Analysis Of Oxygen Sensor Dynamics For Catalytic Converter Diagnostics Using On-Board Logging Data

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Abstract — **A catalytic converter is an important component of modern internal combustion engines, used to reduce the toxicity of exhaust gases by neutralizing harmful components such as nitrogen oxides, carbon monoxide, and unburned hydrocarbons. Successful operation of the converter requires maintaining a stoichiometric ratio of fuel to oxygen, which for gasoline engines is 14.7:1. This ratio is controlled by an automatic control system, the key element of which is an oxygen sensor (lambda probe). This paper aims to experimentally study the efficiency of a three-way catalytic converters (TWC) by analyzing the dynamics of oxygen sensor signals obtained using an on-board diagnostic system (OBD). The diagnostic method is based on comparing ECU signals from sensors before (Sensor 1) and after (Sensor 2) the catalytic converter. Real data from OBD parameter logging (Engine Load, RPM, O2 Sensor Voltages) during movement was used for analysis. Data analysis showed that under conditions of dynamic movement and load changes (Engine Load), the control sensor signal (Sensor 1) fluctuated constantly (0.1–0.9 V), while the diagnostic sensor signal (Sensor 2) remained consistently high (0.6–0.7 V). This behavior confirms that the TWC successfully accumulates oxygen and equalizes the composition of exhaust gases, which indicates its high efficiency and the absence of fault code P0420.**

Keywords — Oxygen Sensor; Catalytic Converter; On-Board Diagnostics (OBD)

I. INTRODUCTION

A. Justification of Research Relevance

To reduce the toxicity of exhaust gases through the reduction of nitrogen oxides and the use of oxygen to burn carbon monoxide and unburned hydrocarbons, a catalytic converter is used in modern internal combustion engines. It is installed in the exhaust system of the engine and the main requirement for its successful operation is to ensure the stoichiometric ratio of fuel and oxygen in the fuel-air mixture, [1].

B. Problem Statement

In contemporary engines, the maintenance of the air-fuel ratio close to the optimal is carried out by means of an automatic control system. The core challenge lies in continuously monitoring and ensuring the proper functioning of the catalytic converter to guarantee compliance with emission standards, especially since its operation is critically dependent on a precisely controlled air-fuel mixture, [2].

C. Review of the Current State of Research

The stoichiometric mixture is a composition, which ensures complete combustion of fuel without residual oxygen, and the coefficient of excess air for this combustible mixture is equal to one. For gasoline internal combustion engines with spark ignition, the stoichiometric ratio is air/fuel, equal to 14.7:1 (mass parts). The main sensor in such systems is a sensor of the concentration of free oxygen in the exhaust gases of the engine — the oxygen sensor (or lambda sensor). Three-way catalytic converters (TWC) to neutralize carbon monoxide (CO), hydrocarbons (CxHy) and nitrous oxide (NO and NO2) use two different types of catalysts: reducing and oxidizing, [3]. Both types are made in the form of a ceramic structure (carrier block) coated with a metal catalyst (usually platinum or its alloy). Unburned residues are oxidized by oxygen released during the NO reduction reaction and also partially contained in the exhaust gases, which releases heat and activates the catalyst, [4].

Today, approaches based on artificial intelligence are increasingly being sought for adaptive emission control and sensor diagnostics [5]. It is also important for Ukraine to reduce emissions from high-mileage vehicle fleets by replacing catalytic converters and oxygen sensors [6]. Therefore, research aimed at creating a program for vehicle inspection and maintenance using OBD is important [7].

II. METHODS

A. Collection of experimental data

To empirically verify the effectiveness of TWC diagnostics, data obtained using an on-board diagnostic system (OBD II) for a 63 kW 86 hp BXW VW CGGB 1.4 MPi 16v engine during a real driving cycle was used. Parameters were logged with time and geolocation recording. The key parameters selected for analysis were: Engine Load (%), Engine RPM (rpm), Speed (OBD) (km/h), Engine Coolant Temperature (°C), O_2 Bank 1 Sensor 1 Voltage (V), and O_2 Bank 1 Sensor 2 Voltage (V). Throttle Position (Manifold) (%), Speed (GPS)(km/h) and Speed (OBD)(km/h) were also taken into account. The data was obtained in csv format.

B. Methodology for analyzing sensor signals

The technical condition of the TWC was analyzed by evaluating the dynamic behavior of oxygen sensor signals. When the catalytic converter is working effectively, the control sensor (O_2 Bank 1 Sensor 1, upstream of the catalytic converter – TWC) should show rapid voltage fluctuations (between 0.1 V and 0.9 V), while the diagnostic sensor (O_2 Bank 1 Sensor 2, downstream of the catalytic converter) should have a stable, slowly changing voltage (preferably 0.6 V... 0.7 V). Any increase in the switching frequency of Sensor 2 would indicate a decrease in the ability of the catalytic converter to accumulate oxygen. The analysis was carried out both when the engine reached operating temperature (above 80 °C) to ensure the correct operation of the sensors, and during the engine warm-up phase and the gradual transition of the sensors to steady-state operation.

III. RESULTS:

Analysis of the oxygen sensors (O_2 S1 and O_2 S2) over time is crucial for evaluating the efficiency of the catalytic converter. O_2 Bank 1 Sensor 1: Rapid and regular voltage fluctuations (from ≈0.1 V to ≈0.9 V) are observed. This is normal behavior for a narrowband sensor, which actively helps the ECU maintain a stoichiometric ratio (λ≈1) by constantly correcting the fuel mixture. O_2 Bank 1 Sensor 2: The voltage is stable, mostly staying in the range of ≈0.6 V...0.7 V, and has very slow and low-amplitude changes. This indicates that the catalytic converter is successfully accumulating oxygen and equalizing the composition of the exhaust gases, [8].

There is no direct dependence on load (Engine Load) and speed (RPM) for O_2 Bank 1 Sensor 1; a constant switching cycle is maintained for mixture correction.

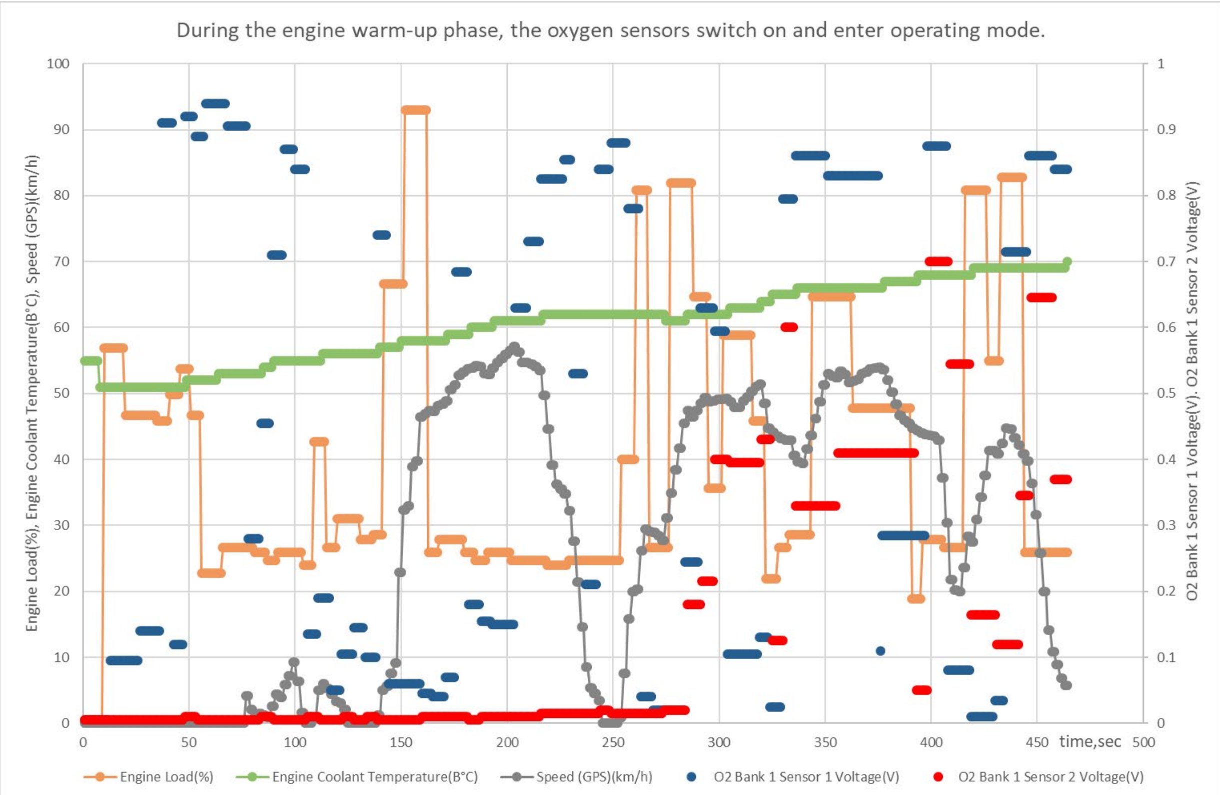

Fig. 1. graphs of oxygen sensors operation during engine warm-up.

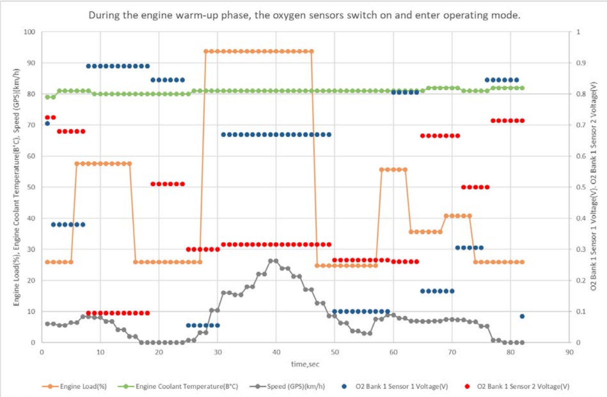

Fig. 2. Engine operation in "city" mode, frequent sudden load changes during acceleration, low speeds, reduction of voltages S1 and S2 (from 0.9 and 0.7 to 0.67 and 0.32 V, respectively) with an increase in Engine Load (up to 95%)

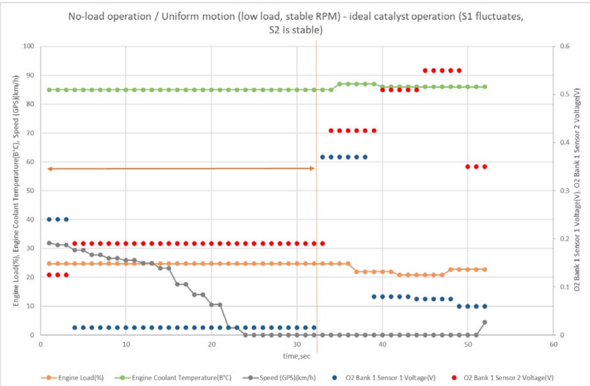

Fig. 3. Engine operation during smooth deceleration, idle speed, consistently low voltage S1 and S2 (up to 0.25 V)

IV. Conclusions

The analysis of real log data confirmed the theoretical basis for KN diagnostics. The dynamics of oxygen sensors (Fig. 2, 3) clearly showed that Sensor 1 constantly corrected the mixture, while Sensor 2 remained stable, which is direct evidence of the high current efficiency of the catalytic converter.

In addition, it was found that the stability of the Sensor 2 signal is maintained across the entire range of engine load and speed, confirming the reliability of the catalytic converter in dynamic driving conditions (Fig. 2).

The results obtained demonstrate that on-board logging is an effective tool for continuous monitoring and assessment of the technical condition of the catalytic converter before critical fault codes such as P0420/P0430 appear.

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