

A Novel Method to Evaluate the Combustion Quality of Gasoline Engines: Exhaust Waveform Using AutoEKG Fuel System Analyzer

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ABSTRACT

A tool was developed by Illinois Tool Works (ITW) called the "AutoEKG®FSA" (AutoEKG Fuel System Analyzer) which evaluates combustion quality in an engine by measuring the exhaust pulses of the engine. While many factors are known to influence combustion quality and the wave pattern produced by the instrument, the primary factor in this study was the presence of an asphalt-like material in the air intake system. By examining the waveforms measured by the AutoEKG®FSA system before and after carbon cleaning, it has been observed that the engines studied not only run better after the removal of carbon in the system, but the improvements may be measured using this system.

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INTRODUCTION

There are many factors which affect the combustion efficiency of a gasoline engine including compression ratio, fuel composition, spark plug wear, and air flow. Of primary concern in this study is the latter; air flow into the engine. Most modern engines are designed with a precise turbulence in mind, with many fast-burn engines having a build-in turbulence known as "swirl".

When the swirl is disrupted, air flow is constricted or likewise deviated from the design specifications and the engine performance degrades in terms of power [1], fuel economy [2], and drivability (1). As the engine runs engine oils, soots, gasoline, and other compounds combine and deposit on the surfaces of the engine including the combustion chamber walls, piston face, and throughout the intake system and hereafter, will be known as 'carbon'. The literature shows that gasoline composition and oil formulation both affect these deposits [3,4]. For example, gasolines with high levels of olefins and particularly aromatic compounds produce more intake valve deposits (IVD) than fuels comprised largely of saturated aliphatic compounds [3]. Additionally, fuels with higher percentages of ethanol have reduced intake valve deposits over fuels without ethanol for flex-fuel vehicles [5]. The presence of an Exhaust Gas Recirculation (EGR) system is also expected to increase carbon deposits since soot-bearing exhaust is fed into the air intake system.

When carbon deposits are thick, the area through which air enters the combustion chamber is constricted, which reduces the available energy as much as 22% in a conventional engine, and even greater losses in fast-burn engines [1]. Additionally, under cold acceleration, valve deposits disrupt air-fuel mixing, leading to "hesitations and stumbles" [1], even when the swirl within the engine is not disrupted [1]. An uneven buildup of carbon on either the port or valve is expected to cause a greater perturbation of swirl than an even buildup.

Because the carbon deposits also tend to be porous, fuel may be adsorbed into the residue when the engine is cool leading to excessively lean combustion [6]. Conversely, as the engine heats up, this fuel is desorbed from the carbon and rich combustion may occur [6]. At equilibrium, which is never fully achieved, the adsorbed fuel is equivalent to the amount of fuel injected for a given cycle [6]. Additionally, thick carbon deposits can cause the valves to not seat properly leading to air leakage, low engine pressures and other problems resulting in inefficient combustion.

Evaluating the combustion efficiency of an engine and its relation to carbon buildup is a challenging topic because of the complexity of the system. One means of measuring the carbon deposit effects was proposed by Glidewell and Chui [7] who used pressure waveforms to diagnose clogging of fuel injectors [7]. Despite adequately determining clogging problems with injectors and fuel delivery, this type of system is limited to fuel metering problems and cannot

diagnose any problems downstream. Other diagnostics of intake and valve carbon tend to rely on visual inspection, or mechanically cleaning the system and weighing the individual parts.

The AutoEKG system designed by Automotive Test Solutions (ATS) assesses combustion quality by examining the movement of exhaust gases out of the tailpipe of a vehicle. This movement is translated by the AutoEKG into a waveform which allows identification of misfires as well as providing a visual means of observing uneven combustion within the engine. In this work, a novel method is discussed in detail to evaluate the combustion quality of gasoline engines by exhaust waveform.

METHODS AND MATERIALS

The method followed in this study for each vehicle involved several stages. First, each vehicle was driven a short distance during which measurements from the engine's computer were taken using an OBDII diagnostic scan tool to identify problems with, Diagnostic Trouble Codes (DTC), fuel control, volumetric efficiency and catalytic converter efficiency. Additionally, these initial test drives were used to identify if the vehicle was misfiring before any carbon cleaning was performed. Driving also served to warm the vehicle to operating temperature before testing. Following this driving test, the AutoEKGFS probe was placed into the exhaust tailpipe of the vehicle, the spark-firing detector (antenna) was placed on the engine near the firing coils and the AutoEKGFS program was run according to the on-screen directions. The AutoEKGFS test was run a total of four separate times and an average score was determined. High score suggest a clean and efficiently running engine.

Four cylinder engines tend to show uneven bottoms to the waveform when the engine has carbon buildup. A typical 6-8 cylinder engine waveform has a high ratio of directional change to locus length for an engine with significant carbon buildup. Clean four cylinder engines show more even combustion between cylinders as evidenced by an even-bottom waveform where 6-8 cylinder engines have a smoother waveform with fewer directional changes and longer locus length.

Following the AutoEKGFS test, the engine was allowed to cool for several minutes before being examined visually. Typically, the fuel injection rail was removed and a boroscope was fed into the intake port and pictures were taken of both the intake port and the intake valves. When possible, several ports and valves were examined. When the fuel injection rail was unavailable, the boroscope was fed through the air intake system into the intake port to take pictures.

A visual carbon score was assigned to each set of intake ports and intake valves that were inspected, and the final score was taken as the average between those two values. As with the AutoEKGFS score, the higher the score, the cleaner the engine. An engine with even carbon buildup will generally score higher than an engine with uneven buildup as a rough surface is expected to disrupt air flow more than a smooth surface. [Figure 1a](#) and [1b](#) show a clean control engine's port and valve, respectively as an example, where [Figures 1c](#) shows a dirtier engine's port and valve.

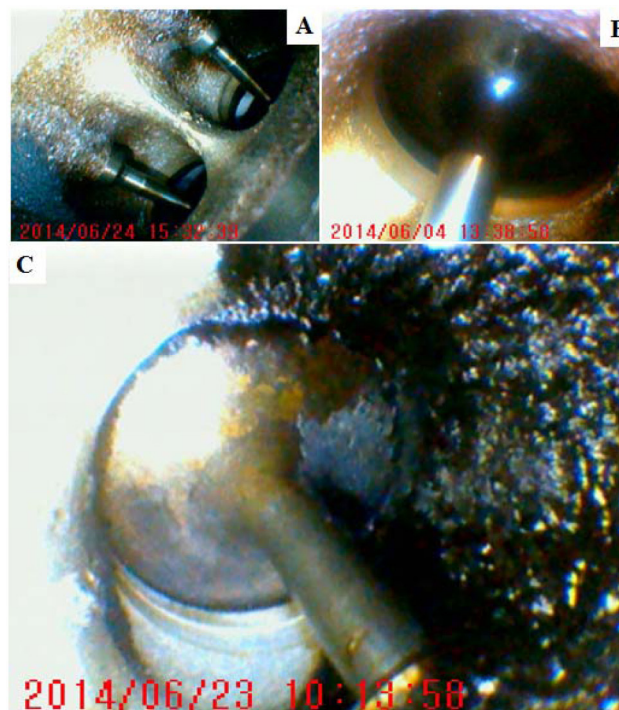


Figure 1. a) port and b) valve of clean 2003 Chrysler PT Cruiser and c) port and valve of a dirty 2006 Honda CR-V, note carbon buildup much thicker on one side of port than the other.

After the scores for AutoEKGFS and visual scan were made, the vehicles were cleaned using a combination of a cleaner and a wash solution which alternated during cleaning. Additionally, a fuel treatment was added to the fuel tanks of each non-control vehicle which contains Polyetheramine and di-tert-butyl peroxide (DTBP).

Each cleaning agent is commercially available. Control vehicles were not cleaned with any of these three products. When required, the cleaning process was repeated.

Once the cleaning process was completed, the vehicle was returned to its owner who was instructed to drive at least one tank of gasoline before the next series of tests. When the vehicle was returned, the diagnostics including the AutoEKGFS and visual evaluation were repeated and the scores were recorded. At this time, any additional issues with the vehicle were diagnosed and when possible, repaired. If any additional repairs were required for the vehicle, the AutoEKGFS was run again to obtain the final score.

The vehicles in this study were all privately-owned, port-injected, and had between 30,000 miles to 214,000 miles. The majority of the vehicles in this study had been driven 70,000 mile to 150,000 miles in total. Vehicles were selected from a wide range of makes including Dodge-Chrysler-Jeep, General Motors, Nissan, Honda, Acura, Kia, Toyota, and Ford, and a majority were models from 1996 or newer.

BACKGROUND

Tool Function

As noted briefly, the AutoEKGFS system evaluates combustion quality within a vehicle's engine by examining exhaust gas flow.

During engine operation each combustion cylinder vents hot gases into an exhaust manifold which in turn vents through the catalytic converter, mufflers and finally the tail pipe of the vehicles. Certain vehicles may be equipped with additional exhaust treatments such as EGR and sound modifiers. As each cylinder expels waste gases, a pressure pulse is generated in the exhaust system which eventually vents to atmosphere through the tail pipe.

The AutoEKGFSa probe, which is inserted into the exhaust tail pipe of the vehicle, measures the pressure pulse just prior to venting to atmosphere. As air flows into the tool, it flows into a venturi, which decreases the pressure of the pulse and funnels the air into a sensor. After flowing through the venturi, the reduced-pressure pulse impinges on a piezoelectric pressure transducer which converts the pressure pattern to a voltage. The voltage pattern is then converted to a digital signal which is read by proprietary software. Because the program takes measurements for 50 seconds, multiple exhaust pulses are measured by each cylinder resulting in an exhaust pressure waveform.

Additionally, the AutoEKGFSa tool also includes an antenna which is placed on the engine. This antenna detects the electrical pulse associated with the firing of a spark plug which is also sent to the software to mark engine timing. The spark plug timing is used within the program (along with a secondary algorithm based on the number of cylinders) to include subdivisions in the waveform to aid in analysis.

Waveform Analysis

Within a single test, a set of 10 sub-tests are evaluated (in five second intervals) on several criteria based upon the engine configuration. For example, an engine with two, three, or four cylinders will be evaluated by how even the troughs (bottom) are on the waveform, the number of directional changes divided by the locus length (length of each segment, DC/LC), and the height of the 'bump' (secondary

pressure rise) prior to negative pressure. Each cylinder is compared only to itself in the software. An uneven-bottomed waveform is shown in [Figure 2a](#) where a more even-bottomed waveform is shown in [Figure 2b](#), from Vehicle 13 (Toyota Rav4) before and after cleaning, respectively. The green lines on [Figures 2-3](#) are the engine timing markers setting the cylinders identification and the yellow line is the exhaust pressure measurement. The longer, thicker green line marks the beginning of each set of the engines firing cycle; the antenna signal has been removed for ease of viewing.

A six or eight cylinder engine, on the other hand is evaluated based on the trough (bottom) differences, and the number of directional changes divided by the locus length (length of each segment, DC/LC). This measures how 'rough' the wave for each cylinder is and may be seen for Vehicle 11 (Ford Edge) before and after cleaning in [Figure 3a](#) and [3b](#), respectively. The DC/LC difference is most noticeable at the peaks and troughs of the waveform compared to the midline in [Figure 3](#).

The difference in measurement regime based on the number of cylinders is a product of the exhaust setup. A typical exhaust system for a four-cylinder engine has one exhaust manifold attached to the exhaust pipe with catalytic converter and muffler in-between. However, most six- and eight-cylinder engines do not have a straight block, but rather two individual cylinder banks attached to separate exhaust manifolds which then connect to the exhaust system through either a "Y" or "H" pipe configuration, depending on the manufacturer. The converging exhaust manifolds may produce a waveform with multiple resonances and therefore not produce a clean sinusoidal pattern. The more complicated waveform requires then, a different algorithm to examine combustion efficiency. As noted before the primary algorithm to evaluate six- and eight-cylinder engines evaluates the efficiency of the engine through DC/LC, where a smoother waveform (fewer directional changes and longer locus length) will produce a higher score and indicate a clean engine.

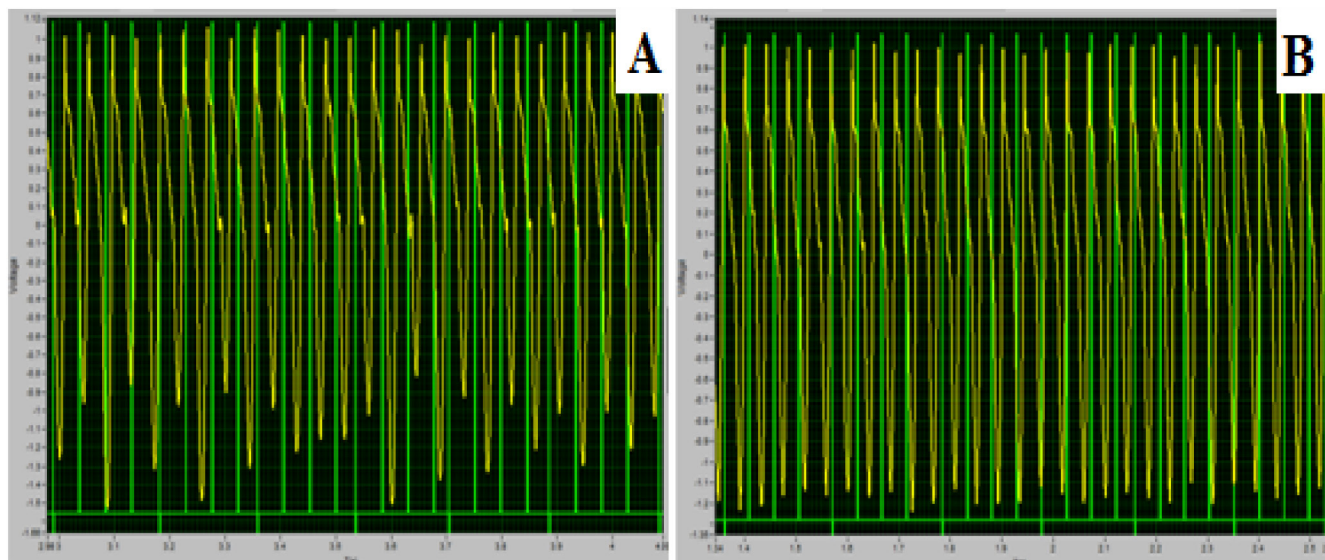


Figure 2. Waveforms for a Four-Cylinder Toyota Rav4 A) Before and B) After Carbon Cleaning