Evaluation of Sensors for On-Board Diesel Oil Condition Monitoring of U.S. Army Ground Equipment

Joel Schmitigal
Steve Moyer
U.S. Army RDECOM-TARDEC

ABSTRACT

The U.S. Army Tank-Automotive Research, Development and Engineering Center (TARDEC) recently completed a Science and Technology Objective (STO) to develop and demonstrate a compact on-board smart sensor system for monitoring the operational condition of in-service diesel engine oils. The goal of such technologies is to reduce or eliminate the Army's dependence on traditional oil analysis methods, by providing real-time condition monitoring and to project the remaining usable life of the lubricant. Commercially available and prototype sensors were obtained and evaluated on a diesel test engine. Algorithms were then developed from the sensor and laboratory data to determine the real-time condition of the oil and to calculate the remaining usable life of the oil.

INTRODUCTION

The U.S. Army Tank-Automotive Research, Development and Engineering Center (TARDEC) recently completed a five year Science and Technology Objective (STO) to develop and demonstrate a compact on-board sensor system for monitoring the operational condition of in-service diesel engine oils of U.S. Army vehicles and ground support equipment. The goal of such technologies is to reduce or eliminate the Army's dependence on traditional oil analysis methods, by providing real-time condition monitoring and to project the remaining usable life of the lubricant. Commercially available and prototype sensors were obtained and evaluated in a laboratory setting and then on an engine test stand. The 6.5 Liter AM General diesel engine was selected for engine testing due to its usage in the ubiquitous High Mobility Multi-Wheeled Vehicle (HMMWV), the relatively small oil volume, use of an external oil cooler, and its inexpensive cost. Sensors were evaluated on their capability to monitor soot accumulation and oxidation, as well as detection of coolant leaks and fuel dilution, on the test engine stand. Sensor technologies investigated included dielectric constant, infrared spectroscopy, voltammetry, electromagnetic viscometry, conductivity, and impedance spectroscopy. Algorithms were built using the sensor and laboratory data to determine the real-time condition of the oil and to calculate the remaining usable life of the oil. In the final year of the program three sensors were selected and incorporated into a sensor suite, and a retrofit kit was fabricated and is presently being field tested onboard Army vehicles to validate system algorithms and overall performance.

SENSORS EVALUATED

Initial sensors for evaluation were selected based on work performed for the Army and detailed in [1,2]. Additional sensors were obtained and tested during the course of the sensor evaluation.

SENSORS

Dielectric sensors

The dielectric constant is a measure of an oil's ability to resist an electrical charge from conducting through it. The CSI Oil View Model 5500 from Emerson Process Management (Knoxville, TN) was utilized to monitor the dielectric constant of oil. An additional dielectric sensor was procured from Lubrigard Ltd. (Dorset, UK) which provides the fluid's dissipation factor, or tan delta.

Conductivity sensor

The Diesel Oil Condition and Level Sensor (D-OCLS) from Delphi (Troy, MI) performs an A.C. conductivity measurement and reports the conductivity of the oil as well as the dielectric constant [3]. Soot particles are electrically conductive therefore imparting conductivity on the oil which then enables the concentration of soot to be calculated.

Electromagnetic viscosity sensor

The SPL571 electromagnetic viscosity sensor from Cambridge Applied Systems (Medford, MA) provides a measure of the oils viscosity. The sensor works by measuring the time it takes for a piston to move through

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **04 JAN 2005**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Evaluation of Sensors for On-Board Diesel Oil Condition Monitoring of U.S. Army Ground Equipment**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Schmitigal,Joel; Moyer,Steve**	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000**	8. PERFORMING ORGANIZATION REPORT NUMBER **14113**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) **TACOM/TARDEC** 11. SPONSOR/MONITOR’S REPORT NUMBER(S) **14113**

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

Presented at SAE 2005 World Congress, Detroit, MI, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**5**	

the oil, thereby providing the absolute viscosity of the fluid. By measuring the temperature the sensor is able to provide a temperature compensated value. By entering in the density of the fluid it is able to calculate the kinematic viscosity of the fluid.

ENGINE TEST STAND SENSOR EVALUATION

The diesel engine used in the sensor evaluation was a 6.5 liter, 8 cylinder engine manufactured by AM General, and used in the Army's HMMWV. The engine was set-up and run according to the ASTM D 5966, Evaluation of Engine Oils for Roller Follower Wear in Light-Duty Diesel Engine. The engine was equipped with an external heater and cooler so the fluid temperature could be controlled independently of the engine.

The engine was operated for approximately 8 hours each day. Once per day, the oil was cooled to approximately 70 °C to record sensor responses. Oils utilized in the engine tests were qualified to MIL-PRF-2104 and had an API service rating of CH-4. Oil samples were taken approximately every 15 hours of operation. The oil samples were subjected to used engine oil analysis testing described below.

USED ENGINE OIL ANALYSIS

Oil analysis was conducted with the intention of replicating tests performed by the Army's Oil Analysis Program (AOAP) laboratories. Additional testing beyond what is normally performed by AOAP was performed as desired. The oil analysis results were compared to the sensor output data to identify trends and to establish relationships. Algorithms were then built for determining the real-time condition of the oil and to estimate the remaining usable life of the oil.

Fourier Transform Infrared Spectrometry (FTIR)

The FTIR technique, developed by the Joint Oil Analysis Program (JOAP), was used to measure compositional changes and detect contaminant levels of the used oils. FTIR was used to monitor the oxidation, soot, nitration, sulfation, water contamination, ethylene glycol contamination and diesel fuel dilution.

Inductively Coupled Plasma – Atomic Emission Spectrometer (ICP-AES).

The metal content of the samples, wear debris and additive concentrations of the used oil samples were measured by ICP-AES as described in ASTM Method D5185.

Kinematic Viscosity

The kinematic viscosity of the used oil samples were obtained at 40ºC as described in ASTM Method D445. The viscosity measurements were used to monitor viscosity increases due to increasing oxidation and soot levels and viscosity decreases due to fuel dilution.

Infracal Soot Meter

The soot levels of the used oil samples were measured using an Infracal soot meter (Wilks Enterprise, South Norwalk, CT). The soot meter reported the soot levels in percent soot. The soot meter was calibrated and verified with standards quantified by the thermogravimetric analysis method described in ASTM D 5967.

Karl Fischer titration

The total water content was measured by performing Karl Fischer titration as described in ASTM method D4928.

Total Acid Number (TAN) and Total Base Number (TBN)

The TAN and TBN measurements for the used oil samples were performed as described in ASTM methods D644 and D4739, respectively.

Fuel Dilution by Gas Chromatography

Fuel content was determined by gas chromatography as described in ASTM D 3524.

RESULTS

Sensors were evaluated to determine their ability to detect soot, oxidative byproducts, fuel dilution and water.

SOOT DETECTION

Engine tests were run to optimize soot production and minimize other chemical compositional changes to the oil by keeping the oil temperature below 80 °C during testing. Engine oil temperatures were kept low by an external oil cooler.

Sensor response

All the sensor technologies were able to detect soot production, when produced independently of other chemical compositional changes in the oil. The conductivity sensor was able to quantify soot content without regard to other chemical compositional changes.

Conductivity sensor

The primary function of the D-OCLS sensor from Delphi is the calculation of soot concentration. Figure 1. shows a comparison of sensor response versus soot concentration as measured by the Infracal Soot Meter. The D-OCLS was found to have some variation from the laboratory instrumentation with an average difference being -0.2% soot. The D-OCLS was also shown to track very well over time as shown in Figure 2, compared to the response from the Infracal Soot Meter

Dielectric constant and electromagnetic viscosity sensors

The dielectric constant and electromagnetic viscosity sensors were also able to respond to the presence of soot particles. Figure 3 shows the change in dielectric constant caused by soot particulates. Figure 4 shows the affect of soot particles on viscosity during the same engine test, shown in Figure 3, in which oxidation was at a minimum.

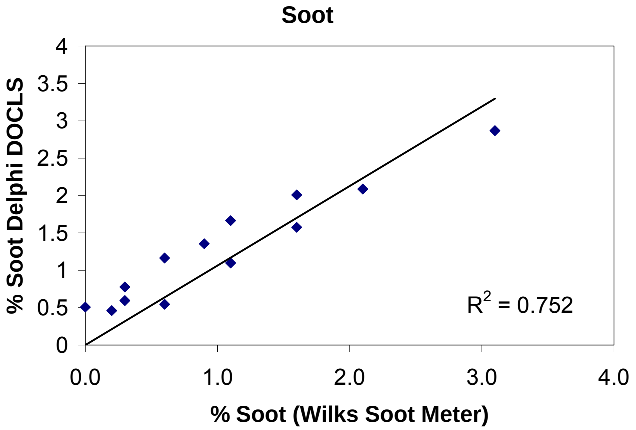

Figure 1. Delphi DOCLS response versus soot concentration as measured by the Infracal Soot Meter

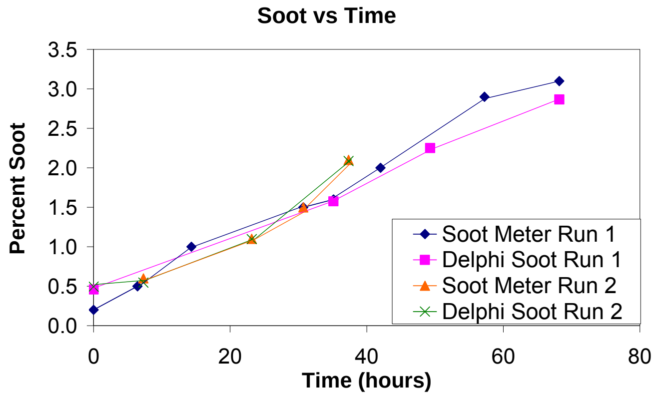

Figure 2. Comparison of Delphi DOCLS and soot meter tracking with time

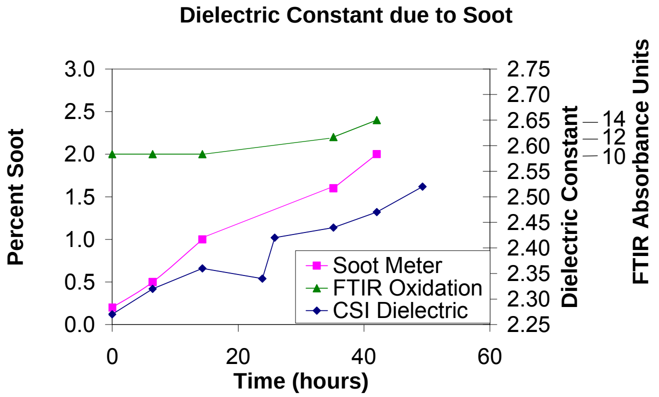

Figure 3. Change in dielectric constant due to soot with minimal oxidation effects.

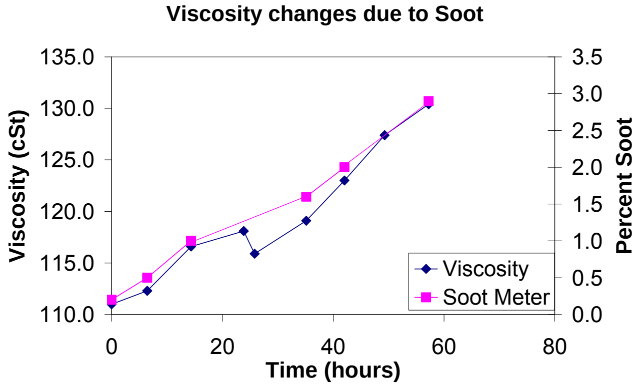

Figure 4. Effect of soot concentration due to soot particles over time.

OXIDATIVE BYPRODUCT DETECTION

Detection of the chemical compositional change of oxidation was tested by heating the test engine oil to 150 ºC during operation. The dielectric constant measurements showed a response due to this accelerated oxidation testing as shown in Figure 5. Early response of viscosity measurements to this accelerated oxidation test remained consistent with samples containing the same amount of soot but less oxidation experienced in earlier engine evaluations. The viscosity was seen to increase later in the test presumably after the oils antioxidant additives had been depleted, and well after the Army's FTIR oil analysis system would have condemned the oil due to oxidation, shown in Figure 6. Oil addition points can clearly be seen at 105 and 170 hours of operation time.

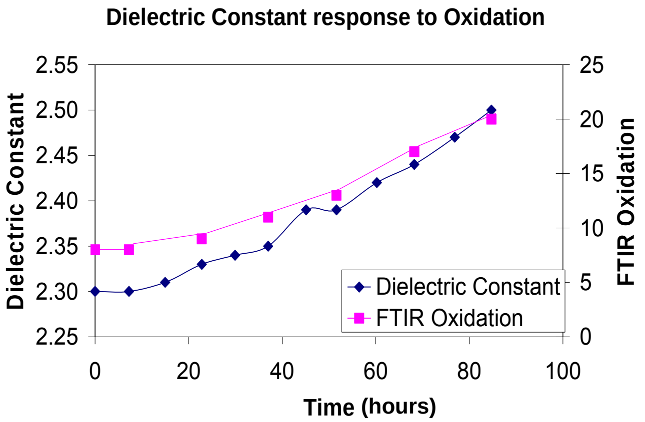

Figure 5. Change in dielectric constant due to oxidation as measured by FTIR.

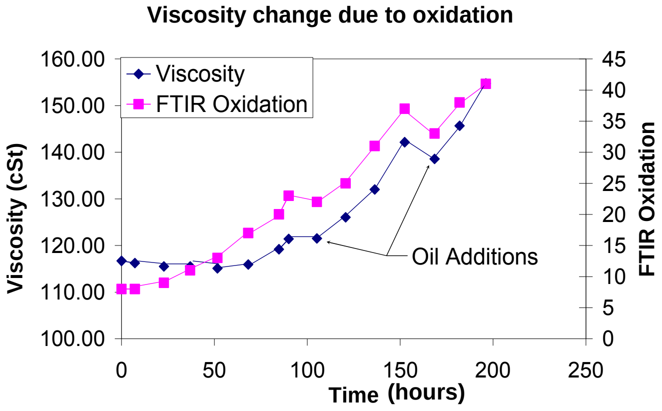

Figure 6. Change in viscosity due to oxidation as measured by FTIR.

FUEL DILUTION DETECTION

A fuel dilution situation was simulated by injecting fuel at a consistent rate into the test engine while running. The fuel was injected at an approximate rate of 0.5 mL per minute. The dielectric constant and conductivity sensors did not show any response due directly to the fuel induction. These sensors did show a change but this can be attributed to a soot increase of 1.5% from baseline, as observed from other test runs. The effect of fuel dilution on the viscosity of the oil resulted in a leveling off of the viscosity over time, seen in Figure 7, rather than the normal increase in viscosity found from soot loading as shown in Figure 4. This is different than was seen by creating artificial fuel dilution standards in the laboratory in which a dramatic drop in viscosity was observed. The difference can be attributed to the increase in viscosity due to soot, and possibly the removal of some of the lighter components of the fuel due to evaporation.

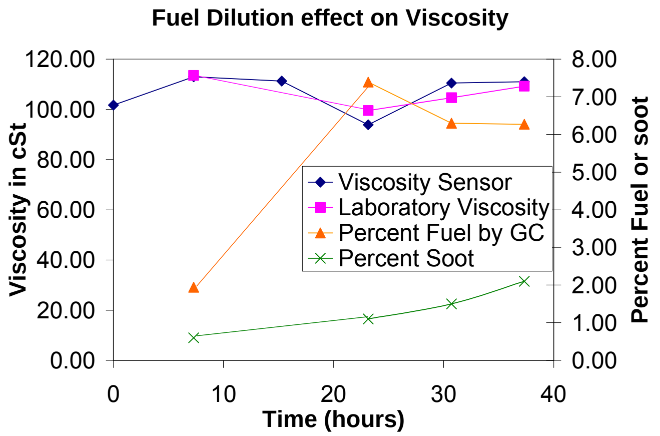

Figure 7. Fuel dilution caused a leveling off of viscosity during soot loading.

WATER DETECTION

The water detection tests were run before the procurement of the conductivity and electromagnetic viscosity sensors. These tests are planned to be repeated to evaluate the effect of water on these sensors. To simulate a coolant leak a 50/50 mix of antifreeze and water was added to the engine oil sump as detailed in [2]. The amount of water present in the oil was determined by Karl Fischer titration, changes in dielectric constant sensor and viscosity are plotted in Figure 8. The change in dielectric constant clearly indicates that this sensor is capable of detecting water in oil. Analyzing the change in viscosity, as measured in the laboratory, caused by water indicates that this sensor might be able to detect a rapid coolant leak. Both sensors have the capability to detect water but a slow coolant leak could easily be masked by the normal degradative processes of oxidation and soot loading.

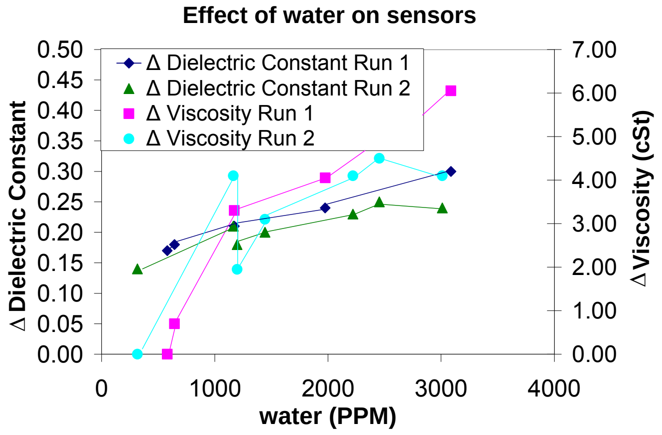

Figure 8. Change in dielectric constant and viscosity due to water induction.

FIELD TESTING

The final phase of the STO program was to demonstrate the oil sensing ability on military vehicles. To perform this demonstration a sensor cell was constructed which incorporates the CSI Oil View Model 5500 from Emerson process management, D-OCLS from Delphi, and the SPL571 viscosity sensor from Cambridge Applied Systems, shown in Figure 9. The system was built to be minimally intrusive to the vehicle by clamping on to the vehicles frame for support, and obtaining oil from existing oil lines, and returning oil to an existing orifice. Algorithms were built with the test data described above to provide a correlation to from sensor output to traditional laboratory analysis. Field testing is currently ongoing.

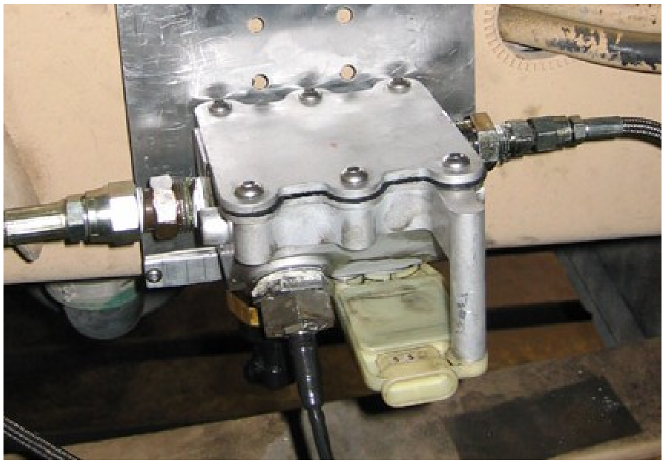

Figure 9. Sensor cell employed for field testing of onboard oil condition monitoring system.

CONCLUSION

This paper describes the U.S. Army TARDEC's effort in determining the ability to employ onboard sensors for the detection of oil condition in onboard vehicle applications. The sensor suite currently being field tested by the Army has the ability to monitor soot content and oxidation, as well as detect fuel dilution and rapid influxes of water contamination. Adoption of an onboard oil condition monitoring system will reduce or eliminate the Army's dependence on traditional oil analysis methods, or proposed hard time oil change intervals, by providing real-time condition monitoring and to project the remaining usable life of the lubricant.

ACKNOWLEDGMENTS

The authors wish to thank TARDEC's Petroleum and Water Business Area and Research Propulsion Laboratory, Robert Kauffman from the University of Dayton Research Institute, and American Systems Technology, Inc for their work on this program.

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