Development of Engine Oil Deterioration Monitoring System

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ABSTRACT

An oil deterioration monitoring system has been developed to more accurately judge oil change intervals. The system calculates oil life using an oil deterioration algorithm. When the oil deterioration variable reaches a predetermined value, the oil change meter recommends an oil change. The algorithm first estimates oil temperature, which is a parameter of the oil deterioration factor. Then the factor and engine speed are used to calculate how much of the oil's service life has been used. The oil deterioration factor is dependent on oil temperature. It was calculated from oil life test results gathered from endurance tests where oil temperature was varied. A market survey was conducted to verify the applicability of the measures to a variety of driving modes. These results were correlated in calculations of oil life. It has been demonstrated that this system is successful in enabling U.S. users to change their oil at more appropriate intervals.

1. Introduction

Engine oil serves to protect the engine by lubricating, cleaning, sealing, and cooling, and helps prevent rusting and corrosion. The efficacy of these oil functions is reduced as the vehicle is driven, eventually requiring that the oil be replaced. Changing the oil sooner rather than later helps prevent engine damage. On the other hand, longer intervals between oil changes are desired to preserve the environment by conserving oil resources, and lowering vehicle maintenance work.

The deterioration of engine oil and the oil change interval vary according to the engine driving conditions. For example, if the engine is repeatedly driven over short distances and shut off, the oil temperature will not reach a sufficient level to allow the water content to evaporate. This will lead to NOx, nitric, and nitrous acid contamination in the oil from blow-by. This ultimately produces low temperature sludge. Driving at high oil temperatures causes the oil to oxidize, which increases the oil's viscosity and breaks down the component additives. The level of oil deterioration varies according to the history of driving conditions. This makes it difficult for the user to determine the optimal period for changing the oil.

This paper introduces an oil deterioration monitoring system that has been developed to address these issues. The monitoring system displays the oil change recommendation on a monitor after calculating the oil change interval that is dependent on the vehicle's driving conditions.

2. Development Goals

The oil deterioration monitoring system was developed to address the following two goals.

(1) Optimize the distance for which oil replacement is required
(2) Provide a simple monitoring system that does not require a sensor

Figure 1 shows the surveyed results of the number of miles at which drivers in the U.S. change their engine oil and the number of miles that could be traveled if the oil had reached its usable life.

The figure shows survey results gathered by Honda in America during 1999 and the results of a questionnaire

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(n = 7414) conducted over the Internet in 2002 between April 18 and June 27 by USA TODAY. The results from the survey conducted by USA TODAY demonstrate a greater distribution of longer oil change maintenance periods.

Oil replaced by drivers in North America was collected and analyzed. The blue line shows the estimated results of the oil service life distances based on the degree of oil deterioration.

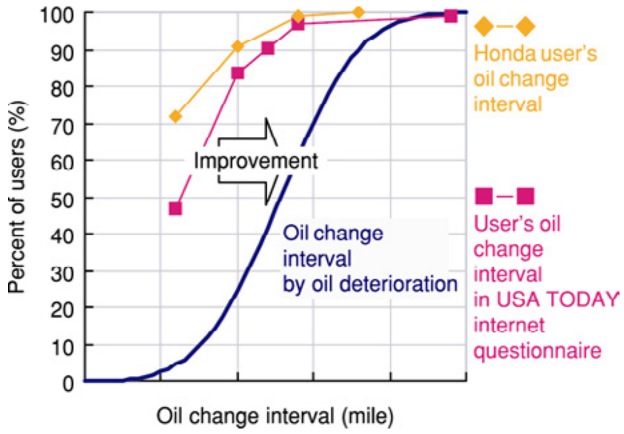


Fig. 1 Oil change interval

It was discovered that the drivers in North America actually changed their oil earlier than required. The oil deterioration monitoring system is required to have a level of effectiveness that could improve the distribution of the user's oil change interval to the maximum potential oil life interval.

Various testing has been conducted to directly detect oil deterioration. Optical sensors evaluate oil deterioration by measuring the degree of pollution in the oil while capacitor type sensors evaluate the degree of oil deterioration by measuring the changes in the oil's dielectric constant. However, neither of these methods is able to distinguish the correlation between these deterioration levels(1). Although changes in the oil's viscosity are an important indicator of its condition, it is difficult to determine the change of oil viscosity associated with the different types of oils(2). Measurement of the neutralization number is an effective means of evaluating the deterioration of the oil additives, consumption, and oxidation of the base oil. At Dayton University, they have developed an in-vehicle technology for measuring these conditions(3). An additional technology was developed that measures nitric ester concentration through infrared spectroscopic analysis(1). However, these methodologies have not been successfully adapted for actual use.

The system introduced in this paper is a simple and practical system that does not use such sensors and encourages drivers to change their oil at optimal periods.

Table 1 lists the oil maintenance systems employed by other car manufacturers.

Table 1 Oil maintenance indication system

Maker	System name	Oil change interval	Method	Model/Year	Note
BENZ	Active service system	Max 30 000km	Algorithm	97M	With oil level sensor
BMW	BMW maintenance system	Max 30 000km	Algorithm	98M	With oil level sensor
AUDI	AUDI variable service	Max 30 000km	Algorithm	00M	With oil level sensor
GM	Oil life system	4 800 ~ 16 000km	Algorithm	98M	

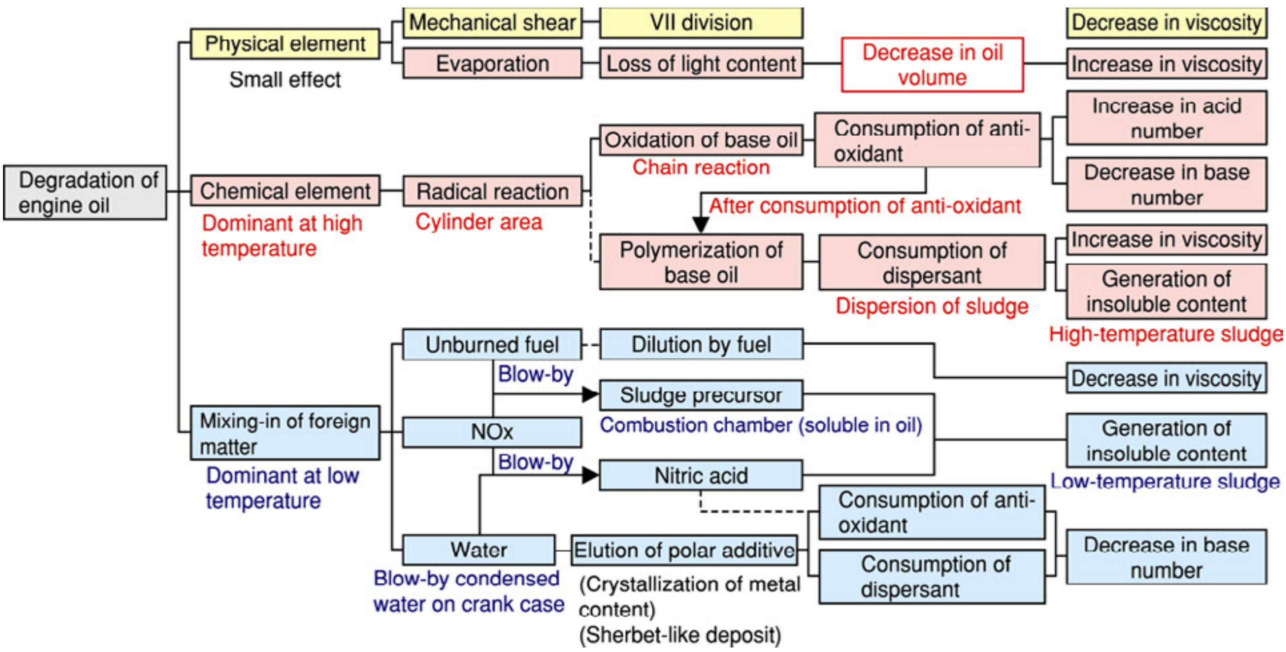


Fig. 2 Mechanism of deterioration of engine oil

3. Causes of Oil Deterioration and Oil Life Estimating Methods

3.1. Causes of Oil Deterioration

Figure 2 shows the causes of engine oil deterioration. Engine oil is made up of base oil and additive components. The following conditions have been identified as causes of engine oil deterioration.

(a) Oxidation, deterioration and evaporation of the base oil component

(b) Functional reduction due to deterioration and consumption of the additive components

(c) Foreign matter contamination

Condition (a) is dominant at high oil temperatures. As the base oil component in the cylinder area oxidizes, the antioxidants are consumed. This is linked to the increase of the acid value and the reduction of the base number. Furthermore, as the antioxidants are consumed, the base oil polymerizes and the dispersant agent is consumed. This leads to increased viscosity and the production of insoluble content. Condition (c) is influenced by contamination from blow-by gas components at low temperatures. The blow-by gas consists of non-combustible fuel, water and NOx. This produces a sludge precursor, nitric acid, and promotes the production of insoluble content and the consumption of the additive components.

A reduction in oil viscosity leads to concerns such as wear in the valve train. An increase in viscosity increases friction and leads to deterioration in fuel consumption and engine startability at low temperatures. Decreases in the base oil number and increases in acid value cause corrosive wear in the bearings from acid ions. The insoluble content then restricts the oil flow, causing various issues due to the lack of oil. The base number, acid value, viscosity level and insoluble component volume are all critical in determining oil life.

3.2. Perspectives on Estimating Oil Deterioration

The deterioration of oil as described in Section 3.1 can be largely explained by fluctuations in the oil temperature. As shown in Fig. 3, deterioration of the engine oil is accelerated as temperatures increase or decrease from the medium temperature of 80 °C[4]. As the oil temperatures increase beyond 80 °C deterioration through oxidation increased. This promotes oxidization of the base oil, deterioration, and consumption of the additive components. As the oil temperatures fall below the 80 °C mark, the oil additives deteriorate from blow-by gas contamination. The oil life curve can be calculated from running durability tests that vary load, trip distance and running temperatures. Using oil temperature measurements as an independent variable and applying it to the oil life curve yields the oil deterioration factor. Oil life is then calculated from the oil deterioration factor. The oil life calculated value has been verified by in vehicle testing.

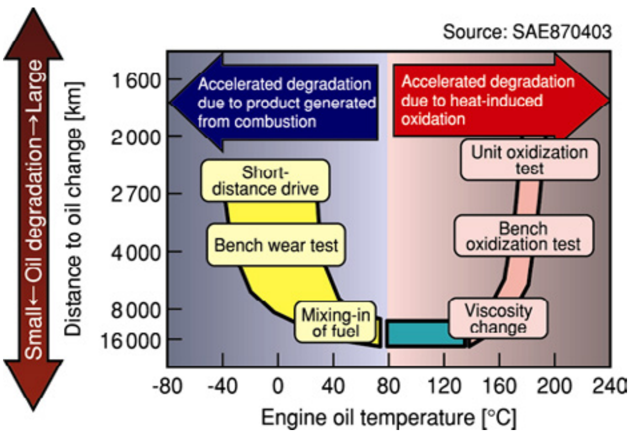


Fig. 3 Effect of oil temperature on engine oil deterioration

4. Engine Oil Deterioration Monitoring System

4.1. Engine Oil Deterioration Monitoring System Configuration Overview

Figure 4 provides a configuration overview of the engine oil deterioration monitoring system.

To estimate the oil temperature, sensors are used to measure the water coolant temperature, engine speed, vehicle speed, intake air temperature, and the intake air pressure. The deterioration factor is then determined according to the estimated oil temperature. The amount of oil deterioration is calculated from the deterioration factor and the engine speed. By resetting the oil deterioration monitoring system each time the oil is changed reinitializes the oil life calculation process. When the oil life falls below the predetermined value setting, the indicator for replacing the oil is displayed on a monitor. The driver is able to verify the oil life all the time through the monitor.

4.2. Engine Oil Deterioration Factor (DF) that is Dependent on Oil Temperature

Based on the perspective described in Section 3.2, the engine oil life curve was obtained according to the oil

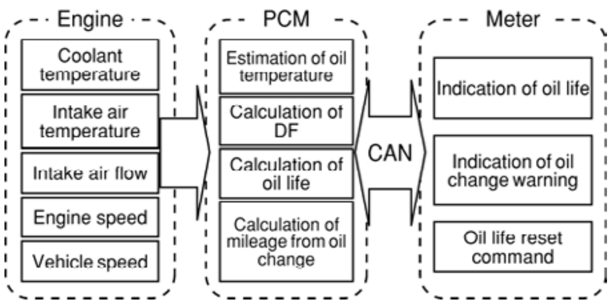


Fig. 4 Oil deterioration monitoring system

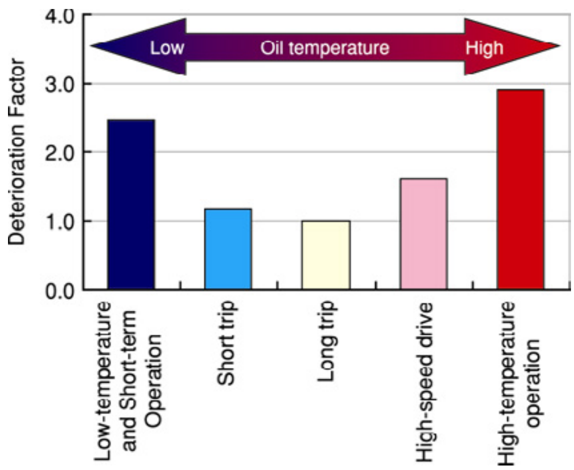


Fig. 5 Deterioration factors for driving conditions

temperature. This was done through endurance testing at different oil temperatures. Figure 5 shows the results of calculations for the deterioration factor, which represents the difference between the current oil life and the longest oil life value obtained from the endurance tests. As described in Section 4.3, the oil life is calculated by the estimated cumulative engine speed and the oil deterioration factor. The factor indicated in Fig. 5 is a ratio of the cumulative engine speed until oil life runs out for each endurance condition. This value is called the DF (deterioration factor) and is represented by using the oil temperature as the working parameter. The results of each of the respective endurance tests shown in Fig. 5 are arranged according to average temperatures thereby creating DF characteristics. To verify DF characteristics the endurance test results were calculated according to the method described in Section 4.3. It has been verified that the calculated values become constant when oil life is at 0.

4.3. Calculating Method of Oil Life

Oil life is calculated by integrating the values attained by multiplying the engine speed and DF values. That value represents the oil life consumption and is calculated by formula (1).

$$REVOLF = \Sigma\ (REVSEC \times DF) \qquad (1)$$

REVOLF : Oil life consumption (times)
REVSEC : Engine speed (times/sec)
DF : Oil deterioration factor that is dependent on oil temperature

After the engine is started and the oil temperature increases, the calculation is conducted by using the DF value, which is dependent on the oil temperature. After the oil is replaced, the calculation is reset with the oil life consumption set to zero. After that, the oil life consumption increases as the engine is driven. The calculation is conducted so that the ratio of remaining oil life becomes zero when the oil life consumption reaches a predetermined value.

Oil deterioration endurance tests were revaluated to confirm when the ratio of remaining oil life becomes zero. The test methods were different from that used in determining the DF characteristic. The testing was conducted under the following conditions.

(1) When the DF characteristic test was conducted, oil was flushed and all deteriorated oil was completely removed. In the confirmation testing, a typical oil change was assumed and new oil was added to the remaining quantity of deteriorated oil.

(2) Oil life of commercially available oil

Since there is a range of oil available on the market, unit tests were applied for selecting oils that deteriorate faster. Of those, the oils that hold a relatively high North American market share were used to verify oil life consumption in actual vehicle testing.

The results of the verification mentioned above, errors in estimated oil temperature and other errors were considered to establish oil life consumption so that the ratio of remaining oil life becomes zero.

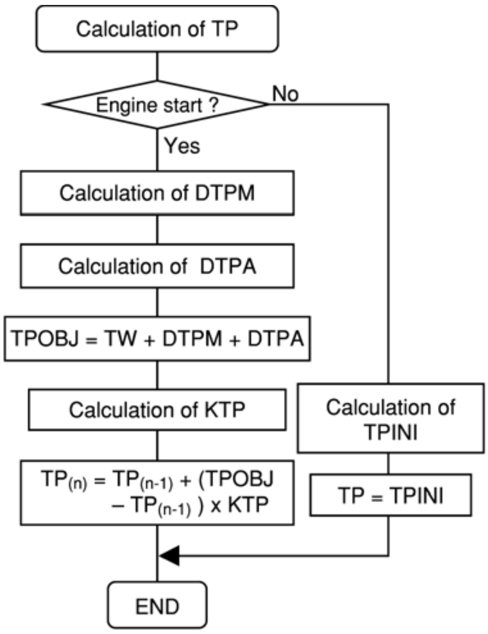
4.4. Estimating Method of Oil Temperature

Figure 6 outlines the oil temperature estimation algorithm.

The temperature of the oil immediately following IG ON is equal to the water temperature. However, during a hot start, a value approximating the oil temperature when the engine was stopped is used as the initial value in the calculation.

DTPM, the correction term of target value for the estimated oil temperature is set so that the X axis is the parameter calculated from amount of fuel injection and the engine speed, and the Y axis is the map data of vehicle speed. This map is assembled from the measured oil temperatures in the conditions from fully open throttle to fully closed throttle.

The estimated oil temperature is corrected in relation to the outside air temperature. The outside air temperature is estimated from the intake air temperature and the vehicle speed. The oil temperature immediately after the vehicle has been started from cold is equal to the water temperature. Since the estimated oil temperature increases from the water temperature, correction with the outside air temperature is not required immediately after the engine is started. Instead the



DTPM : TPOBJ correction value against engine condition
DTPA : TPOBJ correction value against ambient temperature
TPOBJ : Target value of TOILP
TW : Water temperature
KTP : Coefficient for estimation
TP : Estimated oil temperature
TPINI : Initial value of TOILP

Fig. 6 Oil temperature estimation algorithm

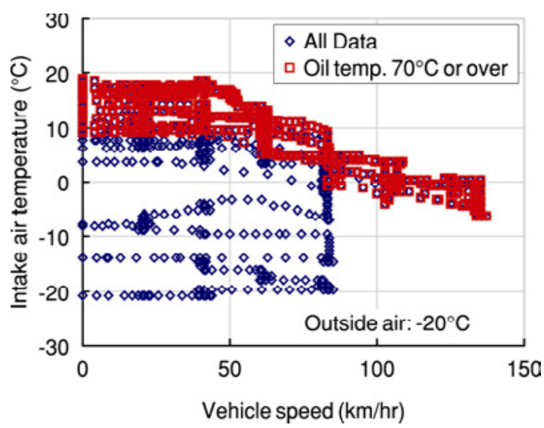


Fig. 7 Vehicle speed and intake air temperature

steady state oil temperature is corrected with the outside air temperature. Restricting the correction with the outside temperature only to steady state oil temperatures improves the accuracy of estimating the outside air temperature. Figure 7 shows the relationship between the vehicle speed and the intake air temperature when the outside air temperature is –20 °C. For example, when the oil temperature for estimating the outside air temperature is greater than 70 °C, the correlation between the vehicle speed and the intake air temperature is recognized. However, there is no correlation in all the data plotted for conditions after the engine started.

Formula (2) shows how the oil temperature is estimated.

$$TP_{(n)} = TP_{(n-1)} + (TPOBJ - TP_{(n-1)}) \times KTP \qquad (2)$$

TP : Estimated oil temperature (°C)
TPOBJ : Target value for estimated oil temperature (°C)
KIP : Estimated coefficient

The estimated coefficient corrects the values so that they reflect actual oil temperature variations. It is calculated through reverse calculation of the actual measured oil temperature as follows.

$$KTP = (Toil_{(n)} - Toil_{(n-1)})/(TPOBJ - Toil_{(n-1)}) \qquad (3)$$

Toil : Actual oil temperature (°C)

4.5. Other

The calculated results of the oil life are not erased even when the battery terminals are disconnected while the vehicle is being serviced or repaired. Also, the calculated oil life results are retained even when the PCM is replaced with a new part.

5. Accuracy of Oil Deterioration Monitor

5.1. Accuracy of Oil Temperature Estimation

The accuracy of the oil temperature estimation was verified on actual vehicles fitted with the oil deterioration monitoring system. During the verification process the actual oil temperature was measured with a temperature sensor. Errors in the calculated value for the oil life determined by the actual oil temperature, and estimated oil temperature are treated as oil temperature estimation errors. Figure 8 shows the oil temperature estimation error. The difference in the calculated results of the estimated oil temperature is –6.6% ~ +3.6% within 3σ in respect to the calculated results from the actual oil temperature ranges.

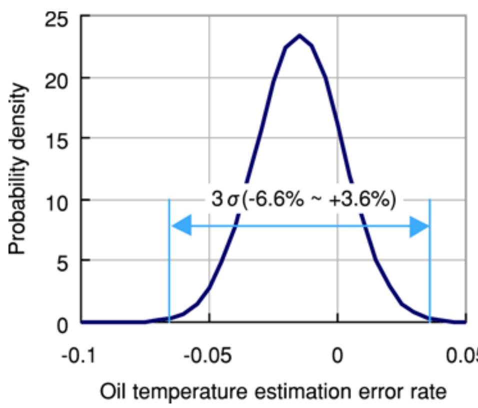


Fig.8 Data comparison for oil life calculations

5.2. Accuracy of Oil Life Estimation

The accuracy of the oil life calculated value was verified in vehicles configured as described in Section 5.1. In the verification method employed, a few samples of oil taken from vehicles fitted with the monitoring system were analyzed. The error arising from the difference between the calculated value and the set value for oil life at the remaining oil life service was then verified. The maximum degree of error measured as the calculated value for the oil life compared to the actual level of deterioration was 15%. The error values including estimated oil temperatures can reach 20%.

The calculated oil life data was set with consideration to the above error rates.

6. Effect of System Introduction

The travel distance at which the calculated oil life would reach zero was estimated for American drivers. The means for estimating the oil life is based on a distribution of the average vehicular speed in America and the oil life distance corresponding to the average vehicular speed.

Since oil life is calculated over the cumulative engine speed, it is possible to travel a longer distance at the same engine speed when a high gear is used. The higher the average speed, more frequent use of high gear also increases the oil life distance.

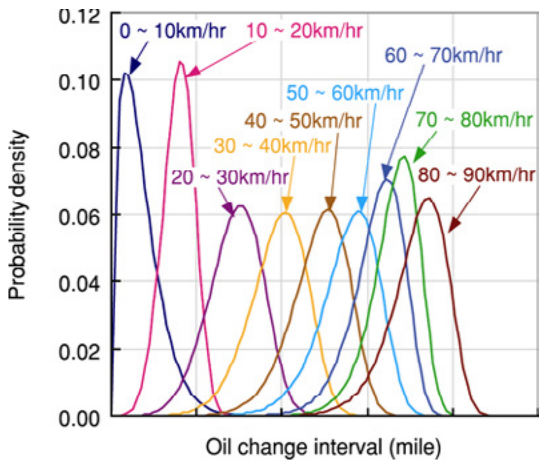


Fig. 9 Vehicle speed and oil life

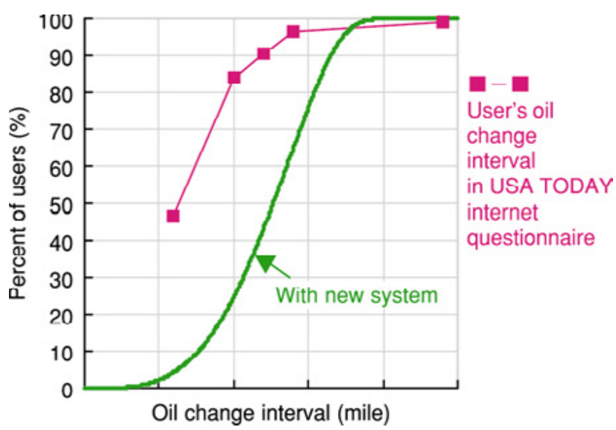


Fig. 10 Oil change interval with new system

Data from each driving cycle taken from vehicles fitted with the monitoring system in America and Japan were used in the calculation and processing illustrated in Fig. 9. The life distance at which the oil life reaches zero was calculated with the oil life consumption and travel distance from one driving cycle. Then a statistical measure was conducted at average vehicular speeds. The average vehicular speed distribution in America was overlapped and the cumulative ranges were attained as shown in Fig. 10. This showed that the oil change intervals are larger in comparison to actual oil change intervals. This new system has enabled the average driver to reduce their number of oil changes by 30%.

7. Conclusion

The oil deterioration monitoring system conducts calculations from the oil deterioration factor that is dependent on the oil temperature and the cumulative engine speed. The accuracy of this system has been verified and the calculations were conducted to avoid the calculation error from the actual oil deterioration. The distribution of the oil change interval based on the set data has enabled optimal oil change intervals for the drivers in America.

References

(1) Murakami, Y., Matsumoto, E., Nogami, Y.: Research and Development of an Oil Deterioration Sensor, Nissan Gihou, No. 30, P. 92-98 (1991)

(2) Greenberg, A.: Cost Puts Direct Oil Condition Sensing in Back Seat, Automotive Electronics Journal, January 15th, p. 9, 12 (1990)

(3) Kauffman, R. E.: Development of a Remaining Lubricant Evaluation Technique. Part: Cyclic Voltammetric Methods, Lub. Eng., 45-11, p. 709 (1988)

(4) Schwartz, S., Smolenski, D. J.: Development of an Automatic Engine Oil-Change Indicator System, SAE Paper, No. 870403

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