ENGINE OIL CONDITION MONITORING WITH FPS2800 OIL PROPERTY SENSOR

THIS WHITE PAPER DOCUMENT PRESENTS THE ALGORITHM DESIGN STRATEGIES DEVELOPED AND APPLIED BY TE CONNECTIVITY TO DIRECTLY MONITOR ENGINE OIL CONDITION.

The FPS2800 oil property sensor from TE Connectivity, predicting remaining oil life and inducing oil change interval optimization, minimization of dramatic engine failure and maintenance costs reduction. After a general description of the sensor measurement principle, the different engine oil contaminations and ageing phenomena and the associated sensor detection and measurements capabilities, the general oil condition algorithm strategy on the FPS2800 sensor is detailed and supported by state of the art references.

Introduction

To optimize oil quality and induced engine efficiency, engine and oil manufacturers usually recommend an oil change interval in months or hours of operation, which is dependent of each specific application. Oil quality is generally monitored externally with punctual samplings analyzed in dedicated laboratories. External monitoring has several disadvantages. First external monitoring is not able to detect rapid oil contamination or quality changes that could induce dramatic engine and system failures. Secondly, the manufacturers choose to recommend restrictive oil change intervals to decrease failure risks. This solution causes high maintenance costs and oil waste.

The internal engine oil condition monitoring with the TE Connectivity FPS2800 sensor definitively allows a simplification of oil quality management, a higher capability detection of slow and rapid oil contamination or quality and an economic and environmental friendly optimization of oil change intervals.

Although this paper demonstrates oil condition algorithm feasibility, presented models and analysis are highly dependent on oil type and application characteristics. Specific studies should then be performed before implementation in each application to adapt and optimize the described models.

I. OIL PROPERTY SENSING

A. OIL PROPERTY SENSOR

The TE Connectivity FPS2800 sensor directly and simultaneously measures the viscosity, density, dielectric constant and temperature of non-conductive oil. Relying on tuning fork technology, the sensor monitors the direct and dynamic relationship between multiple physical properties to determine the quality, condition and contaminant loading of fluids such as engine oil, fuel, transmission and brake fluid, hydraulic and gear oils, refrigerants and solvents. The multi-parametric analysis capability improves fluid characterization algorithms. The FPS2800 sensor provides in-line monitoring of fluids for a wide range of OEM and aftermarket installations including fluid reservoirs, process lines and pressurized high flow conduits (e.g., engine oil gallery) for applications that include on and off highway vehicles, HVAC&R, compressors, industrial equipment and turbines. This paper will focus principally on the engine oil application but most of analysis can be adapted or replicated for other applications.

FIGURE.1.1: FPS2800 OIL PROPERTY SENSOR

This paper describes also the advantages for oil monitoring of a new measurement of FPS2800 sensor, the fluid resistivity.

B. MEASUREMENT PRINCIPLE

FPS2800 measurement is based on a tuning fork flexural resonator. This resonator is composed of quartz, a piezoelectric material capable of being deformed upon application of a voltage and reciprocally electrically polarized under the action of mechanical stress. The two tines oscillate and generate a response indicative of the physicochemical and electrical properties of the fluid wherein the sensor is immersed [1,2,3].

FIGURE.1.2: TUNING FORK

A sinusoidal excitation voltage applied on tuning fork thin electrodes causes mechanical stress and periodic elastic deformation.This vibration produces a corresponding current through the electrodes. The ratio of the excitation voltage on the induced current allows measuring the impedance of the system which will be dependent of the excitation frequency, the elastic properties of the piezoelectric material and the properties of the fluid. The quartz tuning fork impedance response in air has a sharp resonance at about 31 kHz. In a fluid, resonance frequency and amplitude are reduced due to the increased mass load and frictional forces on the system.

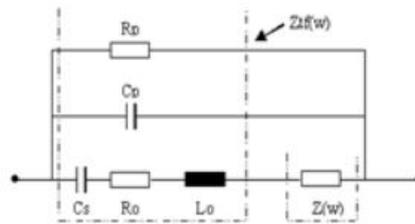The calculation of fluid properties is allowed by the use of a tuning fork equivalent electrical model.

FIGURE.1.3: TUNING FORK EQUIVALENT ELECTRICAL MODEL

Tuning fork complex impedance in air is modeled by the following formula:

$$Z_{TF}(\omega)=R_P//C_P//(R_0+i\omega L_0+\frac{1}{i\omega C_s})$$

Serial capacitance Cs, resistance R0 and inductance L0 are only dependent on geometrical tuning fork parameters. Fluid impact is described by an additional term:

$$Z(\omega)=Ai\,\omega\rho+B\sqrt{\omega\rho\eta}(1+i)$$

where ω is the excitation frequency, η is the dynamic viscosity, ρ is the density, A and B are constants depending on resonatorgeometry.

The dielectric constant ε and the electrical resistivity P are measured thanks to parallel capacitance Cp and resistance Rp:

$$C_P(\varepsilon)=(\varepsilon-1)\frac{\partial C_P}{\partial\varepsilon}+C_{P,Vaccum} \qquad R_P(P) = P\frac{\partial(R_P)}{\partial P}$$

After a calibration step necessary to calculate each parameter,FPS2800 sensor is able to measure dynamic viscosity, density,dielectric constant and Rp, an image of resistivity, of the unknown oil wherein it is immersed.

C. ENGINE OIL

Engine oils are composed by paraffinic, naphthenic and aromatic hydrocarbons, mixed with different additives, and elaborated to fulfill several functions: lubrication, sealing, power transmission, engine parts cooling, cleaning and acid components neutralization.

Objective of lubrication is to reduce friction between sliding surfaces to minimize wear. Insufficient lubrication could lead to engine heating, oil degradation acceleration and risks of engine failures. Sealing between cylinder and piston rings is necessary to avoid blow-by fuel contamination and nitrogen oxide contamination from the combustion gas. Sealing is also required between the valve and the valve steam guides to avoid unburned fuel reaching the oil. Power transmission helps engine efficiency ensuring tappet clearance and camshaft adjustments.

Proper lubrication, sealing and power transmission are ensured by appropriate oil viscosity.

Viscosity of a fluid is a measure of its resistance to gradual deformation by shear stress. Dynamic viscosity can be defined considering a fluid trapped between a fixed plate and a second moving plate with a velocity u.
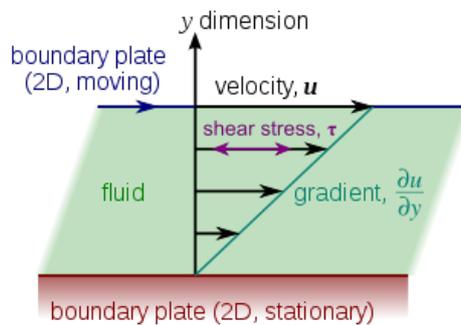

FIGURE.1.4: SHEAR STRESS OF FLUID BETWEEN TWO PLATES

Friction between each fluid layer of area A leads to a force F resisting to their relative motion.

$$F = \eta.A.\frac{\partial u}{\partial y}$$

Dynamic viscosity η represents the proportionality factor between F and the local shear velocity. Viscosity can be also expressed in other form, the kinematic viscosity μ (cSt) which is the ratio of the dynamic viscosity η (cP) to the density ρ (gm/cc) of the fluid. Viscosity is deeply linked to fluid temperature.

Kinematic viscosity μ(T) can be modeled with the following expression (ASTM D341):

$$\log(\log(\mu + 0{,}7) = B - C.\log(T + 273{,}15)$$

where T is temperature in °C, log is base 10 log, and B and C are oil dependent constants.

Density ρ can be modeled in a simple linear form:

$$\rho = D + E.T$$

where D and E are oil dependent constants. Dynamic viscosity η(T) can be deduced from kinematic viscosity μ(T) and density ρ(T).

Base oils viscosity has naturally high temperature dependence, characterized by a low viscosity index (VI). To ensure efficient engine performance, oil viscosity should be sufficiently high at high temperature and not too thick at low temperature to provide easy engine start up. To increase VI, engine oils contain VI improver additives, composed of long–chained hydrocarbon polymers, tightly folded at low temperatures and getting unfolded at high temperature. Lubrication is also improved by antiwear additives which prevent friction of metallic surface during extreme operating conditions. Exemple of antiwear is Zinc dithiophosphate (ZDP).

Incorrect sealing could lead to functional deficiency or foam formation. Foam inhibitors additives with silicon compounds,prevent stable oil foam formation and improve air removal ability.

Oil cleaning is ensured by two types of additives: the dispersants and the detergents.

A dispersant is composed by a long non polar oleophile tail and a polar head. The function of the dispersant is to maintain in suspension solid or liquid contamination particles in the oil and thus avoid any agglomeration that could lead to sludge formation. The two phenomena involved are peptisation and solubilisation (Moller and Nasser, 2002). Peptisation consists to wrapp solid oil contamination particles (diameter of 50-150 nm) like dust, soot and to keep them in suspension. Solubilisation is the same mechanism but related to liquid contaminations like acids or condensates (inferior to 20nm).

A detergent is a colloidal metal based additive (Klamann, 1982) and has a similar structure than the dispersant but its tail is shorter and the strength of its polar head is higher. Detergent purposes are to avoid or remove carbon, varnish or lacquer deposits and to neutralize acids created from the combustion and from the oxidation and nitration processes. Indeed contamination acids are dangerous because they can cause corrosion and increase oil degradation.

Engine oils provide also alkaline reserve to prevent acidification. The alkaline reserve can be measured thanks to Total Base Number (TBN) value. In the same way, acidity can be measured by the Total Acid Number (TAN). Ph value is not suited for measurement in oil because media is not aqueous. TAN and TBN measurement unit is mgKOH/g, which corresponds to the equivalent mass of potassium hydroxide required to neutralize one gram of solution. Neutralization is ensured by the use of detergents. Some over-based detergents composed by calcium carbonate or magnesium carbonate achieve high level of protection against acidity. However they could lead to ash formation that could be problematic for diesel particulate filter.The manufacturers tend to use relative low ash engine oils, meaning lower TBN and alkaline reserve (Sappok and Wong, 2010), reducing chemical degradation resistance.

During oil ageing, polar compounds and charge carriers degradation products are created. In parallel, base additives compounds are depleted, decreasing protection against acidification. The electrical and chemical behaviors have a direct impact on oil dielectric constant ε and resistivity.

Dielectric constant ε or relative permittivity is the ratio of media permittivity on vaccum permittivity. Dielectric constant represents the capacity of the media to be polarized under the application of an electric field. Concretely, the polarization is the consequence of the reorientation of molecular dipoles in the lubricant. During oil ageing, dipole moments could change because of microscopic chemical reactions like oxidation or nitration or because of addition of polar contaminants like water (ε water=80) or soot. Sen et al (1992) has described and measured the dielectric constant of liquids alkanes. The study confirmed dielectric ε has the following equation:

$$\varepsilon = F + G.T$$

where T is temperature in °C, F and G are oil dependent constants.

Indeed, dielectric constant ε could be linked with density ρ, using Clausius-Mossotti relation:

$$\frac{\varepsilon - 1}{\varepsilon + 2} = 4.\pi.\rho.Na.\frac{\alpha}{3.M}$$

where Na is Avogadro's number, α the molecular polarizability volume and M is the molar mass of the substance.

The resistivity P of a media measures the drag force encountered by free charge carriers moving through the medium under the application of an electric field. Oil resistivity is dependent on fluid viscosity, on density of free charge carriers and on specific oil chemical composition. In a first approximation, resistivity P can be modeled in a simple linear form:

$$P = H + I.T$$

where T is temperature in °C, H and I are oil dependent constants.

FPS2800 oil general measurement in temperature is presented on Fig.1.5. Two engine oil samples (15W40, new and 1000h aged) have been measured at standard engine oil application temperature range. Temperature homogeneity was ensured by mechanical stirring. The results demonstrate FPS2800 capability to measure oil viscosity η, density ρ, dielectric ε and Rp an image of resistivity, for the entire application temperature range.
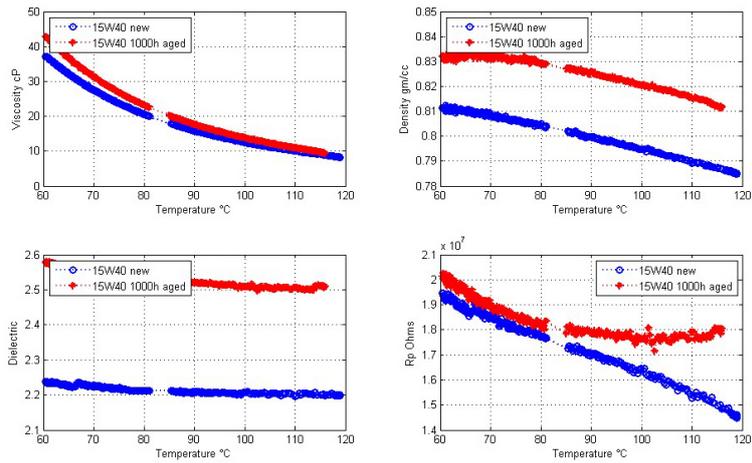
FIGURE.1.5: ENGINE OIL (15W40), NEW AND AGED MEASURED BY FPS2800

Viscosity, density, and dielectric are increased during ageing. Without any contamination, the three parameters increase can be considered as the normal behavior, even if we can also observe viscosity decrease due to oil shear. The resistivity increase at high temperature is due to free charge carriers additives depletion. The gradients of variations will depend on oil type and application characteristics, as temperature or contaminations.

II. OIL AGEING PROCESSES AND FPS2800 SENSOR DETECTION CAPABILITIES

Engine oil, during its whole life, follows different degradation and contamination processes due to high temperature, exposition to chemically reactive combustion by-products and various contaminations. The following sections describe these processes and how each process is detectable by FPS2800 sensor.

A. OXIDATION

When exposed to high temperature, engine oil reacts with air oxygen. This reaction is called oxidation. Oil molecules chemically combines with air oxygen to form carbonyl compounds products (C=O) such as aldehydes, ketones, esters and carboxylic acids in different concentrations. Actually, the process corresponds to two degradations: the evaporation of slight oil components and the oxygen element incorporation in oil components. This oxidation induces a polymerization of oil molecules and the formation of oil insoluble products that lead to an increase of viscosity. This oxidation induces also various formation and depletion of polar and conductive compounds that will impact oil dielectric constant and resistivity.

The oxidation process is accelerated by heat, light, metal catalysts like copper or iron and the presence of water, acids, or solid contaminants that could generate deposit formation. Oxidation is also favored by oil shear. Hydrocarbon compounds and polymer viscosity improver's additives break with shear, creating carboxylic acids, carbon active sites, which can be oxidized and which will induce a new polymerization. Eventually oxidation is accelerated by biodiesel or ethanol due to their hygroscopic properties.

Oxidation is measured in laboratory using Fourier Transform InfraRed (FTIR) spectroscopy method specified by standard test method ASTM D7418 or by ASTM D7214. The measurement is based on a quantification of the carbonyl function (C=O), corresponding to the 1700cm-1 frequency peak analysis on the absorbance spectrum. Oxidation measurement is expressed in A/cm.

FPS2800 oxidation measurement is presented on Fig.2.1. Engine oil (15W40) has been stored in laboratory at 150°C during 3000 hours and regularly sampled and analyzed until complete degradation. The results demonstrate FPS2800 capability to detect and measure oil oxidation, mainly with viscosity, dielectric and resistivity measurements.

Viscosity is highly increased during all oxidation process. Resistivity is a very useful parameter because it can be directly linked to the four different phases of oil oxidation process.

During Phase 1, tested oil resistivity is increased up to 10% at 120°C. This phenomenon could be explained by the depletion of some free charge carriers additives. Viscosity starts its continuous increase and dielectric shows a very slight drop. Phase 1 corresponds to the predominance of a fast chemical process involving very reactive additives.
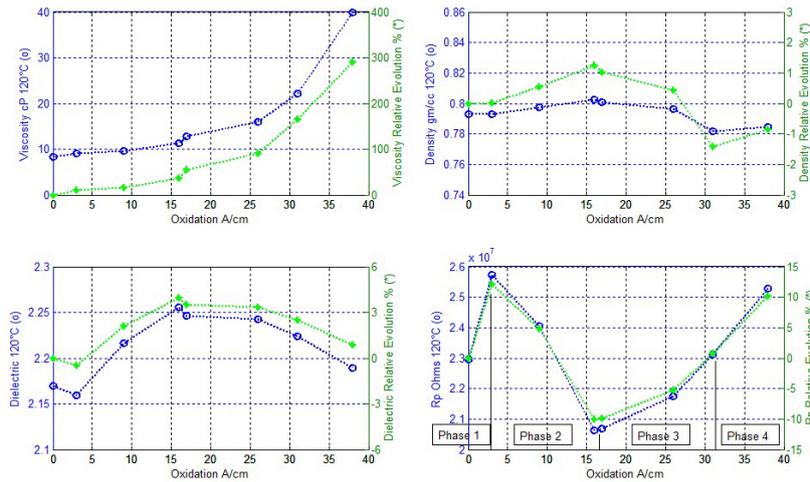
FIGURE.2.1: ENGINE OIL (15W40) OXIDATION MEASURED BY FPS2800 AT 120°C

During Phase 2, tested oil resistivity is decreased up to -10% at 120°C, relatively to initial value, and dielectric shows a significant increase. Phase 2 corresponds to a predominance of a slow chemical process that releases charge carriers and polar compounds.

During Phase 3, resistivity shows a new increase, linked to a new depletion of charge carriers, and dielectric is stabilized.

Phase 4 corresponds to the dramatic high viscosity increase before oil complete degradation and potential jelling.

Even if the density changes stay relatively slight, they could be linked to the four different oxidation phases.

The four different oil degradation phases and the corresponding viscosity and resistivity behaviors are described in the literature [4,5,6,7,8]. Temperature has relatively low impact on the four parameters oxidation behaviors, relative changes are similar for each temperature, except on resistivity. Phase 1 resistivity increase is amplified at high temperature and subdued at lower temperatures.

During Phase 1 and Phase 2, oil condition is considered as good, level of degradation is quite low. Phase 3 corresponds to a consequent level of oil degradation. Entering Phase 3 is the appropriate timing to perform oil change. During Phase 4, oil has already reached very high level of degradation. There is a high risk of engine dramatic failure. Oil change has to be performed immediately.

Oxidation process depends on engine application characteristics and engine oil composition. FPS2800 oxidation measurements of three different 15W40 engine oils are presented on Fig.2.2. The three engine oils have been stored at 150°C and regularly measured by FPS2800 until end of Phase 2 of oil oxidation. The results show different measurement gradients between the oils but the general trends described above are confirmed.
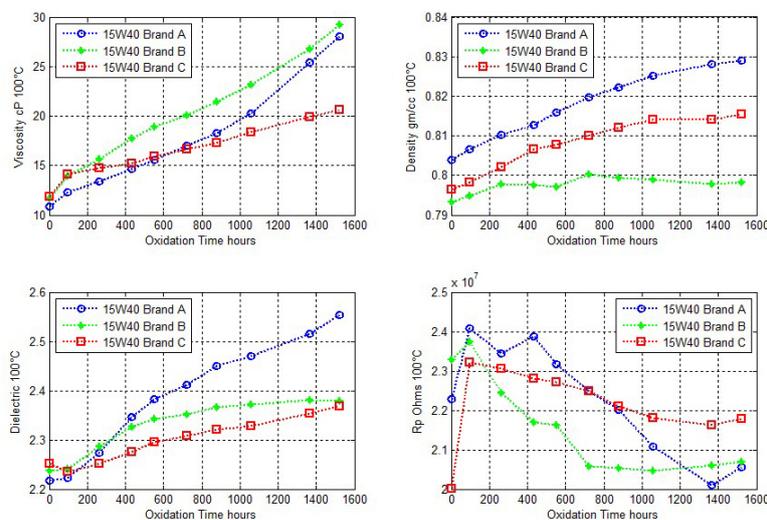

FIGURE.2.2: ENGINE OIL (15W40 BRAND A, B & C) OXIDATION MEASURED BY FPS2800 AT 100°C

Brand C oil shows a consequent resistivity increase during Phase 1 and then relatively low increases of viscosity and dielectric during Phase 2. Brand A oil shows a lower resistivity increase during Phase 1 but much higher increases of viscosity and dielectric during Phase 2. These different gradients could be linked to additives composition. Indeed, the type and concentration of additives present in oil will favor or prevent different reactions involving oxidation and degradation products.

Since oxidation is dependent on oil composition and engine application characteristics, precise and complete oxidation modeling seems difficult. However, one can determine a typical physical change, focusing on Phase 1 and Phase 2. The solution consists to model Phase 1 and Phase 2 and detect the entrance in Phase 3 linked to a consequent level of degradation. For example, 15W40 engine oil presented in Fig.2.1 could be modeled with the following equations, at constant temperature:

$$\eta_{th} = \eta_i.(1 + 21.10^{-3}.Ox.)$$

$$\rho_{th} = \rho_i.(1 + 0.5.10^{-3}.Ox.)$$

$$\varepsilon_{th} = \varepsilon_i.(1 + 1.5.10^{-3}.Ox.)$$

$$Rp_{th} = Rp_i.(1 - 12.10^{-3}.Ox.)$$

These models are plotted on Fig.2.3 with the related accuracy specifications in full blue lines. The red circles represent the entering of Phase 3 detection when:

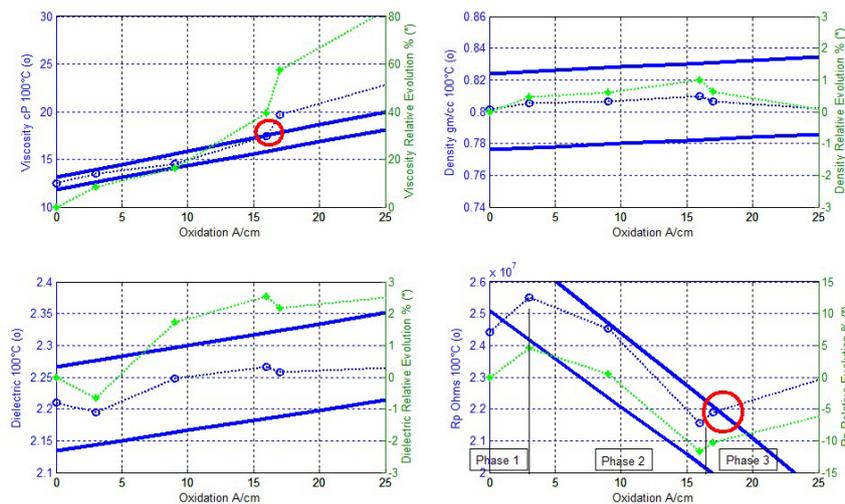$$\eta \geq 1.05.\eta_{th} \quad \text{and} \quad Rp \geq 1.05.Rp_{th}.$$

FIGURE.2.3: ENGINE OIL (15W40) OXIDATION MEASURED BY FPS2800 AT 100°C

B. WATER CONTAMINATION

Water contamination comes from fuel combustion process or from exterior engine system. Water in oil can be dangerous for the engine because it could induce excessive wear for example by cavitation or corrosion. Water promotes also oil oxidation, acid by-products and sludge formation and thus poor engine reliability.

Water has three different states in oil: dissolved water, emulsion and free water. Dissolved water is characterized by dispersed individual water molecules chemically linked to the oil. Above an amount called solubility, the excess water will saturate and will not be chemical linked to the oil, free water is formed leading to a two phases system. Because of higher water density than oil density, free water accumulates typically at the bottom of oil pan. When mixing ratio is sufficiently high or under presence of surfactant additives, an emulsion can be formed. Emulsified water is homogeneously dispersed into the oil.

Typical water solubility and associated water states are presented in Fig.2.4.
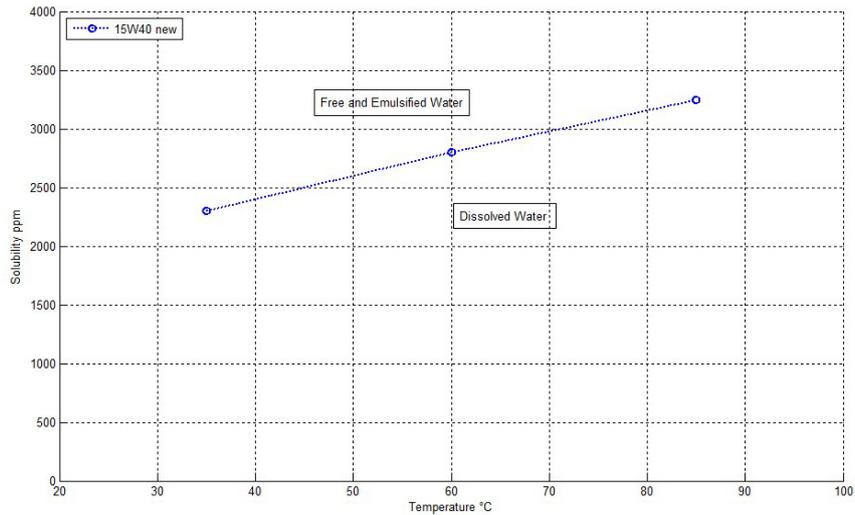
FIGURE.2.4: TYPICAL WATER SOLUBILITY IN ENGINE OIL AND ASSOCIATED WATER STATES

Solubility depends on temperature, oil additives, contamination and oxidation [9]. Pure oils and hydraulic oils have low solubility.Typical engine oil solubility is about 2000ppm at 50°C.

Solubility of hydraulic oil, fresh and aged 15W40 engine oils, measured by TE Connectivity HTM2500B3C4OIL water content sensor, are presented in Fig.2.5.
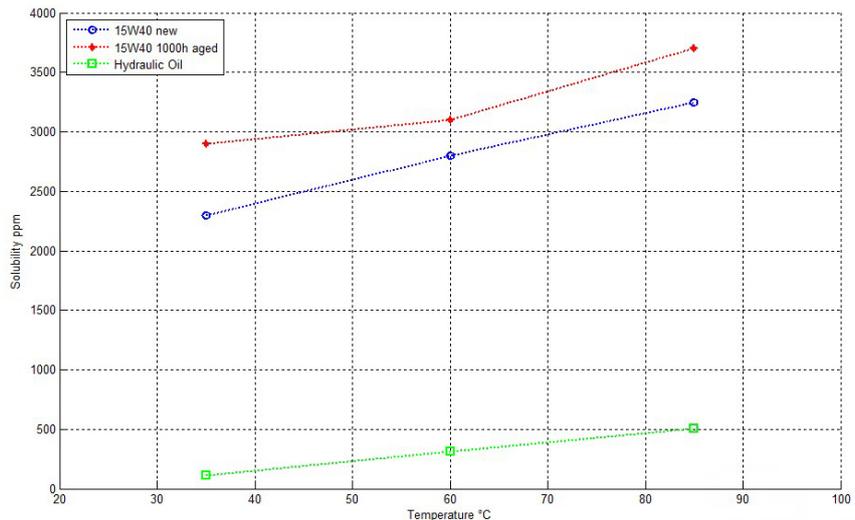

FIGURE.2.5: WATER SOLUBILITY IN HYDRAULIC AND ENGINE OIL MEASURED BY TE CONNECTIVITY WATER CONTENT SENSOR

Water in oil is typically measured in laboratory with Karl Fisher titration (ISO12937 or ASTM D1533). Karl Fisher measures total absolute water in ppm with high accuracy. However this method is not totally appropriate with engine oil because measurement could be impacted by specific engine oil additives. Aquatest (ISO/DIS 9114 or ASTM D7358) and FTIR (ASTM D7418) are alternative methods to measure total absolute water from 100ppm with 100ppm accuracy. These three methods do not differentiate dissolved or free water. TE Connectivity HTM2500B3C4OIL water content sensor is able to measure water activity and then to deduce solubility, independently of oil ageing [19].

Water activity α_{Water} can be defined by the following formula:

$$\alpha_{Water} = \frac{[H_2O]}{[H_2O]_{Saturation}}$$

where 0< α_{Water} <1, $[H_2O]$ is the concentration of dissolved water in oil (ppm) and $[H_2O]_{Saturation}$ is the concentration of dissolved water in oil (ppm) at saturation point. TE Connectivity HTM2500B3C4OIL water content sensor and its water activity measurement would be the relevant sensor solution to measure highest accuracy water content under saturation point.

FPS2800 water dilution measurement is presented on Fig.2.6. Engine oil (15W40) has been stabilized at 50°C and diluted with deionized water. Emulsion homogeneity was ensured by magnetic stirring. The results demonstrate FPS2800 capability to detect and measure water contamination, mainly with dielectric and resistivity measurements.
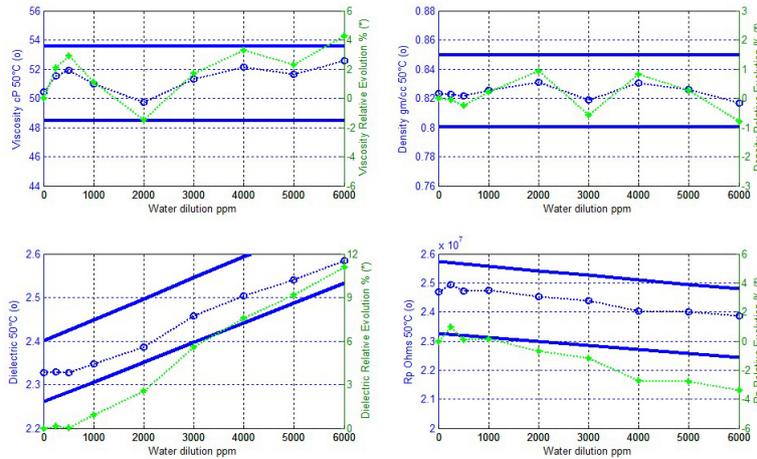

FIGURE.2.6: WATER DILUTION IN ENGINE OIL (15W40) MEASURED BY FPS2800 AT 50°C

Viscosity and density do not show any changes. Dielectric is linearly increased and resistivity is linearly decreased with water dilution. These noticeable changes have been described in the literature [3,6,10] and can be respectively explained by the high dielectric of water (ε_{Water} = 80) and the auto-ionization of water that can release free charge carriers, protons, into the oil.

FPS2800 measures dissolved and emulsion water, which guarantees a good compatibility with the application. Indeed, engine operation ensures emulsion by a high enough mixing ratio. When engine oil reaches high temperature, water may evaporate, so the detection has to be performed before evaporation so preferably just after the engine start-up during the oil temperature increase.

Water in engine oil can be modeled with the following equations, at constant temperature:

$$\eta_{th} = \eta_i$$

$$\rho_{th} = \rho_i$$

$$\varepsilon_{th} = \varepsilon_i.(1 + 20.10^{-6}.WatDil_{(ppm)})$$

$$Rp_{th} = Rp_i.(1 - 6.10^{-6}.WatDil_{(ppm)})$$

These models are plotted on Fig.2.6 with the related accuracy specifications in full blue lines.

C. COOLANT CONTAMINATION

Engine coolant contamination comes from leakage from engine cooling system. Coolant is composed of ethylene glycol or propylene glycol (40 to 60%), water (60 to 40%) and several additives in relative low concentrations (about 5%). Ethylene glycol and propylene glycol are miscible in water and in most organic solvents but are not miscible in oil. Common coolant additives include sodium silicate, disodium phosphate, sodium molybdate, sodium borate, and ensure the functions of lubricants, buffers and corrosion inhibitors. Coolant contamination in engine oil can be dangerous for the engine, having several negative impacts.Low coolant contamination can cause heavy sludges deposits, acid compounds formation like glycolic or methanoic acids, and accelerates oil oxidation. High coolant contamination could lead to an emulsion or a gel [10] when mixed with the oil, and induces occlusions of walls and oil passageways, risks of filter blocking, reduction of oil flow and serious general decrease of lubrication efficiency.

Coolant in oil is typically measured in laboratory with FTIR (ASTM D7418) or ICP-AES spectrometry (ASTM D7151) mainly through quantification of the coolant additives elements Na, B and/or K within the oil.

FPS2800 coolant (50%water) dilution measurement is presented on Fig.2.7. Engine oil (15W40) has been stabilized at 50°C and diluted with coolant. Emulsion homogeneity was ensured by magnetic stirring. The results demonstrate FPS2800 capability to detect and measure coolant contamination, mainly with dielectric and resistivity measurements.
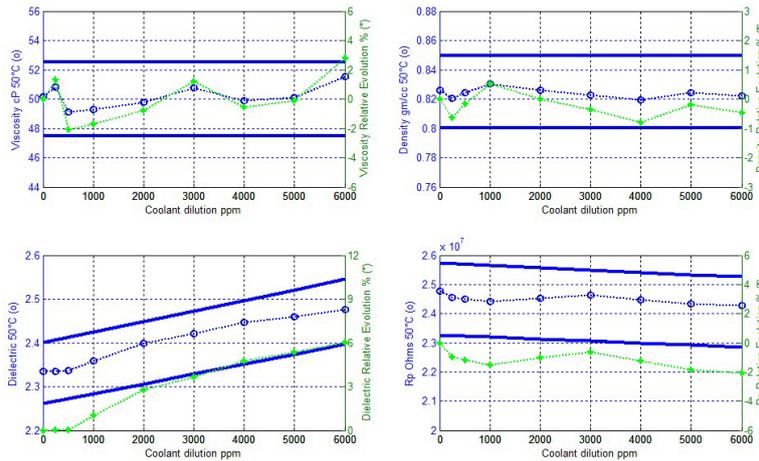
FIGURE.2.7: COOLANT DILUTION IN ENGINE OIL (15W40) MEASURED BY FPS2800 AT 50°C

Viscosity and density do not show any changes. Dielectric is linearly increased and resistivity is linearly decreased with coolant dilution. These results are perfectly coherent with water dilution results described in previous section. Indeed, the tested coolant is composed of 50% water and the dielectric and resistivity slopes are twice lower than water dilution results. The changes can be respectively explained by the high dielectric of water (ε_{Water} = 80) and the auto-ionization of water that can release free charge carriers, protons, into the oil.

FPS2800 measures dissolved and emulsion water coming from coolant blend, which guarantees a good compatibility with the application. Indeed, engine operation ensures emulsion by a high enough mixing ratio. When engine oil reaches high temperature, water may evaporate, so the detection has to be performed before evaporation so preferably just after the engine start-up during the oil temperature increase.

Coolant in engine oil can be modeled with the following equations, at constant temperature:

$$\eta_{th} = \eta_i$$

$$\rho_{th} = \rho_i$$

$$\varepsilon_{th} = \varepsilon_i.(1+10.10^{-6}.CoolDil_{(ppm)})$$

$$Rp_{th} = Rp_i.(1-3.10^{-6}.CoolDil_{(ppm)})$$

These models are plotted on Fig.2.7 with the related accuracy specifications in full blue lines.

D. FUEL CONTAMINATION

Fuel contaminations in engine are caused by imperfect fuel combustion and imperfect sealing. Unburned fuel reaches the crankcase through the space between piston and cylinder and between the piston groove and the ring. Fuel dilution can be enhanced in particular conditions during DPF regeneration process.

Internal combustion engines use fuels like diesel or gasoline which are mostly hydrocarbons compounds mixed with a variety of additives. Generally obtained by a specific fractional distillate of petroleum, they are nowadays more and more blended with biofuels such as biodiesel and ethanol. Blended with petroleum diesel, biodiesel is a vegetable oil or animal fat-based fuel composed of long chain of alkyl esters. In the US, fuel standard ASTM D7467 specifies blends from B6 to B20, which corresponds to blends with 6% to 20% of biodiesel. In Europe, fuel standard EN 590 specifies blends up to B7. In gasoline fuels, ethanol is blended up to 10% (E10) in common markets, and can be blended up to 85% (E85) in the flexible fuel vehicles applications (ASTM5798). In the future, the biofuels blending rates are expected to grow to fulfill environment protection rules.

Fuel physical properties can be modeled as for oil physical properties:

$$\log(\log(\mu+0{,}7)) = B - C.\log(T+273{,}15)$$

$$\rho = D + E.T$$

$$\varepsilon = F + G.T$$

$$R_p = H + I.T$$

where T is temperature in °C, B, C, D, E, F, G, H and I are fuel dependent constants. Dynamic viscosity η(T) is deduced from kinematic viscosity μ(T) and density ρ(T).

FPS2800 measurements of different fuels are presented on Fig.2.8. Fuel temperature homogeneity was ensured by magnetic stirring. The results demonstrate FPS2800 capability to accurately measure fuel properties and allow robust fuel type differentiation.
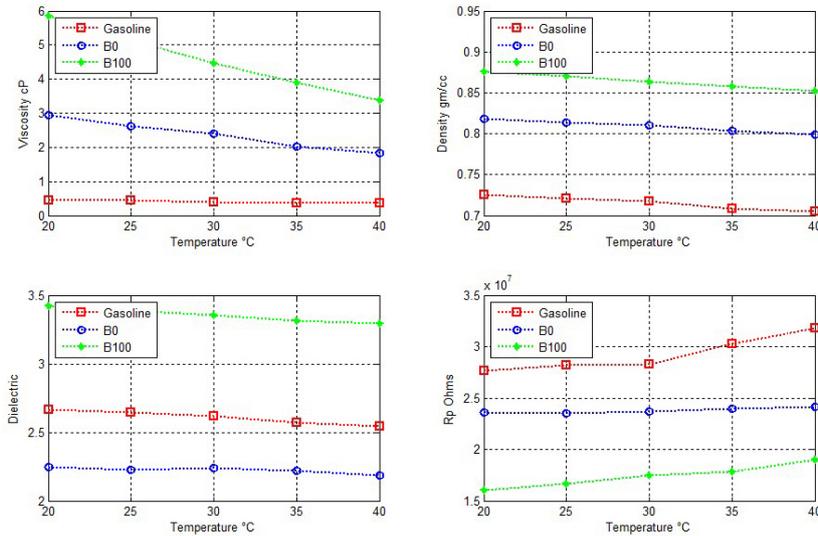

FIGURE.2.8: GASOLINE, DIESEL B0, RAPESEED B100 BIODIESEL MEASURED BY FPS2800

B100 biodiesel have higher viscosity, density and dielectric value than pure petroleum fuels. Gasoline shows a much lower viscosity than diesel fluids. Lower resistivity of biodiesel is explained by its hygroscopic characteristic. Fuel properties measurement allows fuel differentiation between gasoline, B0 and B100 but also with alternative fuels like kerosene or hydrotreated vegetable oil (HVO) [11]. More FPS2800 measurements in fuels and high detection capability results are available in the literature [12]. TE Connectivity proposes also specific additional integrated algorithms to provide biodiesel concentration [20] or fuel differentiation [21].

Fuel contamination in engine oil can be dangerous for the engine, because it could promote oil oxidation, acidic compounds and soot formation. These degradations are even more increased with biofuels because of biodiesel or ethanol hygroscopic characteristics. Fuel dilution will also deteriorate oil lubrication properties and amplify risks of wear.

Fuel contamination in oil is typically estimated in laboratory with a method using flash point (ISO 2719) and viscosity measurements (ASTM D445) or with a more accurate and more expensive method using gas chromatography measurement.

FPS2800 fuel dilution measurement is presented on Fig.2.9. Engine oil (15W40) has been stabilized at 100°C and diluted with diesel N°2 fuel. Blending temperature homogeneity was ensured by mechanical stirring. The results demonstrate FPS2800 capability to detect and measure fuel contamination, mainly with viscosity measurement.
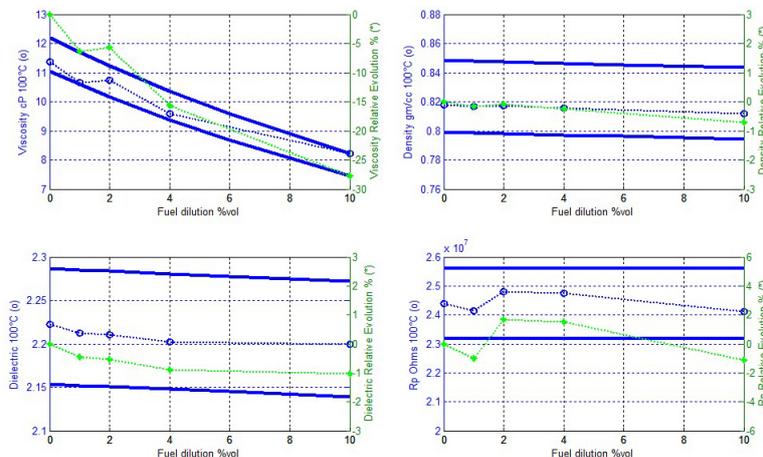

FIGURE.2.9: FUEL DILUTION IN ENGINE OIL (15W40) MEASURED BY FPS2800 AT 100°C

Resistivity does not show any consequent change. Density and dielectric are linearly changed with fuel dilution. Slopes are depending directly of density and dielectric of the two fluids (Yang et al, 2004) because they are miscible. The main change is measured with viscosity which is exponentially decreased with fuel dilution.

As engine oil and fuel are miscible fluids, the Refutas method (2000) can be used to calculate the theoretical kinematic viscosity µ of the blend. The method consists to determine a Viscosity Blending Number (VBN) for each component from their kinematic viscosity and then calculate the VBN of the blend at a fixed constant temperature [12]:

$$VBN_{Fuel} = 14,534 . \ln(\ln(\mu_{Fuel_{th}} + 0,8)) + 10,975$$

$$VBN_{Oil} = 14,534 . \ln(\ln(\mu_{Oil_{th}} + 0,8)) + 10,975$$

$$VBN_{Blend} = VBN_{Oil} .(1 - FuelDil_{(\%)} /100) + VBN_{Fuel} . FuelDil_{(\%)} /100)$$

The kinematic viscosity of the blend can then be estimated using the VBN of the blend using the following equation.

$$\mu_{Blend_{th}} = \exp(\exp(\frac{VBN_{Blend} - 10.975}{14.534})) - 0,8$$

Fuel contamination in engine oil can be modeled with the following equations, at constant temperature:

These models are plotted on Fig.2.9 with the related accuracy specifications in full blue lines.

$$|\eta_{Blend_{th}} = \mu_{Blend_{th}} . \rho_{Blend_{th}}$$

$$\rho_{Blend_{th}} = \rho_{Oil_t} .(1 - FuelDil_{(\%)} /100) + \rho_{Fuel_t} . FuelDil_{(\%)} /100$$

$$\varepsilon_{Blend_{th}} = \varepsilon_{Oil_t} .(1 - FuelDil_{(\%)} /100) + \varepsilon_{Fuel_t} . FuelDil_{(\%)} /100$$

$$Rp_{Blend_{th}} = Rp_{Oil_t} .(1 - FuelDil_{(\%)} /100) + Rp_{Fuel_t} . FuelDil_{(\%)} /100$$

E. SOOT CONTAMINATION

Soot is composed of impure carbon particles resulting from the incomplete fuel combustion.

Soot contamination in engine oil can be dangerous for the engine because soot loaded oil can cause deposits inducing further engine problems (Moller and Nassar, 2002). Soot particles can be abrasive and increase engine wear (Sato et al, 1999).Dispersant additives can manage a certain level of soot in the oil but they cannot avoid viscosity increase with excessive soot contamination.

Soot contamination can be measured in laboratory with FTIR (ASTM D7418). Soot contamination is expressed in %.

FPS2800 soot contamination measurement is presented on Fig.2.10. Engine oil (15W40) has been stabilized at 100°C and contaminated with standard diesel particulate matter (NIST2975). Oil homogeneity was ensured by magnetic stirring. The results demonstrate FPS2800 capability to detect and measure soot contamination, mainly with viscosity and dielectric measurements.
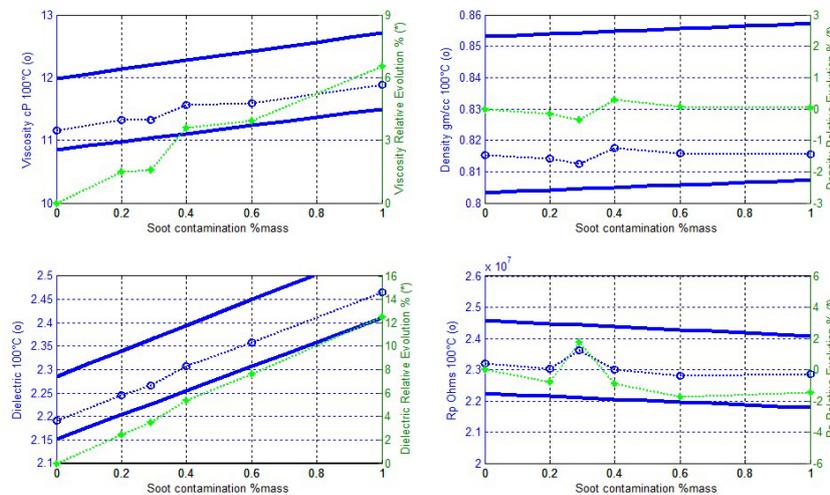

FIGURE.2.10: SOOT CONTAMINATION IN ENGINE OIL (15W40) MEASURED BY FPS2800 AT 100°C

Viscosity and dielectric are highly and linearly increased with soot contamination. Soot may induce slight density increase and slight resistivity decrease. These noticeable changes have been described in the literature [13] and can be respectively explained by the shape, the high polarisability and the charge characteristics of soot particles.

Soot contamination in engine oil can be modeled with the following equations, at constant temperature:

$$\eta_{th} = \eta_i.(1 + 6.10^{-2}.SootCont_{(\%mass)})$$

$$\rho_{th} = \rho_i.(1 + 0,5.10^{-2}.SootCont_{(\%mass)})$$

$$\varepsilon_{th} = \varepsilon_i.(1 + 12.10^{-2}.SootCont_{(\%mass)})$$

$$Rp_{th} = Rp_i.(1 - 2.10^{-2}.SootCont_{(\%mass)})$$

These models are plotted on Fig.2.10 with the related accuracy specifications in full blue lines.

F. METAL CONTAMINATION

Metal contamination comes from wear induced by bad lubrication and from corrosion. Main metals to be monitored are Fe or Cu or Al, which are components of main engine parts.

Metal contamination is dangerous for the application because it could accelerate oil degradation. Metal contamination is above all a sign of abnormally wear.

Metal contamination can be measured in laboratory with ICP spectrometric analysis (NFT 60 106). Metal contamination is expressed in mg/kg equivalent to ppm mass.

FPS2800 iron Fe contamination measurement is presented on Fig.2.11. Engine oil (15W40) has been stabilized at 100°C and contaminated with <10µm Fe particles up to ppm in mass. Oil homogeneity was ensured by magnetic stirring. The results demonstrate FPS2800 capability to detect and measure extreme high levels of Fe contamination, with viscosity, density and dielectric measurements.
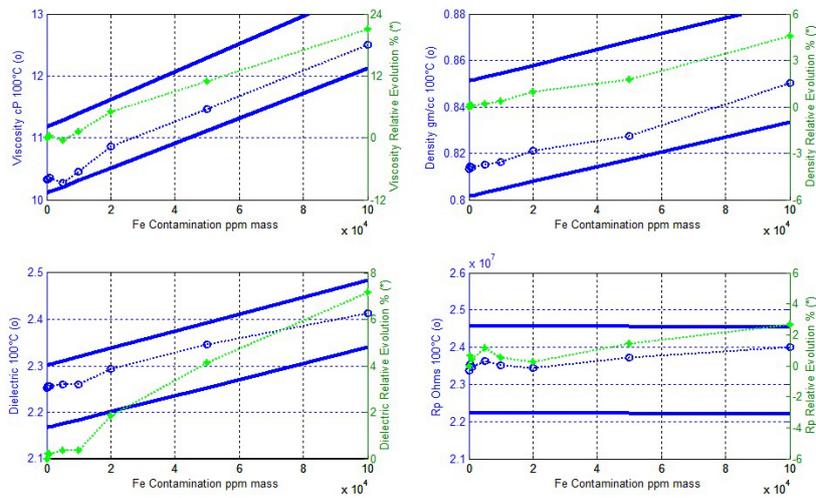

FIGURE.2.11: FE CONTAMINATION IN ENGINE OIL (15W40) MEASURED BY FPS2800 AT 100°C

Viscosity, density and dielectric are highly and linearly increased with Fe contamination. Fe contamination also induces slight resistivity decrease. These noticeable changes can be explained by the shape, the high polarisability and the charge characteristics of metal particles.

Fe contamination in engine oil can be modeled with the following equations, at constant temperature:

$$\eta_{th} = \eta_i.(1 + 2.10^{-6}.FeCont_{(ppm.mass)})$$

$$\rho_{th} = \rho_i.(1 + 0,4.10^{-6}.FeCont_{(ppm.mass)})$$

$$\varepsilon_{th} = \varepsilon_i.(1 + 0,8.10^{-6}.FeCont_{(ppm.mass)})$$

$$Rp_{th} = Rp_i.(1 - 0,1.10^{-7}.FeCont_{(ppm.mass)})$$

These models are plotted on Fig.2.11 with the related accuracy specifications in full blue lines.

Similar results can be obtained with copper Cu or alternative metal contaminations.

G. TBN, TAN AND AGEING

Regular punctual TBN and TAN measurement in reference laboratories is a method widely used to monitor oil condition externally. Ageing and contamination processes induce creation of different acid compounds until complete oil degradation. These acid compounds accelerate oil degradation thanks different chemical reactions. For example, metal contamination can be increased by corrosion produced by the acid compounds. To counter acid compounds creation and delay oil degradation, alkaline reserve is added in oil chemical composition. Thus fresh oil have high TBN value, typically from TBN=8 to TBN=14, and low TAN value, typically from TAN=1 to TAN =4. Then, during oil life, due to acid compounds creation, TBN is continuously decreased while TAN is continuously increased. When alkaline species are completely depleted, acid compounds are dramatically increased and general oil degradation is highly accelerated until complete deterioration and jelling. Depending on oil composition and application characteristics, limits on TBN and TAN values could be considered to optimize oil changes.For example, some manufacturers could recommend to perform oil change when TBN=TAN, decreasing the risks of dramatic oil degradation and induced engine failure.

Typical TBN and TAN dynamic behavior is presented on Fig.2.12. TBN and TAN measurements are plotted in function of oxidation. Engine oil (15W40) has been stored at 150°C during 3000 hours and regularly sampled and analyzed until complete degradation. TBN and TAN have been measured by an external reference laboratory. The oil samples correspond to the same samples of the oxidation data presented on Fig.2.1.
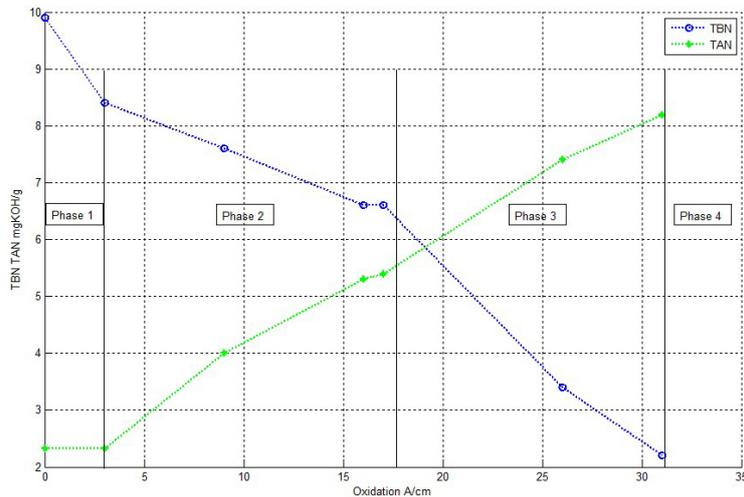

FIGURE.2.12: ENGINE OIL (15W40) TBN & TAN MEASURED BY REFERENCE LABORATORY

The results show a TBN continuous decrease and a TAN continuous increase with oxidation. The same four different phases of oil degradation described in Fig.2.1 can also be considered. During Phase 1 and Phase 2, TBN value is superior to TAN value.From the end of Phase 2, TAN value reaches TBN value and becomes superior to TBN value for the following degradation phases. TBN and TAN measurements corresponding to 38A/cm sample from Fig.2.1 were not performed because of the too high degree of oil degradation, oil was indeed completely jelled.

The correlation between absolute value of difference |TBN-TAN| and resistivity measurement is presented on Fig.2.13. The results demonstrate FPS2800 capability to measure an image of TBN and TAN values thanks to resistivity measurement.

As described on Fig.2.1, resistivity is increased during Phase 1. This Phase 1 is relatively short and the level of increase will depend on oil chemical composition and application characteristics. Then resistivity is decreased during Phase 2 until a minimum and increased again during Phase 3. |TBN-TAN| has a similar behavior, starting from a high value, because fresh oil has alkaline reserve and low acid concentration, being decreased during Phase 2 until a minimum, and then increased during Phase 3, due to acid compound creation and alkaline species neutralization. A clear correlation (R^2=0,83) is demonstrated between resistivity and |TBN-TAN|. Similar correlation has been described in the literature [17, 18].
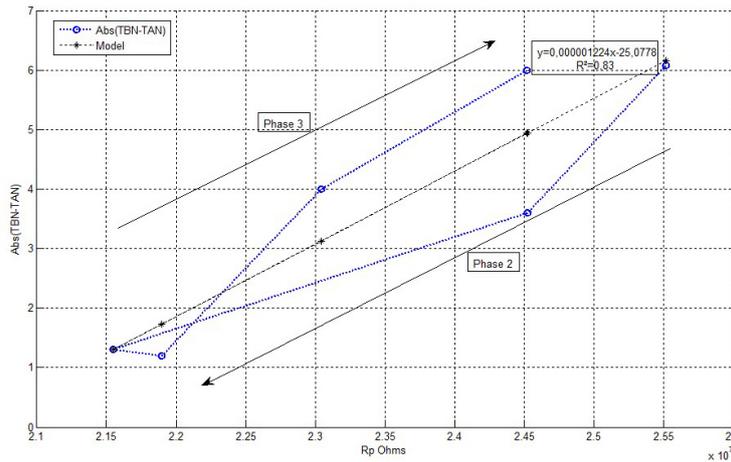
FIGURE.2.13: CORRELATION BETWEEN ABS(TBN-TAN) & FPS2800 RP MEASUREMENT AT 100°C

|TBN-TAN| can be modeled with the following equation, at constant temperature:

$$\left| TBN - TAN \right| = 1{,}224.10^{-6}.R_p + 25{,}07$$

Punctual resistivity measurement will not allow a precise direct measurement of TBN and TAN values. However resistivity monitoring will allow a prediction of |TBN-TAN| and detections of Phase 2

$$\text{(when } \frac{\partial Rp}{\partial t} < 0 \text{ ; } TBN > TA\!$$

and Phase 3

$$\text{(when } \frac{\partial Rp}{\partial t} > 0 \text{ ; } TAN > TB$$

As stated previously, Phase 3 corresponds to a consequent level of oil degradation. Entering Phase 3 is the appropriate timing to perform oil change.

H. WRONG FLUID DETECTION

Wrong fluid filling could be dangerous for the engine. Indeed, engines are designed to operate with determined oil characteristics. Wrong oil filling or wrong fluid filling may degrade engine performance and could induce risks of failure.

FPS2800 measurements in four different oils are presented on Fig.2.14, three engine oils 0W40, 10W30 and 15W40 and one bio ISO32 hydraulic oil. Each oil sample has been stabilized and tested at different temperatures from 50°C to 120°C. The results demonstrate FPS2800 capability to detect any eventual wrong fluid, with viscosity, density, dielectric and resistivity measurements.
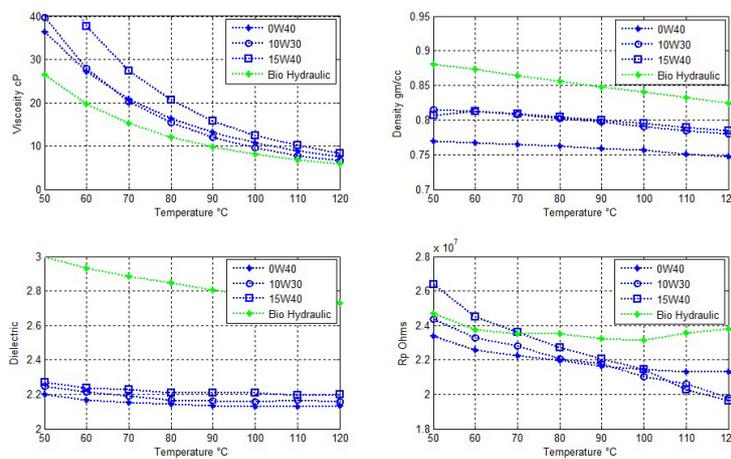

FIGURE.2.14: 0W40, 10W30, 15W40 OILS & BIO HYDRAULIC OIL MEASURED BY FPS2800

FPS2800 is capable to differentiate any type of engine oil or hydraulic oil mainly with viscosity measurement. Indeed, viscosity of each sample is clearly identified, fitting with viscosity grade standard SAE J300: 15W40 has the higher viscosity; 0W40 has lower viscosity than the other engine oils at low temperature and has similar viscosity of 15W40 oil at high temperature; 10W30 has lower viscosity at high temperature than the two other engine oils. ISO32 hydraulic oil has lower viscosity than the three engine oils. Density is depending on oil composition and cannot be predicted by SAE J300 grade. FPS2800 clearly differentiate the different oil with density. The three tested engine oils have similar dielectric ε=2,2 at 100°C, that can easily be differentiated from the tested Bio hydraulic oil with ε=2,7 at 100°C although ISO32 hydraulic oils typically have dielectric between ε =2 and ε =2,4. Some differences between the fluids can also be observed on resistivity values.

An effective wrong fluid detection will be possible, modeling the desired fluid for the considered application, and fixing some thresholds for each physical parameter. The thresholds levels will depend on the application and the different wrong fluid susceptible to be encountered.

I. SYNTHESIS

The different oil contaminations and ageing phenomena impacts on the four physical FPS2800 sensor measurements are synthetized in the following chart. The chart demonstrates FPS2800 capability to detect and measure each oil contamination and ageing phenomena. Indeed each oil contamination and ageing phenomena has differentiable impacts on the four physical FPS2800 sensor measurements.

	Impact on Viscosity	Impact on Density	Impact on Dielectric	Impact on Resistivity
Oxidation	+++ $\eta_r(1+21.10^{-3}.Ox)$	+ $\rho_r(1+0.5.10^{-3}.Ox)$	+ $\varepsilon_r(1+1.5.10^{-3}.Ox)$	- - - $Rp_r(1-12.10^{-3}.Ox)$
Water Contamination	O η_i	O ρ_i	++ $\varepsilon_r(1+20.10^{-4}.Wat_{ppm})$	- - $Rp_r(1-6.10^{-4}.Wat_{ppm})$
Coolant Contamination	O η_i	O ρ_i	+ $\varepsilon_r(1+10.10^{-4}.Cool_{ppm})$	- $Rp_r(1-3.10^{-4}.Cool_{ppm})$
Fuel Contamination	- - - Function of fuel type	+ / - Function of fuel type	+ / - Function of fuel type	+ / - Function of fuel type
Soot Contamination	++ $\eta_r(1+6.10^{-3}.Soot_{\%})$	+ $\rho_r(1+0.5.10^{-3}.Soot_{\%})$	+++ $\varepsilon_r(1+12.10^{-3}.Soot_{\%})$	- $Rp_r(1-2.10^{-3}.Soot_{\%})$
Metal Contamination	+ $\eta_r(1+2.10^{-6}.Fe_{ppm})$	+ $\rho_r(1+0.4.10^{-6}.Fe_{ppm})$	+ $\varepsilon_r(1+0.8.10^{-6}.Fe_{ppm})$	O $Rp_r(1-0.1.10^{-7}.Fe_{ppm})$
TBN / TAN	O N/A	O N/A	O N/A	+++ / - - - $\frac{|TBN-TAN|}{1.224.10^{6}.R_s+25.6778}$
Wrong Fluid Detection	++ / - - Function of fluid type	++ / - - Function of fluid type	+ / - Function of fluid type	+ / - Function of fluid type

Legend:
+++: Strong Increase - - -: Strong Decrease
++ : Moderate Increase - - : Moderate Decrease
+ : Slight Increase - : Slight Decrease
O : No impact +/- : Increase or Decrease
▭ : High Evolution Speed ___ : Slow Evolution Speed
Note: Water and coolant contamination cannot be differentiated.

We can also differentiate two evolution speeds for the different contaminations and ageing phenomena. Oxidation, soot and metal contamination, and TBN / TAN evolution are most of the time slow processes whereas water, coolant, fuel contaminations and wrong fluid filling could be very fast. Different algorithm detection strategies should then be specifically implemented for each contamination or ageing item.

Based on the previous measurements and on FPS2800 sensor specifications, the robustly indicative achievable detection levels determined for each different oil contaminations and ageing phenomena are synthetized in the following chart.

	Lower Limit	Upper Limit	Resolution
Oxidation	0 A/cm (ASTM D7418)	50 A/cm (ASTM D7418)	2 A/cm (ASTM D7418)
Water Contamination	2000ppm	20000ppm	2000ppm
Coolant Contamination	4000ppm	40000ppm	4000ppm
Fuel Contamination	1%	10%	1%
Soot Contamination	0,2% (ASTM D7418)	5% (ASTM D7418)	0,1% (ASTM D7418)
Metal Contamination	20000ppm	100000ppm	20000ppm
TBN / TAN	Detection of the oil degradation Phases	Detection of the oil degradation Phases	Detection of the oil degradation Phases
Wrong Fluid Detection	Function of fluid type	Function of fluid type	Function of fluid type

Presented models and analysis are highly dependent on oil type and application characteristics. Specific studies should then be performed before implementation in each application to adapt and optimize the described models.

III. OIL CONDITION ALGORITHM

To be as effective as possible, an Oil Condition Algorithm (OCA) should be designed for a specific application. One unique oil condition algorithm applicable for any application seems difficult to achieve. Indeed, each application will have different environment characteristics, different application fluids, different contaminations risks, and different ageing levels.

However, an effective oil condition algorithm should include some basic generic functions that could be configurable for each specific application, for example considering different thresholds or priorities. The following section describes these basic generic functions.

In the past, several solutions have been considered in the literature for oil degradation sensing with associated algorithm: classifier architectures based on linear discriminant analysis, Bayesian probabilistic models, robust fault detection and isolation, and neural networks [23, 24, 25].

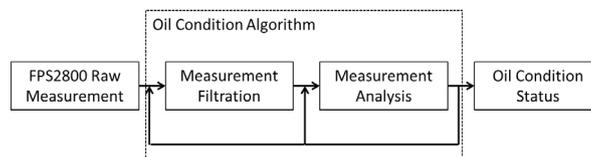The general oil condition algorithm strategy is described in bloc diagram of Fig.3.1.

FIGURE.3.1: OIL CONDITION ALGORITHM BLOC DIAGRAM

The oil condition algorithm described in this paper, and designed to give a reliable oil condition status from FPS2800 raw measurement, will be divided in two separate steps: measurement filtration and measurement analysis.

A. MEASUREMENT FILTRATION

An effective measurement filtration is needed to ensure algorithm reliability and avoid any false detection. Filtration should be performed at several levels. The basic following functions should be considered as possible solutions. Each application would have specific characteristics that could induce specific adjustments.

- **Function A.1 : Aberrant Data Filtration**

Objective is to remove sensor error measurements.

In some conditions, the FPS2800 sensor could transmit error measurements, for example due to out of specifications of oil physical parameters. Viscosity being specified up to 50cP, sensor could transmit error measurements when immersed in fluids with higher viscosities. This function will only transmit correct FPS2800 measurements without any error measurement.

- **Function A.2 : Application Condition Filtration**

Objective is to remove all the measurements that are useless for the application.For example, measurement data above 100°C could be useless when tracking water in oil contamination because of evaporation process.

- **Function A.3 : Noise Filtration**

Objective is to remove all the measurement noise induced by the application to improve general monitoring performance.

For example, a simple infinite input response filter can be implemented. Order of filter could be adapted depending on specific application requirements (temperature gradients...). Filters can be different for the different raw measurements.

- **Function A.4 : Fresh Oil Modelling**

Objective is to construct and store a temperature model of fresh engine oil for the four FPS2800 sensor measurements, with the help of two temperature stabilized measurements necessary to build the models, using the equations described in Section I.C. This fresh oil modelling has to be performed after an oil change. The information of the occurrence of the oil change can be brought by the user or can be detected by an additional specific function.

- **Function A.5 : Current Oil Modelling**

Objective is to construct and store a dynamic temperature model of engine oil for the four FPS2800 sensor measurements and continuously update this model, with the help of two temperature stabilized measurements using the equations described in Section I.C.

- **Function A.6 : Temperature Compensation**

Objectives are to choose the adequate application analysis temperature T1, to calculate and to store the temperature compensated values thanks to Function A.4 and Function A.5 models. Indeed, the four FPS2800 measurements are temperature dependant and during application, it is possible that the stabilized points are not always at the same temperature. This function will allow an iso-temperature analysis with the following functions A.7 and A.8. The outputs of this function are the fresh oil physical parameters $(x)_n$ at fixed temperature T1 and the current physical parameters $(x)_i$ at fixed temperature T1.

- **Function A.7 : Absolute Evolution Calculation**

Objective is to calculate and store absolute evolution between fresh oil and current oil of the four parameters at the temperature T1 determined by Function A.6.

For example, absolute viscosity evolution can be calculated with the following formula:

$$Abs\eta_n = \eta_n - \eta_i$$

where η_i is viscosity of fresh oil at fixed temperature T1, and η_n is viscosity of current oil at fixed temperature T1. The calculation is the same for the three other $(x)_n$ physical parameters: the density ρ, the dielectric constant ε and the electrical resistivity Rp.

- **Function A.8: Relative Evolution Calculation**

Objective is to calculate and store relative evolution between fresh oil and current oil of the four parameters at the temperature T1 determined by Function A.6.

For example, relative viscosity evolution can be calculated with the following formula:

$$\mathrm{Re}\,l\,\eta_n(\%) = 100 \cdot \frac{\eta_n - \eta_i}{\eta_i}$$

where n_i is viscosity of fresh oil at fixed temperature T1, and n_n is viscosity of current oil at fixed temperature T1. The calculation is the same for the three other $(x)_n$ physical parameters: the density ρ, the dielectric constant ε and the electrical resistivity Rp.

- **Synthesis of Measurement Filtration**

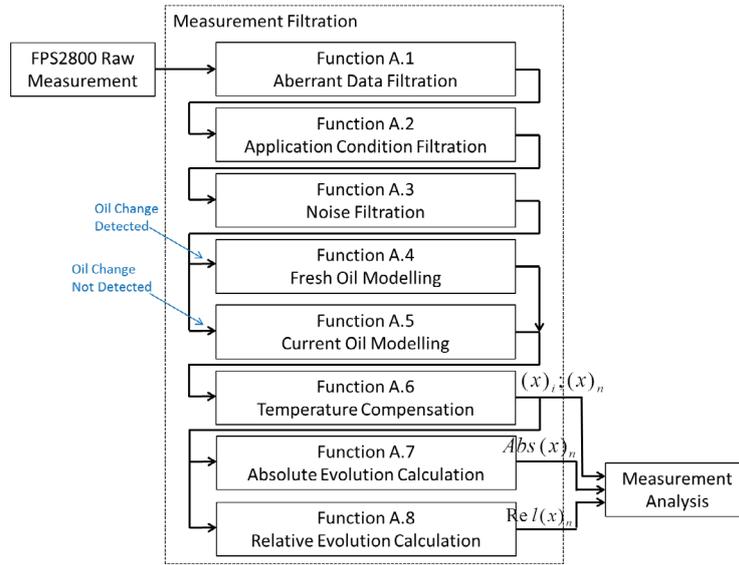The described measurement filtration functions are synthetized in bloc diagram of Fig.3.2.

FIGURE.3.2: MEASUREMENT FILTRATION BLOC DIAGRAM 1

The measurement filtration functions filter and pre-analyse FPS2800 sensor raw measurement to determine the four following values at fixed temperature T1: fresh oil physical parameters $(x)_i$, current oil physical parameters $(x)_n$, absolute evolution $(x)_n$ and relative evolution $\mathrm{Rel}(x)_n$. These four values will be used during measurement analysis step and will increase ageing and contamination detection capabilities.

The described measurement filtration functions should be considered as possible solutions. Each application would have specific characteristics that could induce specific adjustments.

B. MEASUREMENT ANALYSIS

The following functions describe the strategy to reliably monitor oil condition and detect oil contaminations. Each formula described in Section II will be included and analysed by the following functions.

- **Function B.1 : High Risk Issue Detection**

Objectives are to detect high level of contamination or oil ageing that can be dramatic for the application, to detect early water, coolant, fuel contaminations and to detect wrong fluid voluntary or involuntary filling.

These contaminations are associated to high evolution speed. For example, water contamination could happen between two working engine phases and induces an increase of dielectric measurement when engine start-up, in comparison to the dielectric value before the last engine switch off. Detection algorithm should be adapted to this high evolution speed.

These contaminations have a high risk for the application but are relatively simple to manage using thresholds. For example, considering Fig.2.6, if the Measurement filtrations functions return the following relative evolutions at T2=50°C:

$$\mathrm{Re}\,l(\eta)_n = 0\%, \mathrm{Re}\,l(\rho)_n = 0\%, \mathrm{Re}\,l(\varepsilon)_n > 9\% \text{ and } \mathrm{Re}\,l(Rp)_n < -3\%,$$

then oil has high probability to be contaminated with more than 5000ppm water (or more than 10000ppm coolant).

- **Function B.2 : Oxidation Trend Management**

Objectives are to model and store oxidation trend and calculate relative distance to this oxidation trend.

Oxidation is a particular ageing process that necessary happens during all oil life. One solution would be to consider an oxidation trend, modelled in real time and compare it to a typical oxidation trend associated to a specific application.
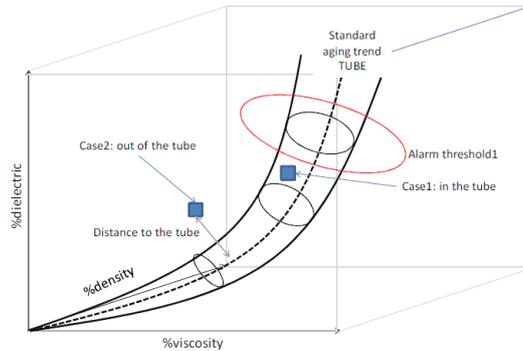
Example of oxidation trend tube is presented on Fig.3.3.

FIGURE.3.3: OXIDATION TUBE AND RELATIVE DISTANCE TO THE TUBE THRESHOLDS

The Fig.3.3 is presented in three dimensions to facilitate visualisation but analysis could be performed on the four different parameters to improve detection capabilities.

In Fig.3.3, the dotted line represents the average typical oxidation trend for one specific application. To consider the possible variabilities between different ageing processes even in similar application conditions, the typical oxidation trend is preferably represented by a tube, in full black lines and full black circles. Two cases are considered for real time measurement in Fig.3.3. In Case 1, real time measurement is still inside the black typical oxidation tube, which means that oil follows expected oxidation process. Whereas in Case 2, real time measurement is out of the tube, which means that oil could be abnormally contaminated. Calculation of the distance of real time measurement to the tube will allow detection and a precise measurement of the contaminations in following function B.3.

- **Function B.3 : Long Term Contamination Detection**

Objectives are to detect contaminations with relative thresholds in comparison to oxidation trend model and to calculate absolute contamination levels.

For example, an alarm threshold is represented with a red circle in Fig.3.3. One threshold could be specifically determined for each of possible long term contamination. A precise measurement of the contamination is then possible using the models detailed in Section II.

- **Function B.4 : Output filtration**

Objectives are to detect any algorithm default or inconsistent output and to manage noise output.

Each application will have specific characteristics and risks on the entire system. This output filtration should then prioritize and ponderate the raw outputs of the algorithm.

- **Synthesis of Measurement Analysis**

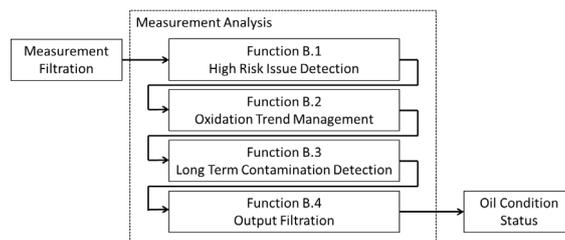The described measurement analysis functions are synthetized in bloc diagram of Fig.3.4.

FIGURE.3.4: EXAMPLE OF MEASUREMENT ANALYSIS BLOC DIAGRAM

The measurement analysis interprets the information from measurement filtration to determine oil condition status.

The described measurement analysis functions should be considered as possible solutions. Each application would have specific characteristics that could induce specific adjustments.

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Conclusion

Associated with a specific oil condition algorithm whose main strategy is described in this paper, TE Connectivity Oil Property Sensor FPS2800 is able to directly monitor engine oil condition, predicting remaining oil life and inducing oil change interval optimization, minimization of dramatic engine failure and maintenance costs reduction.

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Definitions, Acronyms, Abbreviations

DPF: Diesel Particle Filter

ICP-AES: Inductively Coupled Plasma Atomic Emission Spectrometry

OPS: Oil Property Sensor

FTIR: Fourier Transform InfraRed

HVO: Hydrotreated Vegetable Oil

OCA: Oil Condition Algorithm

ROL: Remaining Oil Life

SVM: Support Vector Machine

TAN: Total Acid Number

TBN: Total Base Number

VBN: Viscosity Blending Number

VI: Viscosity Index

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