

Radiofrequency Sensor for Real-Time Engine Oil Quality Monitoring

F. Mejri and T. Aguilu

Abstract— The state mobile parks are very heterogeneous (cars, trucks, buses, tractors, equipment, etc.) with a wide variety of brands. This makes maintenance and drain management more complicated and costly. An adequate solution is proposed in this article not only to facilitate maintenance management but also to optimize its cost. It is based on a passive sensor that evaluates the condition of the lubricant, detects its degradation, and indicates the optimal timing for replacement. This information is displayed directly on the vehicle's interface. Moreover, it is sent wirelessly through an RFID network to the maintenance team responsible for the fleet. This team ensures real-time supervision and quality assurance of the lubricants across multiple vehicles simultaneously. Tracking the condition of the lubricant for each vehicle in the fleet provides accurate drainage intervals. This extends the durability of the lubricant and filters, resulting in significant savings in resources, labor, and operational costs. Additionally, it greatly simplifies the coordination of maintenance schedules. The development of this device is straightforward and cost-effective. It comprises a bifilar line, symmetrical and open at one extremity. It operates in the UHF frequency range. Measuring its input impedance while submerged in the lubricant allows for the direct calculation of the lubricant's dielectric constant, which changes as it deteriorates.

I. INTRODUCTION

The engine of a vehicle is equipped with a sophisticated lubrication system designed to ensure the smooth operation and longevity of all moving mechanical components [1-2]. Its primary function is to minimize friction between mechanical parts, thereby reducing wear and improving overall efficiency. In addition to its fundamental role in friction reduction, the lubrication system plays a crucial part in maintaining engine cleanliness by continuously removing combustion residues, microscopic metal particles, and other contaminants that result from component wear.

Furthermore, the lubricant [3-4] plays a significant role in engine cooling by dissipating the heat generated during operation, thereby preventing overheating and ensuring effective thermal management. It also enhances overall engine performance by reducing energy losses due to friction and by forming a protective film that minimizes direct contact between high-stress components.

However, the effectiveness of the lubricant deteriorates over time due to continuous exposure to extreme temperatures, mechanical stress, and contamination from external sources such as dust, fuel residues, and oxidation byproducts. Even when the vehicle is not in use, the lubricant's chemical properties gradually degrade as a result of oxidation and moisture accumulation. Consequently, periodic lubricant replacement is essential to prevent excessive wear and potential mechanical failures [5-6].

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For modern vehicles, the recommended oil change interval is typically based on operating hours or distance traveled. However, these conventional metrics do not accurately reflect the actual degradation state of the lubricant. Several additional factors influence oil deterioration, including engine operating conditions, exposure to highly contaminated or dusty environments, driving habits, load variations, and extreme temperature fluctuations [7-8].

Despite advancements in automotive technology, most vehicles today are still equipped with basic sensors that primarily monitor oil level and temperature [9]. However, these sensors do not provide direct insight into the real-time condition or degradation level of the lubricant. As a result, oil changes are often performed either too early-leading to unnecessary maintenance costs and environmental waste-or too late, which can significantly compromise engine performance and longevity.

Implementing a more advanced condition-based monitoring system for engine oil would enable precise, real-time assessment of lubricant quality, allowing for optimized maintenance scheduling. Such an approach would not only extend the lifespan of the lubricant and reduce operational costs, but also enhance engine protection and efficiency. Figure 1 illustrates a diverse fleet of mobile vehicles-including cars, trucks, buses, and agricultural machinery-where effective lubrication management is essential to maintaining performance and reliability.



Figure 1. state vehicle fleets [15-17].

Figure 2 illustrates the proposed solution presented in this study, which enables real-time monitoring and comprehensive

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quality assessment of a vehicle's lubricant. The system continuously analyzes key parameters-such as viscosity, temperature, contamination levels, and chemical composition-to accurately determine the lubricant's degradation state. When a critical deterioration threshold is reached, the system triggers a notification, alerting the user to perform an oil change at the optimal time.

This intelligent monitoring approach ensures that the lubricant is used to its full potential, preventing premature replacement while avoiding excessive engine wear caused by delayed maintenance. Additionally, it optimizes the lifespan of related consumables-such as air and fluid filters-by aligning their replacement schedules with actual operating conditions rather than fixed time intervals. By reducing unnecessary oil changes and improving maintenance efficiency, this solution delivers significant cost savings, minimizes environmental impact, and enhances overall vehicle reliability and performance.

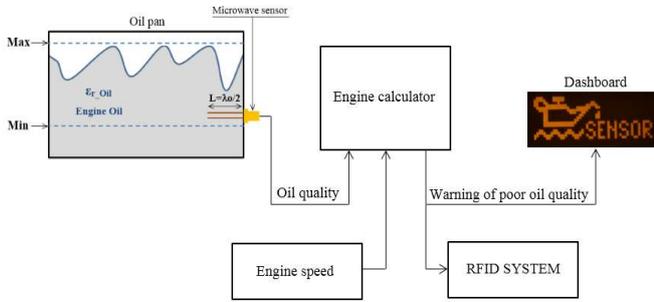


Figure 2. Solution for tracking and managing the condition of the lubricant in a vehicle.

A signal is also triggered when the oil level in the reservoir falls below the minimum threshold, ensuring timely intervention to prevent potential engine damage due to insufficient lubrication. In this critical situation, the dielectric constant of the measured substance shifts to that of air ($\epsilon_r = 1$), indicating the absence of lubricant in the system. This abrupt change is promptly detected by the monitoring system, which then triggers an alert on the vehicle's dashboard to notify the driver.

By integrating this real-time detection mechanism, the system enhances engine protection by preventing dry-running conditions that could lead to increased friction, overheating, and severe mechanical wear. This proactive approach not only improves vehicle safety and reliability but also reduces the risk of costly repairs associated with inadequate lubrication [10-11].

II. PRESENTATION OF THE STUDIED DETECTOR

A. Description of the study structure

The sensor designed to assess the condition of the lubricant is both simple to manufacture and cost-effective, making it a practical solution for real-time oil monitoring. It consists of a balanced two-wire transmission line [12-13] with an open-ended termination, as illustrated in figure 3. The design is based on fundamental transmission line principles, ensuring reliable and accurate measurement of the lubricant's dielectric properties.

The length of the transmission line is precisely selected to correspond to half the wavelength in a vacuum (or air), given by $L=(\lambda_o/2)=125$ mm. This configuration enhances the sensor's sensitivity to variations in the dielectric constant of the lubricant. The two conductive wires forming the transmission line are made of high-purity copper, ensuring excellent electrical conductivity and minimal signal loss. Each wire has a diameter of $d=1.38$ mm, and they are separated by a uniform spacing of $D=2.12$ mm to maintain stable impedance and improve measurement accuracy.

By leveraging this compact and efficient design, the sensor can detect real-time variations in the lubricant's dielectric properties, enabling precise monitoring of its condition and degradation. Its simplicity, durability, and low production cost make it highly suitable for integration into modern vehicle lubrication systems, thereby enhancing maintenance strategies and extending engine lifespan.

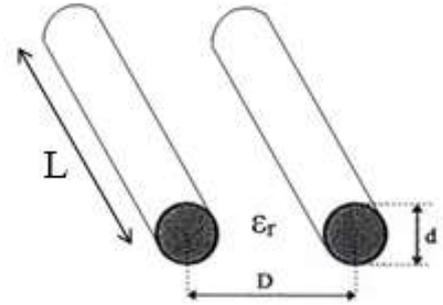


Figure 3. Description of the sensor for monitoring lubricant condition.

The transmission line is placed within a uniform dielectric medium, which can either be air ($\epsilon_r = 1$), as shown in figure 6A, or engine oil, whose relative permittivity ϵ_r is the parameter to be determined (Figure 6B). By immersing the transmission line in different media, variations in the dielectric constant can be accurately measured, providing real-time insights into the condition of the lubricant.

The system is designed to operate at a resonance frequency of $f = 1.2$ GHz, ensuring high sensitivity to changes in the dielectric properties of the surrounding medium. This frequency is selected to optimize the sensor's response while maintaining a compact and practical design suitable for automotive applications.

To characterize the impedance of the transmission line, the following empirical formula is used [14]:

$$Z_C = \frac{276}{\sqrt{\epsilon_r}} \cdot \log\left(\frac{2D}{d}\right) = \frac{Z_{C0}}{\sqrt{\epsilon_r}} \quad (1)$$

Where Z_{C0} is the characteristic impedance of the line when placed in air.

This impedance calculation is essential for accurately interpreting the sensor's response, as variations in the lubricant's dielectric constant directly influence the electrical properties of the transmission line. By analyzing these changes, the system can effectively assess oil quality, contamination

levels, and overall degradation, thereby supporting an intelligent and cost-effective predictive maintenance strategy.

B. Realization of the detector

Figure 4 illustrates the sensor developed to evaluate engine oil quality. The excitation is provided through a coaxial cable connected to an SMA connector.



Figure 4. Introduction to the engine oil quality sensor.

III. VALIDATION OF MEASUREMENT RESULTS

A. Validation of measurement results

Figure 5 presents a comparative analysis between the simulated data obtained using the Advanced Design System (ADS) platform and the experimental measurements acquired with a vector network analyzer (VNA). These results correspond to the sensor's operation in an air medium (as shown in figure 6), where the relative permittivity is $\epsilon_r = 1$.

The analysis demonstrates a strong correlation among the three datasets, with resonant frequencies closely aligned: 1.18 GHz from simulation, 1.19 GHz from experimental measurements, and 1.2 GHz from theoretical calculations. The minor discrepancies observed can be attributed to experimental uncertainties, fabrication tolerances, or slight variations in the test setup.

The close agreement between the theoretical, simulated, and measured results validates the accuracy and reliability of the sensor model. These findings confirm that the proposed detection mechanism functions as intended and provide a solid foundation for further testing in various dielectric environments, such as engine oil, to evaluate its real-world performance.

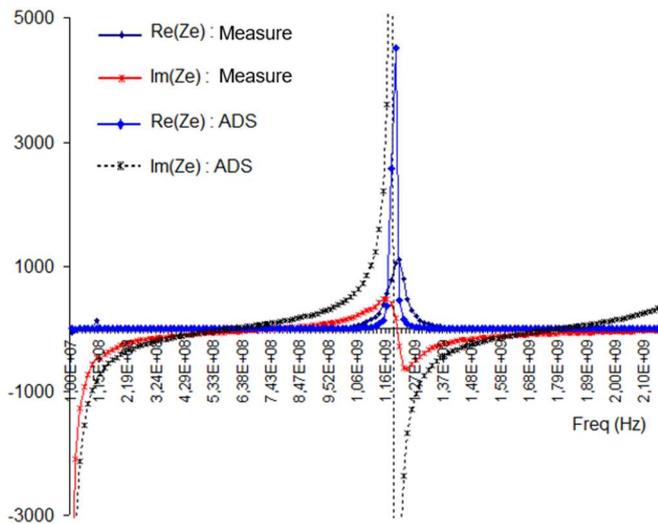


Figure 5. Input impedance of the line placed in the air ($\epsilon_r = 1$).

The relative permittivity deduced from the measurements is as follows:

$$\epsilon_r = \left(\frac{3 \cdot 10^8}{2 \cdot f \cdot L} \right)^2 = 1.017 \quad (2)$$

These measurement results have been thoroughly validated for air, yielding an average error of approximately 3%, confirming the accuracy and reliability of the proposed detection method. This minor deviation can be attributed to fabrication tolerances, slight inconsistencies in experimental conditions, or inherent measurement uncertainties.

In this validation process, an observed relative permittivity of $\epsilon_r = 1$ corresponds to the absence of lubricant or a minimum oil level, as shown in figure 2. This condition indicates that the transmission line is surrounded by air, triggering an alert in the system to signal the need for immediate oil replenishment.

By ensuring accurate detection of oil levels and dielectric variations, this sensor system enhances real-time monitoring capabilities, enabling more efficient and predictive maintenance strategies for vehicle lubrication systems.

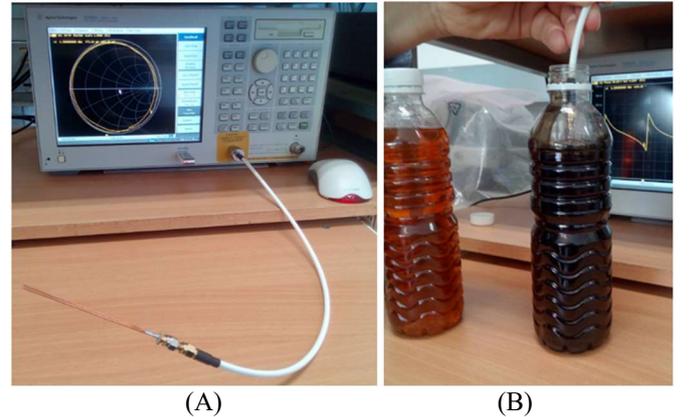


Figure 6. Measurement of the detector input impedance when placed (A) in air ($\epsilon_r = 1$), (B) in engine oil.

B. Assessment of the dielectric constant of motor oil

Engine oil plays a crucial role in ensuring the proper operation and longevity of an engine by reducing friction, dissipating heat, and preventing wear on internal components. When freshly added to the crankcase, it typically has a clear amber color, signifying its optimal viscosity and protective properties.

However, as the engine operates, the oil is subjected to various degrading factors, including thermal stress, oxidative reactions, contamination from fuel residues, metal particles, dust, and mechanical agitation within the crankcase. These factors contribute to the gradual darkening of the lubricant, which serves as a visual indicator of its deterioration.

This color change is more than just a sign of contamination; it reflects the progressive breakdown of the oil's molecular structure, leading to a reduction in viscosity stability, lubricating efficiency, and overall ability to form a protective film on engine components. As a result, degraded oil loses its effectiveness in minimizing friction, regulating engine

temperature, and preventing corrosion, increasing the risk of accelerated wear and potential mechanical failures.

Thus, continuous monitoring of oil quality is essential to ensure timely replacement, prevent engine damage, and optimize vehicle performance and maintenance costs.

The synthetic lubricant analyzed in this study is the commercial formulation "QUARTZ 9000-5W40," a high-performance motor oil known for its advanced additive package and superior stability under extreme conditions (Figure 7). This formulation was selected due to its widespread use in modern vehicles and its ability to maintain high lubrication efficiency across a wide range of temperatures and operating conditions.

Three distinct assessments were conducted on the oil at progressively increasing mileage intervals to evaluate its degradation and performance over time. Samples were collected at the following key stages: 0 km (unused or fresh oil), 5,000 km, and 10,000 km. These intervals were chosen to reflect common automotive service intervals, allowing for a comprehensive analysis of the oil's condition under typical driving conditions.

By comparing these properties at various stages of use, the study aims to provide a detailed understanding of how the oil's performance evolves over time, highlighting any significant deterioration in its lubricating and protective capabilities. This analysis is crucial for developing more accurate maintenance schedules and ensuring optimal engine protection throughout the oil's lifespan.



Figure 7. Analysis of motor oil properties across varying mileage intervals.

Figure 8 illustrates the evolution of the detector's input impedance when immersed in motor oil, providing crucial insight into how the sensor responds to different lubrication conditions. This preliminary analysis corresponds to the state of the unused lubricant (0 km mileage), offering a baseline for comparison as the oil degrades over time.

Figure 8 presents a comparison between the simulation results obtained using the Advanced Design System (ADS) platform and the experimental measurements conducted with a vector network analyzer (VNA). The comparison shows that both datasets exhibit nearly identical resonance frequencies, with the simulated frequency at 877 MHz and the measured frequency at 894 MHz. This slight discrepancy of 17 MHz falls

within the expected range of experimental variability and can be attributed to factors such as the measurement setup, environmental conditions, or minor variations in material properties.

The relative permittivity (ϵ_r) of the oil, determined from the measurements using the appropriate formula (Equation 2), was found to be $\epsilon_r = 1.8$. This value reflects the dielectric properties of the motor oil at its initial stage of use, providing important insights into its interaction with the electromagnetic field and its overall quality at this point.

When compared to the simulated value of $\epsilon_r = 1.87$ (from ADS), the measured result shows an error margin of 3.7%. This difference can be attributed to several factors, including the precision of the measurement equipment, the idealized assumptions in the simulation model, and potential variations in the oil's real-world properties. Nonetheless, this small error indicates that the experimental data is in good agreement with the simulation results, confirming the robustness and accuracy of the model used in both the simulation and physical testing processes.

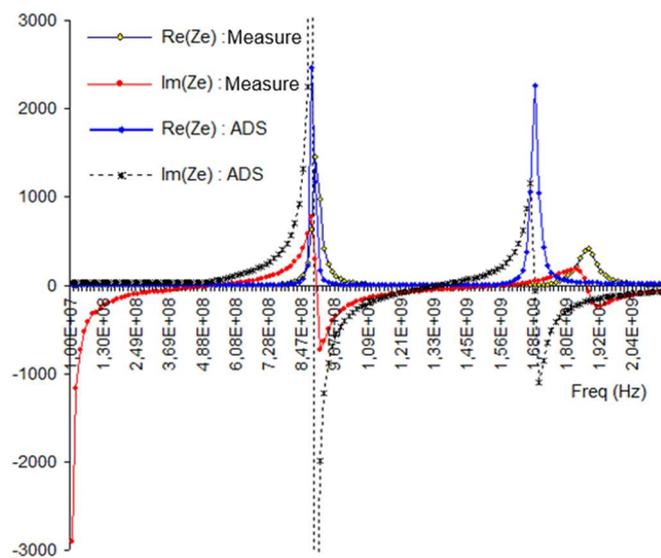


Figure 8. Electrical impedance characteristics of the sensor submerged in motor lubricant – Baseline state (unused oil, 0 km : relative permittivity ($\epsilon_r=1.81$)).

Figures 9 and 10A illustrate the dynamic evolution of the sensor's resonant frequency and input impedance spectral behavior as they correlate with accumulated mileage over time. These measurements were conducted with the sensor immersed in oil, ensuring continuous contact with the engine lubricant and allowing for an accurate and consistent assessment of the oil's degradation.

As the vehicle accumulates mileage, the properties of the engine oil progressively change due to factors such as thermal stress, oxidation, and contamination from particulate matter. These changes directly impact the oil's dielectric properties, which in turn influence the sensor's resonant frequency and input impedance. The measurements shown in figure 9 reveal a clear trend of shifting resonant frequency as the oil ages, corresponding to variations in the lubricant's dielectric constant.

In figure 10A, the spectral behavior of the input impedance is presented, illustrating how the impedance profile changes with increasing mileage. The gradual shift in impedance characteristics reflects the progressive degradation of the oil, offering valuable insights into the sensor's capability to monitor these changes in real time. Continuous immersion in oil ensures that the sensor's readings are consistently affected by the lubricant's evolving condition, providing an accurate representation of how the oil's properties change under normal operating conditions.

This dataset highlights the sensor's effectiveness in monitoring oil quality and provides a valuable foundation for developing predictive maintenance strategies, optimizing oil change intervals, and ensuring sustained protection of engine components.

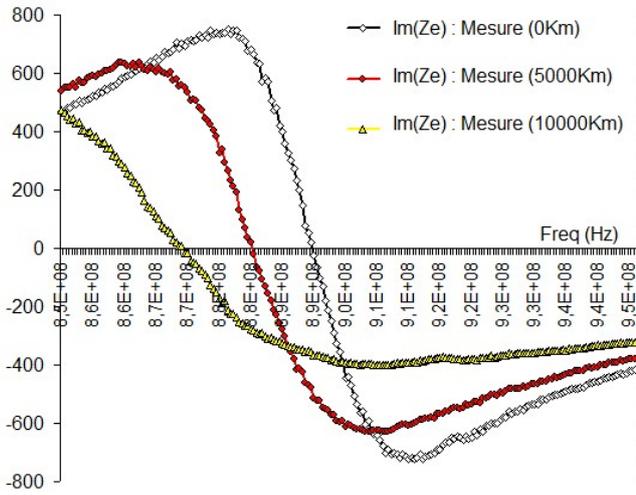


Figure 9. Electrical impedance profile of the sensor submerged in motor lubricant, correlated with progressive mileage intervals (0 km (unused), 5,000 km, and 10,000 km).

Figure 10B illustrates the progressive variation in the relative permittivity (ϵ_r) of the engine lubricant as a function of accumulated mileage, providing a direct correlation between oil quality and its dielectric properties. As mileage increases, the lubricant undergoes various physical and chemical transformations, which are reflected in the gradual shift of its relative permittivity.

It is observed that the lubricant begins to deteriorate significantly when the relative permittivity reaches $\epsilon_r = 1.9$, indicating a decline in the oil's insulating and lubricating properties. At this stage, the oil has undergone substantial oxidation, contamination, and thermal stress, compromising its effectiveness in protecting engine components.

On the other hand, a value of $\epsilon_r = 1.8$ corresponds to fresh engine oil, indicating that the lubricant is still in its optimal condition, providing the necessary viscosity and dielectric properties to maintain engine performance and protect against wear.

This relationship between relative permittivity and oil condition provides a valuable metric for determining the precise point at which the lubricant has degraded to the extent that it can no longer offer adequate protection. It enables the sensor to accurately trigger maintenance alerts, ensuring timely

oil changes, optimizing engine longevity, and reducing the risk of damage caused by deteriorated oil.

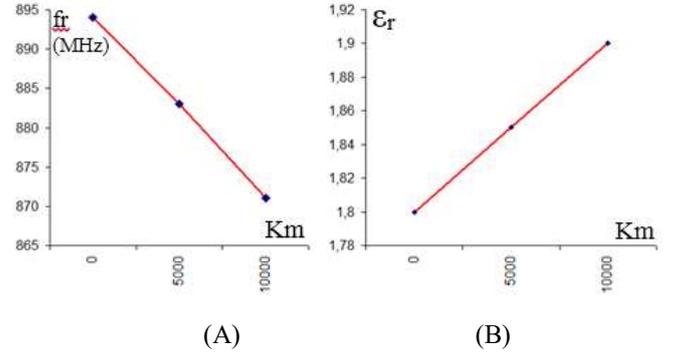


Figure 10. Evolution of the sensor's resonance frequency (A) and variation in the engine lubricant's relative permittivity (B) as a function of the accumulated mileage.

IV. DISCUSSION AND FUTURE WORK

This study has demonstrated the feasibility of using a radiofrequency-based sensor for real-time monitoring of motor oil condition. While the results are promising, several aspects require further exploration to enhance the system's robustness and practical applicability in automotive environments.

First, although prior studies have investigated the relationship between oil degradation and dielectric properties, our work uniquely focuses on a compact resonant RF sensor capable of real-time, in-situ measurements. Future work will include a more detailed comparison with existing sensor technologies to contextualize the advantages of our approach, particularly in terms of integration, cost-effectiveness, and continuous monitoring capabilities.

Second, regarding the repeatability and reliability of the measurements, initial experimental results showed consistent performance with a low error margin (<3%). However, we acknowledge the importance of including error bars, multiple trial runs, and statistical validation in future versions. These additions will offer a more comprehensive understanding of the sensor's stability and repeatability under controlled conditions.

Third, the influence of environmental and mechanical factors—such as temperature fluctuations, engine vibrations, and variations in sensor orientation—was not addressed in the current study. These conditions are typical of real automotive settings and could potentially impact sensor performance. As part of our future research, we plan to design and conduct experiments that specifically assess the sensor's behavior under these dynamic conditions. These efforts aim to improve the sensor's robustness, ensure measurement reliability, and support its deployment in smart vehicle maintenance systems.

Additionally, future investigations will extend to a broader range of engine oils (e.g., 15W-40), allowing for a more complete calibration of the system and an evaluation of its adaptability to different lubricant formulations.

V. CONCLUSION

The objective of this study was to validate the use of a radiofrequency-based sensor for continuous real-time

monitoring and assessment of motor oil condition, providing a more efficient and reliable solution for vehicle engine maintenance. Through comprehensive analysis, the measurement results were successfully validated using ADS software, with an error margin of approximately 3%, confirming the sensor's reliability

The core principle of this approach lies in determining the relative permittivity (ϵ_r) of the engine lubricant by closely monitoring variations in the sensor's resonance frequency. As the engine operates and accumulates mileage, these frequency shifts are directly linked to oil degradation caused by thermal stress, oxidation, and contamination. By continuously tracking these variations, the sensor provides real-time insight into the lubricant's condition, enabling predictive maintenance strategies and ensuring timely oil replacement when it no longer offers adequate protection for engine components.

This study highlights the potential of radiofrequency-based sensors as an effective tool for engine oil management, offering multiple advantages such as cost savings through optimized oil change intervals, improved engine protection via timely oil replacements, and reduced environmental impact by minimizing unnecessary oil disposal. Moreover, the sensor system can be seamlessly integrated into modern vehicles, contributing to the advancement of smart maintenance systems. In the future, this technology could be extended to monitor other critical fluids and components within the vehicle, paving the way for more comprehensive real-time monitoring solutions in the automotive industry.

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