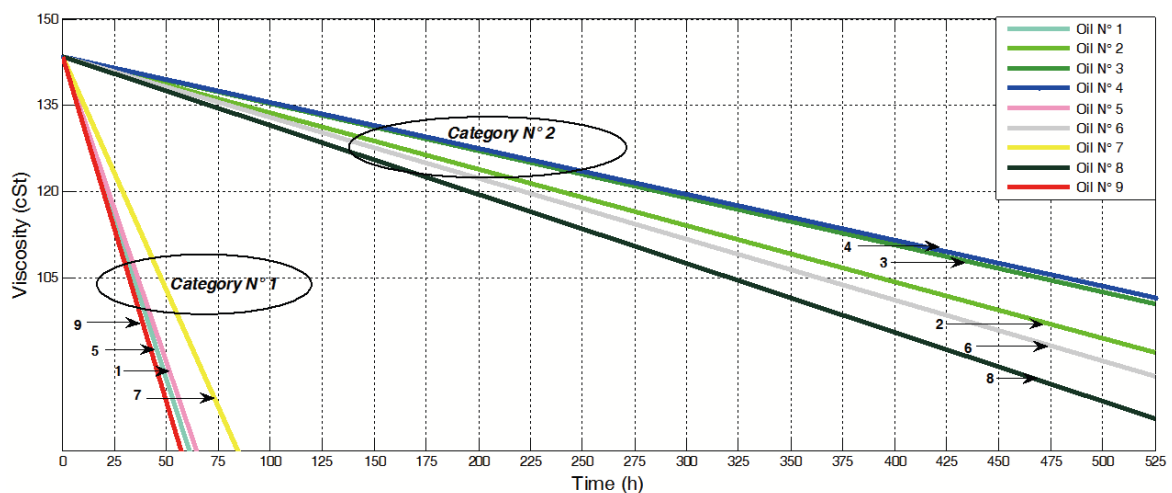


FIGURE 2. The degradation of viscosity of the nine oils engines

As can be observed from Figure 2, there are two (02) categories of viscosity degradation for the studied oil. They are represented as follows:

- The first category corresponds to oils N° 1, 7, 9 and 5.
- The second category corresponds to oils N° 2, 3, 4, 6, 8.

The minimum acceptable viscosity to ensure good lubrication for the studied oil is about 105 cSt. According to the standards, it should be (20-30) percent lower than the viscosity of new oil [17,18].

For the first category, we notice a rapid decrease in viscosity for an operating time not exceeding 100 hours because of the inefficiency of their cooling systems; this situation requires changing the oil of these engines after a very short operating time.

For the second category, we notice that the viscosity of these engines after an operating time of 300 hours is higher than the minimum required viscosity. This shows that these engines are in good working conditions.

During the lifetime of the lubricating oil used, the degradation of the viscosity passed through four states can be cited:

- A: good viscosity: $\eta \geq 130$ (10% lower than the viscosity of a new oil).
- B: acceptable viscosity: $\eta \geq 120$ (20% lower than the viscosity of a new oil).
- C: degraded viscosity: $\eta \geq 105$ (30% lower than the viscosity of a new oil).
- D: highly degraded viscosity: $\eta < 105$ (30% lower than the viscosity of a new oil).

From Figure 2, we can deduce the data shown in Table 2.

TABLE 2. Change of viscosity state of the nine oils every 25 h of operating

Time (h)	Number of oils			
	Good viscosity	Acceptable viscosity	Degraded viscosity	Highly degraded viscosity
0	9	0	0	0
25	5	1	3	0
50	5	0	0	4
75	4	1	0	0
100	2	3	0	0
125	0	5	0	0
150	0	5	0	0
175	0	5	0	0
200	0	4	1	0
225	0	3	2	0
250	0	2	3	0
275	0	2	3	0
300	0	0	5	0
325	0	0	4	1
350	0	0	4	0
375	0	0	3	1
400	0	0	2	1
425	0	0	2	0
450	0	0	2	0
475	0	0	1	1
500	0	0	0	1

From Table 2 we can calculate the transition probabilities for each state change as shown in Figure 3.

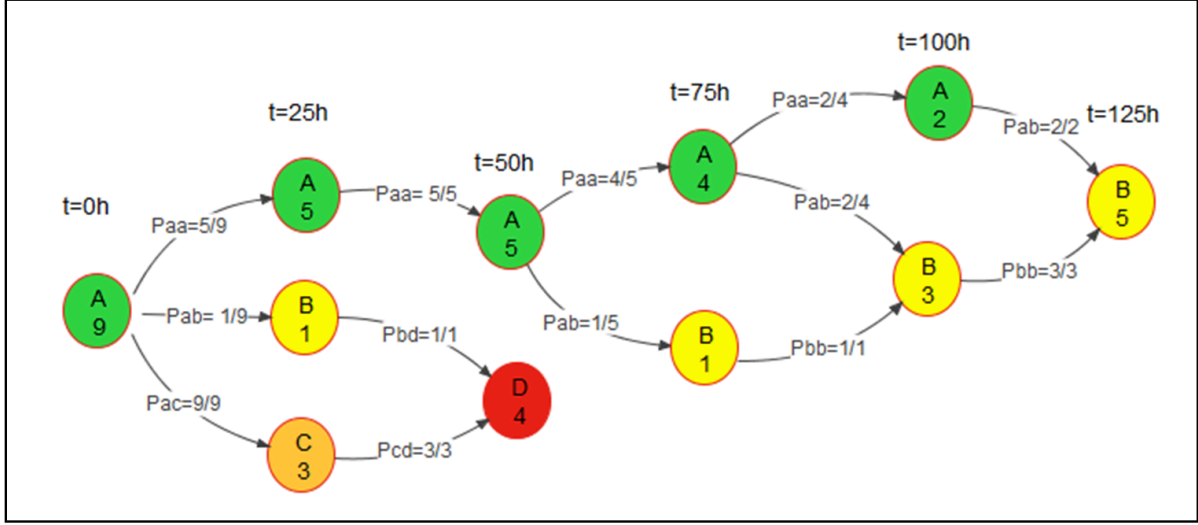


FIGURE 3. Graphical representation of the change in viscosity conditions during 125 h

Hence, we obtain the following transition matrix:

$$M = \begin{bmatrix} 0.57 & 0.361 & 0.069 & 0 \\ 0 & 0.722 & 0.178 & 0.1 \\ 0 & 0 & 0.746 & 0.254 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

After a period of service (represented by a well-defined age class (n)), our model will be given by:

$$X_{(n)} = X_{(0)} M^n$$

$$X_{(n)} = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} 0.57 & 0.361 & 0.069 & 0 \\ 0 & 0.722 & 0.178 & 0.1 \\ 0 & 0 & 0.746 & 0.254 \\ 0 & 0 & 0 & 1 \end{bmatrix}^n$$

Predict the viscosity condition after 50 hours of operation (corresponds to the second age class):

$$X_{(2)} = X_{(0)} M^2 = \begin{bmatrix} 0.325 & 0.466 & 0.155 & 0.05 \end{bmatrix}$$

After the second measurement, there is a 32.5% chance that the viscosity is still in good condition, 46.6% in admissible state, 15.5% degraded and 0.5% in highly degraded state.

And so continue until class age class 32, which corresponds 800 h of operation, we obtain:

$$X_{(32)} = X_{(0)} M^{32} = \begin{bmatrix} 0.0001 & 0.0001 & 0.0001 & 0.999 \end{bmatrix}$$

These powers converge rapidly towards a fixed line matrix, which means that after calculating the 32 power, the matrix does not change much.

After this model, the probabilities of change in viscosity for the oils studied as a function of operating time are illustrated in Figure 4.

From Figure 4, it can be seen that the proposed model yields a good estimate of the probability of viscosity condition change, and a good prediction.

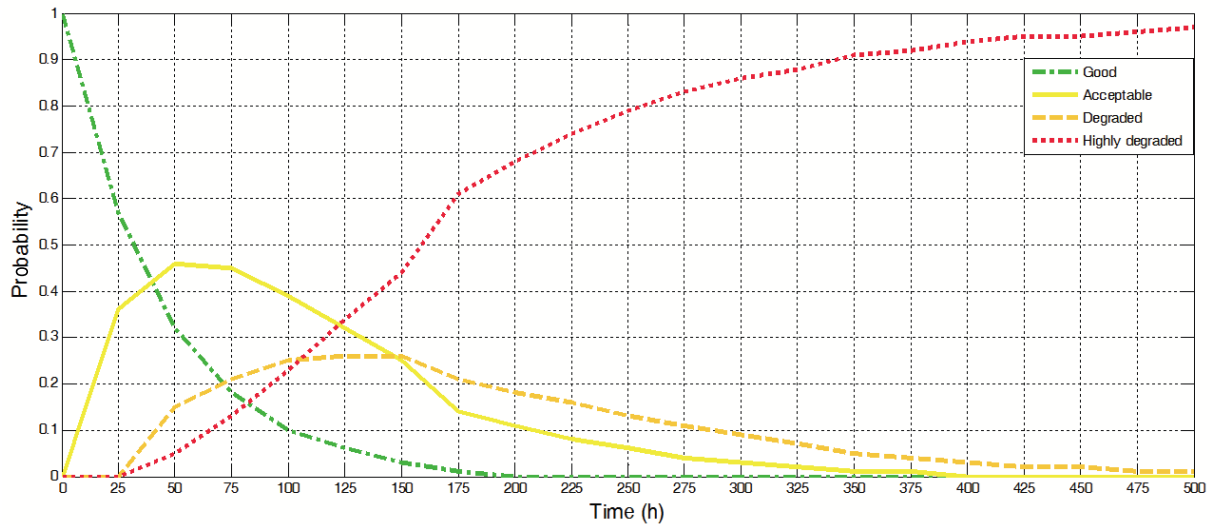


FIGURE 4. Probabilities of different viscosity states according to the proposed model

5. Conclusion. Lubrication is generally an important operation for maintaining moving parts in good condition. Combustion engines are machines in which the lubrication of the various components requires daily monitoring.

Quality lubrication implies maintaining the viscosity of the lubricant used at an acceptable level on one hand and sufficient quantity on the other.

In our work, we proposed a study for the characterization of the viscosity degradation of an oil used for the lubrication of rail locomotives engines operated under the conditions of a steel plant (Algeria).

The Markov model proposed in this study accurately describes the change probabilities of the lubricating oil quality of combustion engines, as it gives an estimate of the state of its viscosity and consequently provides a good prediction of the duration of remaining life. In future work, it is expected to generalize the application of this kind of model to model the evolution of other physical quantities such as the vibration, the wear of such an industrial system.

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