# Control charts for defining the pollutant gas limits in a spark ignition combustion engine with faults

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*Abstract: - In this paper, an analysis of the pollution limits generated due to faults in a spark ignition engine associated to the low ignition voltage and to the change in the air/fuel ratio, using control charts is presented. The data collected corresponds to the emission of gases generated in the vehicle in normal operation and fault conditions, from which the control charts are developed for the mean and range of: Carbon Monoxide (CO), Unburned hydrocarbons (UHC) and Carbon Dioxide ($CO_2$). From the limits defined in normal operating conditions of the engine, the sensitivity of these charts for the detection of out-of-control values, obtained from the induction of the aforementioned faults, is tested. The obtained results show that, under normal operating conditions, the upper control limits obtained do not differ significantly from the maximum admissible values established in international environmental regulations, and that the highest values registered of polluting emissions together with the sudden changes on the developed control charts are found for the rich dosage and therefore all failures that generate this type of mixture must be considered as critical due to the impact it generates in the ecosystem.*

*Key-Words: -* Control charts, Pollutant gases, faults analysis, spark ignition engine

## 1 Introduction

A subject of great worldwide importance is the reduction of tons of carbon dioxide ($CO_2$) in the air as a result of the vehicle fleet. Therefore, it is important to have maximum levels established in each country that regulate emissions from mobile sources, thus determining that vehicles whose emissions exceed the maximum values must undergo an inspection in order to determine the origin of the polluting agents with high level emission, and apply the pertinent corrective actions to reduce the environmental impact they generate.

In the automotive industry, different statistical quality control techniques are widely used. In important brands associated with this industry, special supervision and quality monitoring programs have been generated, as [6] shows. In [2] it is warned that every organization must implement monitoring, measurement, analysis and improvement processes to demonstrate the products or services conformity, where the environmental interaction should be considered.

Control charts have been used in different types of maintenance in order to improve different processes considering failures over time. Thus, [3] identify correct maintenance actions from the analysis of past and recurring failures and plan and program actions aimed at improving the efficiency of the maintenance function. These modalities of application of control charts in maintenance are expanded by other developments such as those presented by: [7], [5] and [1], where First authors focus on evaluating the performance of the diagrams through three metrics: the metric average run length and two of them unconventional, incorporating the concept of lateral variability to monitor the processes. The second authors design an experiment based on the application of control charts to compare the effectiveness it will have on the useful life, the application of predictive maintenance techniques, with a diagnosis of the degradation processes and the last authors design a control chart that uses the sudden death test assuming that the life time/failure of a product follows the Weibull distribution. Also, [9] study a single server queue system with different levels of energy consumption in the associated execution states to address the conflict between energy consumption and customer delay, developing a maintenance model that minimizes the total long-term expected cost of the system based on energy consumption and the use of control charts.

In Latin America, it is common to use vehicles with spark ignition combustion engines, which cause the emissions of polluting gases to the environment and therefore it is imperative to control these gases, taking them to the smallest possible magnitudes. Thus, this research focuses on defining based on control charts, the contamination limits of Carbon Monoxide (CO), Unburned Hydrocarbons (UHC) and Carbon Dioxide ($CO_2$) present in the gases emitted by spark ignition engines. This will allow having up-to-date values of the emissions to the environment given by a vehicle with faults in the ignition system, expanding the use of control charts for improving the environmental conditions.

It is proposed to work based on data obtained from a simulation process in which three types of failures will be induced to these engines, two of them are achieved through alterations in fuel pressure and the third will be a variation on the distance of the spark plug electrode. From these faults, the gases emanations generated by the engine will be measured, comparing the obtained results with the measurements made with the engine under normal operating conditions; this in order to establish the contamination levels that appear after the appearance of a fault.

This work is organized as follows; section 2 describes the methodology with an experimental part developed by [8] and the stages prior to obtaining and analyzing the data. In the third section, the control charts are developed and the sensitivity of those charts is tested for detecting extreme values of emissions when in the engine is induced three types of faults in the combustion system: increase in the fuel pressure, decrease in the average fuel pressure, and low ignition voltage. In section 4 the most relevant conclusions are presented, where it is found that the most critical point of operation is located when the air/fuel mixture is rich.

# 2 Methodology

Based on the opinion of experts, it was possible to determine that the interesting faults for the realization of this investigation refer to the variation in the fuel pressure and the wear of the spark plugs. It´s for this reason that three types of engine failures are generated in order to de-termine the effect of the emissions factors on the exhaust system.
The experimental procedure used to obtain the data is the one developed by [8], where a dyna-mometer MAHA LPS 3000 and a gas analyzer NGA 6000 were used. The tests were developed in the laboratories of the Automotive Mechanical Engineering School of the Universidad Politécnica Salesiana in Cuenca, Ecuador.
The research is carried out by implementing the following phases:

## 2.1 First phase

It contemplates the development of the experiment and the set-up for the first run with the engine in normal operating condition. This engine belongs to a Chevrolet vehicle, model corsa evolution 1.4L, with a cubic capacity of 1388 cc, nominal distance of the spark plugs of 0.8 mm, nominal fuel pressure of 50 psi, consumption 6.81/100 km and a multipoint injection system. The test is performed in the dynamometer test bench and the emissions of CO, UHC and $CO_2$ gases are measured with the NGA 6000.

## 2.2 Second phase

Here the experimental activities are carried out under fault conditions incorporating changes in the fuel pressure and alteration in the spark plug electrode space, in order to simulate faults associated with the air/fuel mixture and ignition.

The pollutant gases emanating from the engine of a Corsa Evolution are taken as the most important measurements and 225 measurements with 5 repetitions of the experiment are considered for the analysis.
The study conditions have been coded considering the normal operation and the three faults of the engine operation as follows: 0: engine condition under normal operating conditions, 1: fuel pressure alteration, pressure 60 psi, 2: alteration in fuel pressure, pressure 40 psi and 3: alteration in the space of the electrode of the spark plugs, electrode space 1.3 mm.

### 2.3 Third Phase

In this stage, the control charts are made for the average emissions ($\bar{X}$ and R). The control charts are made for the average emissions of CO, UHC and $CO_2$ in order to establish the test limits, for which the measurements are analyzed in optimal operating conditions. Once the test limits have been obtained, the sensitivity of these is verified in the presence of faults.

## 3 Control charts for detecting extreme values of emissions under fault conditions in the combustion system

In each measurement, records of carbon monoxide (CO), Unburned Hydrocarbons (UHC) and carbon dioxide ($CO_2$) emissions are obtained. These samples were obtained by applying a systematic type sampling, which allows to sequentially sample a data file such as that obtained from the test bench. With this type of sampling the measurements timing is not lost.
With the use of SPSS statistical software, version 20 [4], the control charts for the mean and the range (as dispersion measure) of the variables included in the research were made, using the engine data without faults in order to be able to establish the test limits. Due to the nature of the research, the control upper limit resulting for the diagrams of the analyzed gases, can be established as the maximum permissible reference; while the control lower limit may suggest the operation reference, but if a measurement is below this value for polluting gases, it should not be interpreted as a situation out of control.

### 3.1 Control charts for the average CO, UHC and $CO_2$

The emissions of carbon monoxide (CO), carbon dioxide ($CO_2$) are reported in percentage (%) and Unburned Hydrocarbons emissions (UHC) are reported in parts per million (ppm). In these, the upper and lower limits of the mean can be established as detailed in figures 1, 2 and 3.
When observing the control diagram for the mean CO shown in Figure 1, the grouping of the observations around the central line is evident, this may suggest a possible stratification. However, due to the characteristics of the analyzed engine and the results reported by the dynamometer, the measurements are usually very homogeneous or similar, therefore, fluctuations or important variations in CO emissions are not expected, where their limits range moves from 0.43% to 0.61%.
The control diagram for the UHC mean depicted in Figure 2 shows the grouping of the observations around the central line, which may suggest a possible stratification. However, due to the characteristics of the engine analyzed and the results reported by the test bench, the measurements of UHC emissions are usually very homogeneous. Thus, average UHC emissions are under statistical control and their limits range from 158.92 ppm to 221.08 ppm.
In the case of $CO_2$ emissions (see Figure 3), it is evident that the shown pattern is in harmony with a stable system of random causes, and there is no evidence of stratification around the central line; just like for carbon monoxide and hydrocarbons. In this diagram there are more variations around the central line, and this may suggest that special attention must be paid for $CO_2$ in the polluting gases. When examining the control limits for the average $CO_2$ emissions, it is observed that the upper control limit is 14.35%, the central line is 13.85% and the lower limit of control is 13.35%.

### 3.2 Results with Faults

In this section, the sensitivity of the control limits to induced variations in the vehicle's combustion system is evaluated. A diagram is presented for each analyzed gas in which the control limits obtained are plotted, and the gases emissions without faults are also represented.
When examining figure 4, it is observed that fault 1 (fuel pressure at 60 PSI) produces carbon monoxide emissions higher than the emissions caused by the other two, reaching a maximum of 4.05%. In fact, with the three engine-induced faults, the emissions significantly exceed the control limits and the oscillations of the emissions in the presence of faults

differ significantly from the pattern of the emissions without faults.

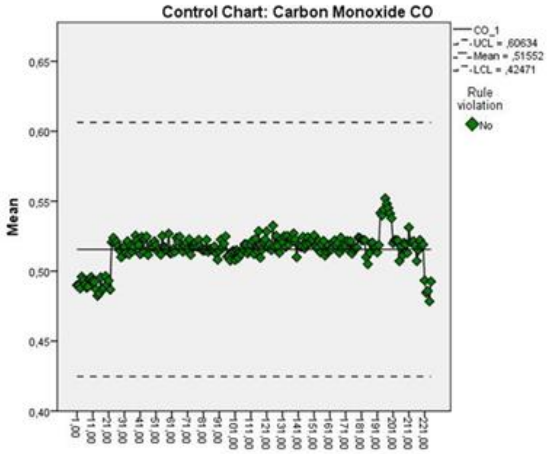


Figure 1. Control chart for the mean of CO

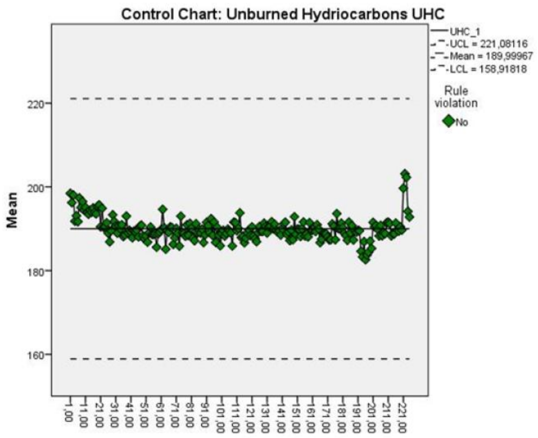


Figure 2. Control chart for the mean of UHC

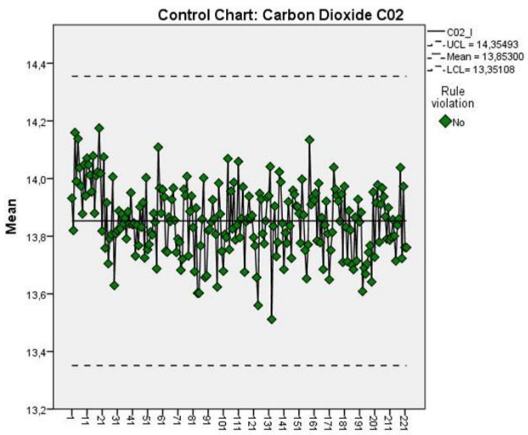


Figure 3. Control chart for the mean of $CO_2$

In figure 5, it is observed that fault 1 (fuel pressure at 60 PSI) produces hydrocarbon emissions higher than the emissions caused by the other two faults. In general, hydrocarbon emissions are above the upper limit of control with fault 1, reaching a maximum of 276.71 ppm. Faults 2 and 3 show large variations or fluctuations behavior, which suggest that the hydrocarbon emissions process is out of control.

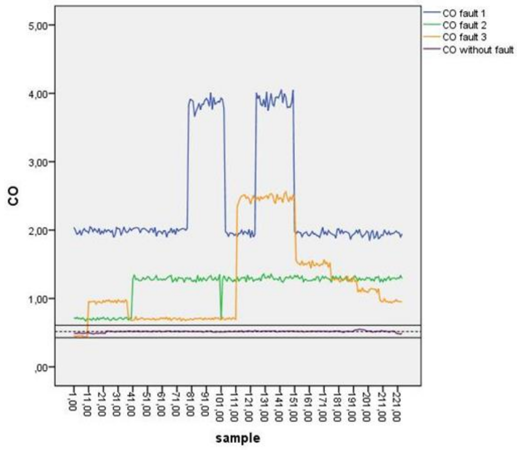


Figure 4. CO Emissions with faults and in Normal Conditions

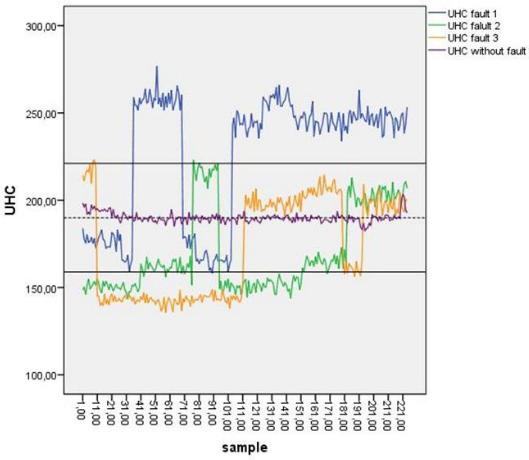


Figure 5. UHC Emissions with faults and in Normal Conditions

When examining figure 6, it is observed that the three types of faults present measurements below and above the control limits. With faults 1 and 2 (variations in fuel pressure) $CO_2$ emissions are higher than those produced or caused by fault 3. When comparing emissions with those reported under optimal operating conditions, the movement or pattern of these emissions differ significantly, and suggest faults. With fault 3 (low ignition voltage), out-of-control emissions are detected below the lower limit, and only a couple of measurements are very close to the upper limit of control.

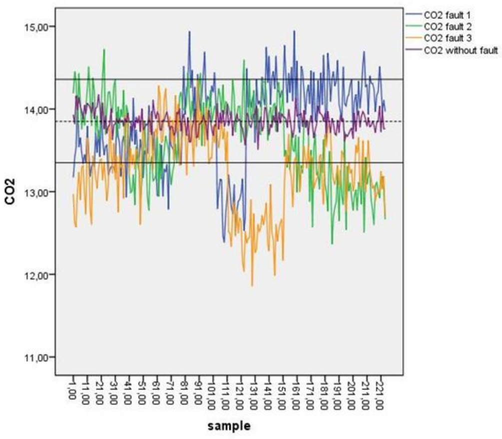


Figure 6. **$CO_2$** Emissions with faults and in Normal Conditions

## 4 Conclusion

In this research, a novel proposal was presented to analyze the emissions of polluting gases generated by faults in spark ignition engines, where a profitable extension of the control charts is shown, which allows defining normal operating ranges and permissible limits of pollution generated from the exhaust gases emanated by them.

According to the results obtained in this research, it can be determined that the increase in fuel pressure (fault 1) and a low level of ignition voltage (fault 3) are the faults that yield the highest emanation values and low respectively; while having only a low level of ignition voltage (fault 3) generates that the combustion process is not carried out correctly, which must be considered in a special way even though it is beneficial for the environment, since it could present a chain of faults in the other systems of the vehicle.

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