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Analysis of 3516 B Engine Damage on a 793 C Truck Based on Oil Using Laboratory Test Schedule Oil Sampling (SOS) Wear Data with Failure Mode Effect Analysis Method (FMEA)

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Abstract. Engine failure is difficult to predict, especially related to the age of engine components. Analysis of engine failure can be done based on the oil seen from the trend of wear rates, predicting the possibility of components that are damaged in the engine. The method used is a combination of oil analysis in order to determine the component that is damaged and determine the age of the component based on the trend of the element value with the Component Meter Unit (CMU) and implement the Failure Mode and Effect Analysis (FMEA) method to support the analysis by going through the process, identifying potential failure modes, determining the severity, occurrence, detection, calculating the Risk Priority Number (RPN), so as to be able to make suggestions for corrective actions. The result of this analysis is that there is slightly above normal wear on the Cu and Pb elements, where in the last sample the values for Cu 3 and Pb 5 are Particle Per Meter (PPM). CMU predictions are also generated before passing the threshold of the wear limit based on the value of each element. Fe at 17931 hours, Cu at 25963 hours, Pb at 14417 hours and Al at 16927 hours. Wear is indicated from the FMEA analysis, there are 3 with the highest RPN, namely cutting filter result with RPN 280, noise with RPN 175 and scratch with RPN 160. From these Cu and Pb elements it can be determined which components are the source of damage, namely rocker arm bushings, wrist pin bushings, governor drive and bushings, timing gear thrust bearings, turbocharger bearings, camshaft lifter roller pins, air compressor bearings, rear cluster gear bearings and main and rod bearings. From this research, new research data can be developed, namely if there are additional parameters such as oil viscosity value.

Keywords: Schedule Oil Sampling, Lubrication System, Diesel Engine, FMEA

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1. Introduction

The need for availability of heavy equipment is needed in the mining industry. The 793 C truck is used to move mining materials and is one of the heaviest equipment used in mining. Toughness and reliability of the machine is needed to support mining activities. Therefore, all engine components must be maintained and cared for properly [1].

Engine used on the 793 C truck is a 3516 B with 16 cylinders. However, engine problems are difficult to predict, especially related to the age of engine components.

One type of engine maintenance method is the oil analysis method. Oil has an important role in achieving maximum engine capability and service life. Oil analysis is very useful in preventive maintenance systems [2].

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The way to avoid failure is to conduct scheduled oil sampling supported by regular maintenance of the lubricating system and the use of appropriate lubricants[1]. Another method to analyze damage to machines is Failure Mode and Effect Analysis (FMEA) to further identify potential failures and their consequences which aims to detect damage and can avoid unwanted failures [3].

Based on the background of the problem above, the problem that the writer can formulate is the unpredictable damage to the 3516 B engine on the 793 C truck. The purpose of this study was to analyze the damage to the 3516 B engine on the 793 C truck with wear element data from oil analysis and the FMEA method to predict engine damage.

This study uses an oil analysis method which has the advantage that it can see the condition of the oil which is an indication of the health of the oil and can see which component parts are damaged and can see the threshold value of each wear element based on the Component Meter Unit (CMU). Next, analyze the damage using the Failure Mode and Effect Analysis (FMEA) method where every possible failure that occurs is quantified to make handling priorities.

There are references to previous research used to make it easier to arrange systematic steps in the research that is being taken both theoretically and conceptually. Previous research is research that has been carried out previously by other parties that are in line with the research theme being taken. An example of previous research is forecasting the use of oil usage hours with iron (Fe) deposits. Where the method used is the oil analysis method which is able to predict the remaining life of the components by taking into account the amount of oil iron residue in the oil in the engine final drive [7].

2. Methodology

The steps in the process of analyzing the 3516 B engine damage on the 793 C Truck are:

2.1 Preparation (Literature Study)

Collecting data contained in the guidelines or literature related to the material analyzed in the discussion of this report, such as the wear limit with Particle Per Meter (PPM) units in Table 1 [4].

Table 1. Wear Limit Engine 3516 B

Element	Normal	Slightly Above Normal	Above Normal
Fe	0-26	27-33	34
Cu	0-2	3-4	5
Pb	0-3	4-5	6
Cr	0	1	7
Al	0-3	4-5	6

2.2 Data Collection and Management

Data collection is obtained from laboratory test data using an Inductively Coupled Plasma (ICP) tool which will take several samples of 3516 B engine oil on a 793 C Truck with a time span according to the oil checking interval to be used as a trend to see the level of wear of each element. Laboratory tests start from the labeling of the oil until the results of the element values are obtained. The data taken are element values with Particle Per Meter (PPM), Component Meter Unit (CMU), Fluid Hour and sample date units. In this study, researchers have obtained data from 22 samples of 3516 B 793 C engine oil as shown in Table 2.

Table 2. 3516 B Engine Oil Sample on 793 C Truck

No	Sample Date	CMU (hours)	Fluid Hour (o'clock)	Fe	Cu	Pb	Cr	Al
1	21-Oct-21	12903	498	24	3	5	0	4
2	19-Sep-21	12405	477	22	3	4	0	4
3	15-Aug-21	11928	482	23	3	5	0	4
4	11-Jul-21	11446	574	22	3	5	0	4
5	13-Jun-21	10872	552	22	3	4	0	4
6	16-May-21	10320	526	21	3	4	0	4

7	08-Apr-21	9794	540	21	2	4	0	4
8	01-Mar-21	9254	464	20	2	4	0	4
9	30-Dec-20	8790	536	20	2	3	0	4
10	23-Nov-20	8254	619	21	2	4	0	4
11	23-Oct-20	7635	453	18	2	3	0	3
12	30-Sep-20	7182	574	18	2	2	0	3
13	31-Aug-20	6608	542	17	2	2	0	3
14	04-Aug-20	6066	590	18	2	1	0	3
15	08-Jul-20	5476	501	16	2	1	0	2
16	10-Jun-20	4975	520	15	2	1	0	2
17	13-May-20	4455	529	15	2	1	0	2
18	14-Apr-20	3926	149	8	2	1	0	1
19	07-Apr-20	3777	348	11	2	1	0	2
20	19-Mar-20	3429	508	11	2	1	0	2
21	20-Feb-20	2921	557	8	2	1	0	1
22	22-Jan-20	2364	509	3	0	0	0	1

From the data, graphs are made to see the trend of the values of each element, on the graph it can be seen that the wear trend increases with the increase in CMU. Where the y-axis is the element value in Particle Per Meter (PPM) and the x-axis is the Component Meter Unit in hours.

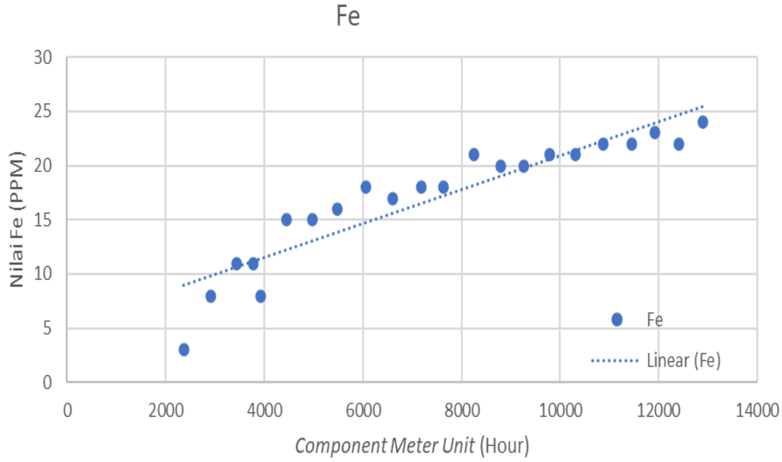

Figure 1. Elemental Fe value to CMU

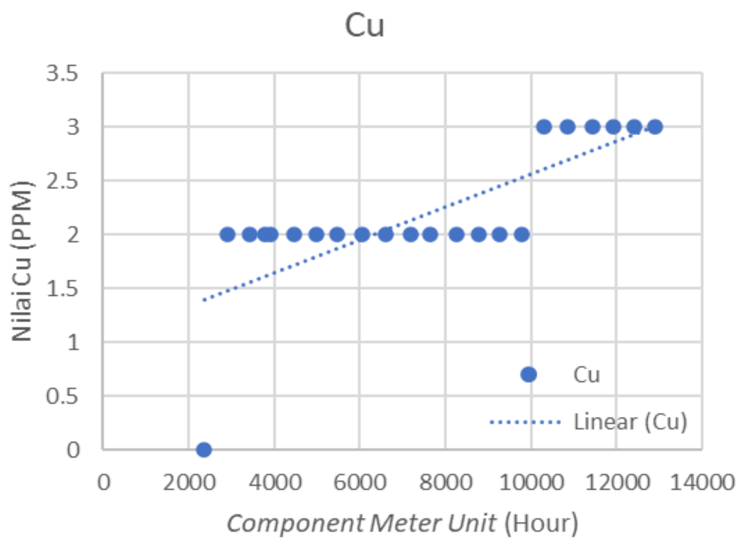

Figure 2. Element value of Cu to CMU

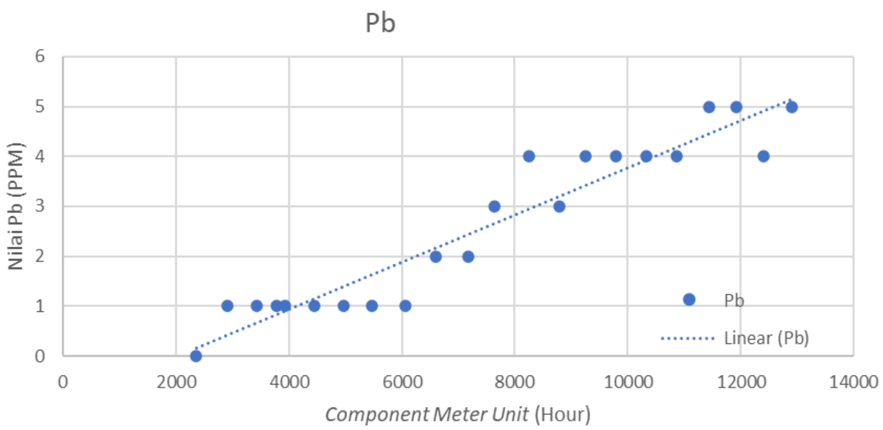

Figure 3. Elemental Value of Pb to CMU

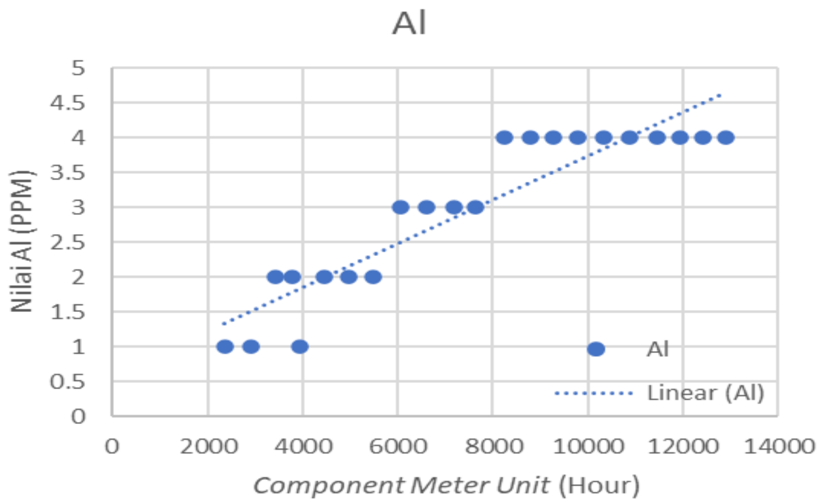

Figure 4. Value of Element Al to CMU

From these data, it can be seen the rate of wear of each element. Then it can determine which elements are experiencing wear with a tendency to increase above the threshold. The following sources of element wear can be seen in Table 3 [4].

Table 3. Source of Elemental Wear

Element	Element Source
Copper(Cu)	Rocker arm bushings, wrist pin bushing, governor drive and bushings, timing gear thrust bearing, turbocharger bearing, camshaft lifter roller pin, air compressor bearing, gear bearing,
Iron(Fe)	Crankshaft, camshaft, valve, valve seat, guides and push rod, cylinder linear timing gear, oil pump shaft, gears and body air compressor
Chromium(Cr)	Piston rings
Lead(Pb)	Main and rod bearing
aluminum(Al)	Main and rod bearing, timing gear bushing, piston, camshaft bearing, oil pump bushing

2.3 Preparation (Literature Study)

Data Analysis

Analyzing the remaining service life of a component, one must know two things, namely information from the factory manufacturer regarding the amount of residual wear of components that exceeds the wear tolerance threshold or in other words the component has been considered damaged and the hours of use of the components that have been used. This is used to determine how many more hours of usage time that can be utilized. To determine exactly when/in what hour the amount of residue exceeds the tolerance threshold, the linear regression method is used. Linear regression are statistical procedures that are often used to predict outcomes. The linear regression equation used can be seen in Equation (1) [5].

$$y = a + bx \tag{1}$$

To find the value of a, you can use the formula in Equation

$$a = \frac{\sum y - b\sum x}{N} \tag{2}$$

To find the value of a can use the formula in Equation

$$b = \frac{N\sum xy - \sum x\sum y}{N\sum x^2 - (\sum x)^2} \tag{3}$$

y = the predicted value/independent variable
a = the trend value in the base period
b = the level of development of the predicted value
x = a unit of year calculated from the base period/independent variable.

In addition to calculating the linear regression equation, it is also necessary to calculate the correlation coefficient to determine the level of relationship that may exist between two variables. The correlation coefficient formula is seen in Equation (4) [5].

$$r = \frac{N(\sum xy) - (\sum x\sum y)}{\sqrt{N(\sum x^2) - (\sum x)^2} \times \sqrt{N(\sum y^2) - (\sum y)^2}} \tag{4}$$

The results of the correlation are compared with the level of the correlation coefficient. The level of correlation coefficient in Table 4

Table 4. Correlation Coefficient Level

Correlation Coefficient Level	Category
0.00 – 0.199	Very low
0.20 – 0.399	Low
0.40 – 0.599	Currently
0.60 – 0.799	Strong
0.80 – 1,000	Very strong

2.4 Preparation (Literature Study)

Identification with FMEA

Failure Mode And Effect Analysis (FMEA) is a method to identify and analyze potential failures and their consequences in order to plan maintenance procedures appropriately to avoid unexpected breakdowns and losses [6].

A. Conducting a Process Review

A review of maintenance procedures should be carried out to identify any abnormalities. Data collection and processing is the initial step to identify the most important factors contributing to the breakdown, followed by data analysis to find correlations.

B. Identify Potential Failure Mode and Make a List of Potential Effects

After knowing the highest element as a contributor to damage to the machine. Furthermore, using the machine profile reference from the factory, it can be seen from which components contain these high elements. So that it can be known the potential failure and potential effects that will occur.

C. Determining Rank Severity

Severity ratingis the level of failure that will have an impact in the form of disturbances to the entire system.

D. Determining Rank Occurence
Occurrence ratingshows the probability of determining the nominal value based on the estimated number of frequencies or the cumulative number of times failures occur due to certain causes.

E. Determining Rank Detection
Determining the detection level is selecting a process control that will specifically detect the root cause of the failure. Detection is a measurement to control failures that can occur.

F. Calculating Value Risk Priority Number (RPN)
Calculates the value of each RPN where RPN is the result of the multiplication of severity (S). occurrence (O), and detection (D), which can be expressed as Equation (5),

$$\text{RPN} = \text{S} \times \text{O} \times \text{D} \tag{5}$$

G. Prioritize Failure Mode Based on RPN Value for Corrective Action.
The next step is to sort the RPN values from the largest to the smallest. Then calculate the percentage of RPN and the cumulative percentage of RPN. Based on the calculation of the RPN obtained from each potential effect.

2.5 Determining the Source of Damage Component
In determining the component that is the source of the damage, the component is selected based on the results of data analysis and several reference standards tables which are then compared with component specifications from the engine catalogue (Machine Profile) of various component manufacturers. The source of the damage can be seen based on the elements in each of the respective components.

2.6 Making Action Results Analysis
At this stage the author makes suggestions of actions that must be taken according to the condition of the machine based on the results of the analysis that has previously been carried out.

3. Result and Discussion
This study presents results in the form of analysis of test results from samples and analysis using the FMEA method

3.1 Test Result Analysis
The analysis uses oil test results data to determine the condition of the oil which is called Schedule Oil Sampling (SOS). The purpose of using the SOS oil test results data in this study is to provide information about the many element values contained in the oil. So that it can be predicted about the wear and tear of an equipment and components that experience excessive wear conditions.

Oil data collection has been carried out 22 times for 3516 B engine oil sampling activities on 793 C Trucks with a time span according to the oil check interval at the SOS Laboratory. From the last test sample, namely the Component Meter Unit (CMU) 12903 hours (see data in Table 2), it can be categorized based on the wear limit of the manufacturer as shown in Table 5.

Table 5. Category Each Element

Element	Last Sample Element Value (PPM)	Category
Fe	24	Normal
Cu	3	Slightly Above Normal
Pb	5	Slightly Above Normal
Cr	0	Normal
Al	4	Normal

Elements Fe, Cr and Al are in the Normal category, while Cu and Pb are slightly above normal. There is wear on the components inside the engine that comes from the source of wear of the Cu elements, namely rocker arm bushings, wrist pin bushings, governor drives and bushings, timing gear thrust bearings, turbocharger bearings, camshaft lifter roller pins, air compressor bearings, gear bearings and from the source of wear of Pb elements, namely Main and rod bearings.

Analysis of damage to engine components can be calculated from the CMU and the value of the element sought from the linear regression value using Equation (1) Previously, it was necessary to find the a value, namely the trend value in the base period using the equation (2) and the b value, namely the rate of development of the predicted value by equation (3) and the correlation level test (r) using the equation (4). The following is the calculation data for each element needed to find the linear regression value and the correlation of the tables (Table 6, Table 7, Table 8, Table 9) below:

Table 6. Calculation of Element Fe

No	Sample Date	CMU as x(Hour)	Element Value of Fe as (PPM)y	x^2	xy	y^2
1	21-Oct-21	12903	24	166487409	309672	576
2	19-Sep-21	12405	22	153884025	272910	484
3	15-Aug-21	11928	23	142277184	274344	529
4	11-Jul-21	11446	22	131010916	251812	484
5	13-Jun-21	10872	22	118200384	239184	484
6	16-May-21	10320	21	106502400	216720	441
7	08-Apr-21	9794	21	95922436	205674	441
8	01-Mar-21	9254	20	85636516	185080	400
9	30-Dec-20	8790	20	77264100	175800	400
10	23-Nov-20	8254	21	68128516	173334	441
11	23-Oct-20	7635	18	58293225	137430	324
12	30-Sep-20	7182	18	51581124	129276	324
13	31-Aug-20	6608	17	43665664	112336	289
14	04-Aug-20	6066	18	36796356	109188	324
15	08-Jul-20	5476	16	29986576	87616	256
16	10-Jun-20	4975	15	24750625	74625	225
17	13-May-20	4455	15	19847025	66825	225
18	14-Apr-20	3926	8	15413476	31408	64
19	07-Apr-20	3777	11	14265729	41547	121
20	19-Mar-20	3429	11	11758041	37719	121
21	20-Feb-20	2921	8	8532241	23368	64
22	22-Jan-20	2364	3	5588496	7092	9
	Total	164780	374	1465792464	3162960	7026

Table 7. Cu Element Calculation

No	Sample Date	CMU as x(Hour)	Elemental Value of Cu as (PPM)y	x^2	xy	y^2
1	21-Oct-21	12903	3	166487409	38709	9
2	19-Sep-21	12405	3	153884025	37215	9
3	15-Aug-21	11928	3	142277184	35784	9
4	11-Jul-21	11446	3	131010916	34338	9
5	13-Jun-21	10872	3	118200384	32616	9
6	16-May-21	10320	3	106502400	30960	9

7	08-Apr-21	9794	2	95922436	19588	4
8	01-Mar-21	9254	2	85636516	18508	4
9	30-Dec-20	8790	2	77264100	17580	4
10	23-Nov-20	8254	2	68128516	16508	4
11	23-Oct-20	7635	2	58293225	15270	4
12	30-Sep-20	7182	2	51581124	14364	4
13	31-Aug-20	6608	2	43665664	13216	4
14	04-Aug-20	6066	2	36796356	12132	4
15	08-Jul-20	5476	2	29986576	10952	4
16	10-Jun-20	4975	2	24750625	9950	4
17	13-May-20	4455	2	19847025	8910	4
18	14-Apr-20	3926	2	15413476	7852	4
19	07-Apr-20	3777	2	14265729	7554	4
20	19-Mar-20	3429	2	11758041	6858	4
21	20-Feb-20	2921	2	8532241	5842	4
22	22-Jan-20	2364	0	5588496	0	0
	Total	164780	48	1465792464	394706	114

Table 8. Elemental Calculation of Pb

No	Sample Date	CMU as x(Hour)	Element Value of Pb as (PPM)y	x^2	xy	y^2
1	21-Oct-21	12903	5	166487409	64515	25
2	19-Sep-21	12405	4	153884025	49620	16
3	15-Aug-21	11928	5	142277184	59640	25
4	11-Jul-21	11446	5	131010916	57230	25
5	13-Jun-21	10872	4	118200384	43488	16
6	16-May-21	10320	4	106502400	41280	16
7	08-Apr-21	9794	4	95922436	39176	16
8	01-Mar-21	9254	4	85636516	37016	16
9	30-Dec-20	8790	3	77264100	26370	9
10	23-Nov-20	8254	4	68128516	33016	16
11	23-Oct-20	7635	3	58293225	22905	9
12	30-Sep-20	7182	2	51581124	14364	4
13	31-Aug-20	6608	2	43665664	13216	4
14	04-Aug-20	6066	1	36796356	6066	1
15	08-Jul-20	5476	1	29986576	5476	1
16	10-Jun-20	4975	1	24750625	4975	1
17	13-May-20	4455	1	19847025	4455	1
18	14-Apr-20	3926	1	15413476	3926	1
19	07-Apr-20	3777	1	14265729	3777	1
20	19-Mar-20	3429	1	11758041	3429	1
21	20-Feb-20	2921	1	8532241	2921	1
22	22-Jan-20	2364	0	5588496	0	0
	Total	164780	57	1465792464	536861	205

Table 9. Al Element Calculation

No	Sample Date	CMU as x(Hour)	Elemental Value Al as (PPM)y	x^2	xy	y^2
1	21-Oct-21	12903	4	166487409	51612	16
2	19-Sep-21	12405	4	153884025	49620	16
3	15-Aug-21	11928	4	142277184	47712	16
4	11-Jul-21	11446	4	131010916	45784	16
5	13-Jun-21	10872	4	118200384	43488	16
6	16-May-21	10320	4	106502400	41280	16
7	08-Apr-21	9794	4	95922436	39176	16
8	01-Mar-21	9254	4	85636516	37016	16
9	30-Dec-20	8790	4	77264100	35160	16
10	23-Nov-20	8254	4	68128516	33016	16
11	23-Oct-20	7635	3	58293225	22905	9
12	30-Sep-20	7182	3	51581124	21546	9
13	31-Aug-20	6608	3	43665664	19824	9
14	04-Aug-20	6066	3	36796356	18198	9
15	08-Jul-20	5476	2	29986576	10952	4
16	10-Jun-20	4975	2	24750625	9950	4
17	13-May-20	4455	2	19847025	8910	4
18	14-Apr-20	3926	1	15413476	3926	1
19	07-Apr-20	3777	2	14265729	7554	4
20	19-Mar-20	3429	2	11758041	6858	4
21	20-Feb-20	2921	1	8532241	2921	1
22	22-Jan-20	2364	1	5588496	2364	1
	Total	164780	65	1465792464	559772	219

From the tables above, a total table can be made from the calculation of the test results for each element in Table 10 based on the elements, namely Fe, Cu, Pb and Al elements. The Cr element is not calculated because the Cr element sample does not have a value of (0).

Table 10. Total Calculation of Test Results for Each Element

Element	CMU ($\sum x$)	Element Value($\sum y$)	$\sum x^2$	$\sum xy$	$\sum y^2$	Number of Samples (N)
Fe	164780	374	1465792464	3162960	7026	22
Cu	164780	48	1465792464	394706	114	22
Pb	164780	57	1465792464	536861	205	22
Al	164780	65	1465792464	559772	219	22

From the results of these calculations can determine the correlation level test (r) using the formula Equation (4) for each element seen in Table 11.

Table 11. Correlation Coefficient Level of Each Element

Element	CMU($\sum x$)	r	Correlation Coefficient Level
Fe	164780	0.9196025	Very strong
Cu	164780	0.7592870	Strong
Pb	164780	0.9541438	Very strong
Al	164780	0.9229590	Very strong

The results of the calculation of the correlation coefficient for each element obtained strong and very strong results so that calculations can be continued to predict the damage to each engine component seen from the Component Meter Unit (CMU) based on the element value. To calculate the prediction for each element, the CMU value is added by 502 hours. 502 hours is the average value of fluid hours on oil samples. The first prediction of the CMU is the final CMU value of the sample plus 502 hours and continues to be added 502 hours for each prediction. Next, calculate the predictions on the sample and CMU to how much the value of each element is close to the tolerance threshold that allows the component to be replaced or repaired.

To make a prediction table on the sample and CMU to what value the Fe element is close to the tolerance threshold that allows the component to be replaced or repaired. Required calculations using linear regression that is looking for the formula Equation (1). The x value in the formula refers to the approximate CMU. It is also necessary to find the value of a using the equation (2) and the value of b using the equation (3) to fulfill the linear equation.

Calculation of the CMU prediction continues until it approaches the tolerance threshold for each element. So the components containing these elements must be immediately examined further regarding replacement or corrective action.

From these calculations, it is possible to predict the life of the component through the CMU prediction which indicates there is further damage that must replace or repair the component based on the Component Meter Unit (CMU) and the value of each element. CMU prediction results can be seen in Table 12.

Table 12. CMU Estimate of Each Element

Element	sample to-	CMU Estimate (Hours)	Estimated Element Value (PPM)
Fe	10	17931	33.306858
Cu	26	25963	4.9884602
Pb	3	14417	5.8790094
Al	8	16927	5.9260214

3.2 FMEA

The 3516 B engine on the 793 C Truck always performs routine maintenance and oil changes. If there is an anomaly on the machine, it is informed as a report from feedback in the form of action taken. The data is processed into a data source for FMEA analysis which has been sorted based on the highest RPN using the formula Equation (5) as seen in Table 13.

RPN Cutting Filter Result = 6 × 9 × 5 = 280
RPN Noise = 5 × 7 × 5 = 175
RPN Scratch = 4 × 8 × 5 = 160
RPN Vibration = 5 × 6 × 5 = 150
RPN Leak = 4 × 6 × 6 = 144

Table 13. FMEA Analysis Results

Potential Failure	Potential Effect	Severity	Occurrence	Detection	RPN
Cutting Filter Result	A large number of particles	6	9	5	270
Noise	Bearing wear, lack of oil, gaps between components	5	7	5	175
Scratch	Wear, large number of particles, fluid hour past the interval	4	8	5	160
vibration	Components that are not tight	5	6	5	150
leak	Insulation is damaged/not tight	4	6	6	144

From the results of FMEA analysis, there are 3 with the highest RPN, namely cutting filter result, noise and scratch.

3.3 Suggested Action Results Analysis

Suggested actions to be taken regarding this anomaly are to immediately check the engine if you hear a loud noise and check the condition of the rocker arm bushing, wrist pin bushing, governor drive and bushings, timing gear thrust bearing, turbocharger bearing, camshaft lifter roller pin, air compressor bearing. , gear bearings and main and rod bearings in the next sample. Take samples after 100 hours and perform a filter cut to monitor the particles in the oil filter.

The results of the prediction of further damage are having to replace or repair components based on theComponent Meter Unit(CMU) and the value of each element can be used as a reference for component replacement and more intensive maintenance. So do not wait for damaged components that can cause damage to other components.

4. Conclusions

Based on the results of the research entitled Engine Damage Analysis 3516 B on 793 C Truck Based on Oil Using Laboratory Test Schedule Oil Sampling (SOS) Wear Data with Failure Mode Effect Analysis (FMEA) Method, it can be concluded that the results of the analysis of damage to the 3516 B engine on a 793 C truck with wear element data obtained slightly above normal wear on the Cu and Pb elements based onwear limitwhere in the last sample the values of Cu 3 and Pb 5 are Particle Per Meter (PPM). By using linear regression calculations and correlation tests, predictions can also be madeComponent Meter Unit(CMU) before crossing the threshold of the wear limit based on the value of each element. Fe at 17931 hours, Cu at 25963 hours, Pb at 14417 hours and Al at 16927 hours. Every possible failure that occurs is quantified for priority handling. Wear is indicated from the FMEA analysis, there are 3 with the highest RPN, namelycutting filter resultwith RPN 280, noise with RPN 175 and scratch with RPN 160. From the Cu and Pb elements it can be determined which components are the source of damage based onmachine profilefrom manufacturers, namely rocker arm bushings, wrist pin bushings, governor drives and bushings, timing gear thrust bearings, turbocharger bearings, camshaft lifter roller pins, air compressor bearings, rear cluster gear bearings as well as main and rod bearings.

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